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Verification Times Underlying the Kyoto Protocol: Global Benchmark Calculations

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Contents

Abstract

IIASA's Sustainable Boreal Forest Resources (FOR) Project is in the process of deriving full carbon accounts for a number of countries (Russia, Austria, Ukraine, etc.). These carbon accounts permit the Project to make generalized findings and to identify knowledge gaps relevant to the implementation of the Kyoto Protocol. In this study we focus on two questions that are central in this process:

1. What are the verification times arising from the different methods of carbon accounting, and can they be expected to be compatible with the commitment periods foreseen by the Kyoto Protocol?
2. How do verification times change as a result of changes in our knowledge of the underlying uncertainties?

To address these questions, we describe the concepts of favorable and unfavorable verification and calculate the verification times for four global-scale examples. We consider full carbon accounting (FCA) and partial carbon accounting (PCA) under both business-as-usual conditions and in combination with a global afforestation program. Although global in scale, the results of our calculations allow us to draw sub-global conclusions. These conclusions refer to:

- which of the two carbon accounting approaches (PCA or FCA), either in combination with Kyoto compliant land-use, land-use change, and forestry (LUCF) activities or not, represents the most practical method for implementing the Kyoto Protocol;

and, if the Kyoto Protocol is based on PCA under partial inclusion of biological sources and sinks resulting from direct human induced land-use change and forestry activities, to

- whether countries can gain an advantage over other countries by positioning themselves under unfavorable verification conditions by implementing Kyoto compliant LUCF projects; and
- whether the implementation of Kyoto compliant LUCF projects increases the difficulty of validating sub-global Kyoto compliant carbon reporting, thereby increasing the difficulty in conducting FCA-based carbon research at large spatial scales.

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1. Introduction

At its third meeting in Kyoto in 1997, the Conference of the Parties (COP) adopted the Kyoto Protocol (hereafter referred to as the Protocol; UNFCCC, 1999) to the UN Framework Convention on Climate Change (FCCC) (UNFCCC, 1992).[1]

The Protocol contains the first 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), but falls short of prescribing non-compliance measures.[2] For Annex I Parties, the targets agreed upon under the Protocol by the first commitment period (2008 to 2012) add up to a decrease in greenhouse gas emissions of 5.2% below 1990 levels in terms of CO equivalents. Non-Annex I Parties are not required to take on specific commitments for emission reductions. Article 3.3 of the Protocol stipulates that biological sources and sinks resulting from direct human-induced land-use change and forestry activities shall also be used to meet 2008-2012 commitments, but limits these sources and sinks to afforestation, reforestation, and deforestation since 1990. Article 3.4 of the Protocol further provides for the possibility of accounting for additional human activities that cause changes in greenhouse gas emissions. These activities refer to those involving the agricultural soils category and the land-use change and forestry categories. In addition, the Protocol endorses emissions trading (Article 17), joint implementation such as 'bubbling' between Annex I Parties (Articles 4 and 6), and a clean development mechanism (CDM; Article 12) that allows Annex I and non-Annex I Parties to act together to reduce emissions (Bolin, 1998; Schlamadinger and Marland, 1998; Schneider, 1998; UNFCCC, 1998; WBGU, 1998; Jonas *et al.*, 1999).

At its Eighth Session in Bonn in June 1998, the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the COP asked the Intergovernmental Panel on Climate Change (IPCC) to prepare a special report on land-use, land-use change, and forestry (LUCF). The purpose of this request is to enable the COP to decide on recommendations on LUCF issues to the COP/MOP (Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol) at its first session (SBSTA, 1998a).

The report should address the methodological, scientific and technical implications of the LUCF-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 LUCF; 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 asked the IPCC to examine, to the extent possible, the scientific and technical implications of carbon sequestration strategies related to LUCF for potential effects on water, soils, biodiversity, and other environmental and socioeconomic effects. These strategies will be included in the special report as appropriate (SBSTA, 1998a). At its Fourteenth Session in Vienna in October 1998, the IPCC agreed to the SBSTA request and approved the outline of the report due out in mid-2000.

This study reflects our Kyoto Protocol research experience. It deals with the following two questions on the global scale:

1. What are the verification times arising from the different methods of carbon accounting, and can they be expected to be compatible with the commitment periods foreseen by the Kyoto Protocol?[3]
2. How do verification times change as a result of changes in our knowledge of the underlying uncertainties?

Their answers are highly relevant because they will shed light on the verification conditions necessary to implement the Kyoto Protocol, both now and in the future.

To address these questions, we describe the concepts of favorable and unfavorable verification. We define these concepts analytically and in a generalizable fashion by taking advantage of the smoothing effect of large spatial and long temporal averages. Our definition addresses the fact that the verification problem is more than a purely statistical problem by considering the characteristic time scales of the dynamic system under investigation. Based on the definition, we calculate the verification times for four global-scale examples, considering both full carbon accounting (FCA) and partial carbon accounting (PCA) under both business-as-usual conditions and in combination with a global afforestation program. For reasons of data availability, we select the decade of 1980-1989 as the basis for our calculations.

Although global in scale, the results of our calculations allow us to draw sub-global conclusions. These conclusions refer to:

- which of the two carbon accounting approaches (PCA or FCA), either in combination with Kyoto compliant land-use, land-use change, and forestry (LUCF) activities or not, represents the most practical method for implementing the Kyoto Protocol;

and, if the Kyoto Protocol is based on PCA under partial inclusion of biological sources and sinks resulting from direct human induced land-use change and forestry activities, to

- whether countries can gain an advantage over other countries by positioning themselves under unfavorable verification conditions by implementing Kyoto compliant LUCF projects; and
- whether the implementation of Kyoto compliant LUCF projects increases the difficulty of validating sub-global Kyoto compliant carbon reporting, thereby

increasing the difficulty in conducting FCA-based carbon research at large spatial scales.

Our paper is structured as follows. In Section 2 we examine two scientific-methodological issues that are of relevance to the Protocol. These are 1) the issue of land indirectly affected by human activities and 2) the issue of additionality. This examination helps us to characterize our four global-scale examples of verification time calculations relative to each other, in addition to the verification time itself as done in Section 4. The methodology for calculating the verification time is described in Section 3. Section 5 combines the findings of Sections 2 and 4 and examines the implications for the Kyoto Protocol.

Although our approach treats uncertainties that underlie the calculation of verification times in a simplified manner, it provides useful insights. This combination of simplicity and usefulness is the reason why we prefer our approach to more complex approaches that may be developed in the future.

2. Partial Carbon Accounting (PCA) Versus Full Carbon Accounting (FCA)

Section 2 follows up on Jonas *et al.* (1999). We consider PCA and FCA and focus on two scientific-methodological issues that are of relevance to the Protocol, the issue of land indirectly affected by human activities (in contrast to land directly impacted by human activities) and the issue of additionality. In Section 5, we combine our insights gained in Section 2 with our findings of Section 4, which focuses on the calculation of verification times on the global scale. Although this procedure is limited, it will enable us to examine the scientific appropriateness of the Protocol. While proceeding in this constrained fashion, we acknowledge that there are a number of other important scientific-methodological questions that are equally crucial in determining the ultimate success or failure of the Protocol.

2.1 Land indirectly affected by human activities

To begin with, we clarify the area-related, terrestrial-ecosystems aspects of FCA and PCA. Country X may serve as an example (cf. Figure 2-1):

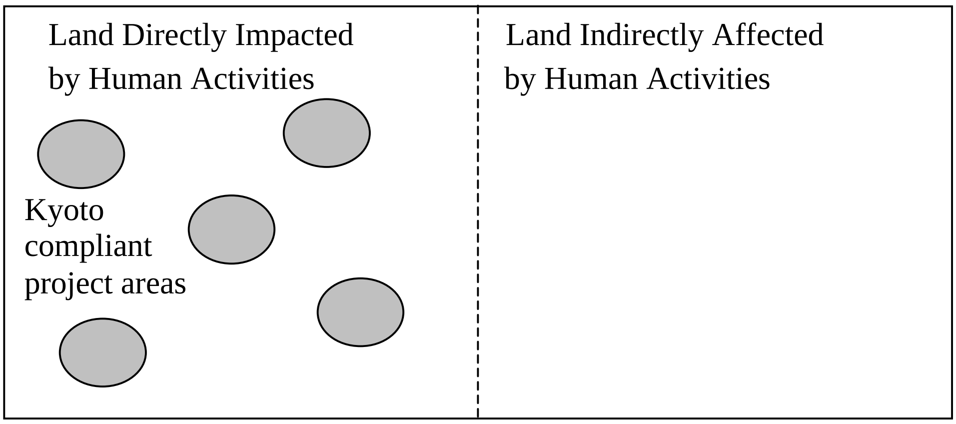


Figure 2-1: Country X, the land of which is subdivided into land directly impacted by human activities and land indirectly affected by human activities.

When using the term FCA, we refer to all terrestrial ecosystems of country X irrespective of whether they are directly impacted or indirectly affected by human activities.[4] (See Appendix I for our complete definition of FCA.)

Users of greenhouse gas guidelines [including the Revised 1996 IPCC Guidelines (IPCC, 1997a, b, c)] increasingly use the term FCA as well. They refer, however, only to the directly human-impacted areas of country X. They do not consider the indirectly human-affected areas. We term this method of accounting for carbon pools and fluxes PCA.

In referring to the Kyoto Protocol, experts occasionally use the term FCA as well. They refer, however, only to Kyoto compliant land-use change and forestry activities (Kyoto compliant activities or projects hereafter), the variety of which may eventually increase because of Article 3.4. These experts believe that a greater variety of Kyoto compliant activities will more accurately reflect the breadth of greenhouse gas guidelines. Lands of country X outside the stipulated project areas that are indirectly affected by human activities are not considered. We also term this method of accounting for carbon pools and fluxes PCA.

Problem 1: PCA — as used in the aforementioned context (i.e., under partial inclusion of biological sources and sinks resulting from direct human-induced land-use change and forestry activities) — is spatially incomplete in considering carbon fluxes into/out of the terrestrial ecosystems. Greenhouse gas guidelines as well as the Kyoto Protocol focus only on areas where direct human-induced changes have taken place and/or are taking place. Separating land directly impacted by human activities from land indirectly affected by human activities, however, may result in carbon accounts that are not only meaningless, but may even lead to false accounting, particularly if adverse effects cannot be recognized immediately (Jonas *et al.*, 1999). Therefore, the scientific challenge prior to using PCA within the framework of the Kyoto Protocol (i.e., under partial inclusion of biological sources and sinks resulting from direct human-induced land-use change and forestry activities) is to demonstrate that indirect human effects are negligible.

2.2 Additionality

Articles 3.3 and 3.4 of the Kyoto Protocol refer only to areas of Kyoto compliant activities and therefore to PCA.[5] Article 6 (joint implementation) and Article 12 (clean development mechanism), as well as other articles, refer to Article 3 and therefore also to PCA. In contrast to Articles 3.3 and 3.4, however, Articles 6.1(b) and 12.5(c) introduce the concept of additionality.[6]

The two basic questions we want to pose here are: what considerations arise in following the concept of additionality, and what requirements are necessary in following the concept of additionality?

What Considerations Arise in Following the Concept of Additionality?

Determining additionality (on a project or a national level) requires a post-t_0 baseline scenario that is continuous in time — in addition to the starting value for year t_0 (t_0 baseline)[7] — for the calculation of the carbon sequestered. In other words, it requires a description of what would have happened to the carbon stock had a specific Kyoto compliant project not been implemented in year t_0. The post-t_0 baseline helps to substantiate that the carbon sequestration claimed is real and additional and the result of a Kyoto compliant activity, over and above what would have occurred in the absence of the emission reduction project (e.g., Sedjo, 1998; Sedjo *et al.*, 1998).[8]

Additionality and post-t_0 baselines are inextricably linked. Determining additionality is inherently problematic because it requires answering the counter-factual question (Vine *et al.*, 1999): What would have happened in the absence of a specific, Kyoto compliant project?

Figure 2-2 illustrates the additionality concept graphically for country X under PCA conditions, as stipulated under the Kyoto Protocol. All Kyoto compliant activities of country X may comply with the additionality concept.

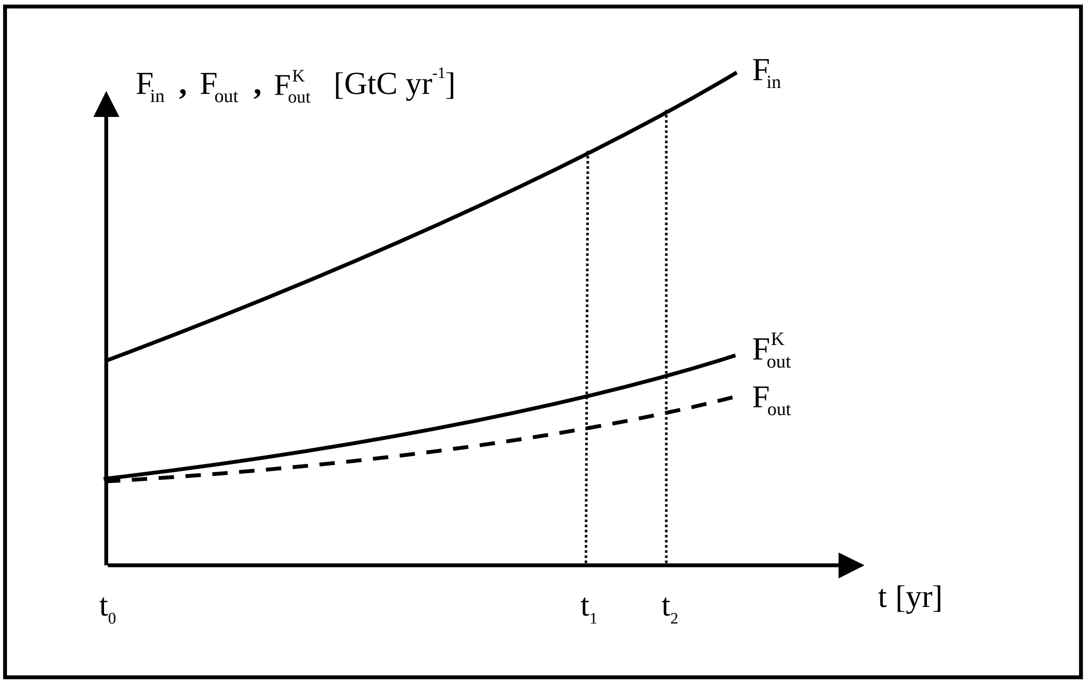


Figure 2-2: The concept of additionality under PCA conditions as stipulated under the Kyoto Protocol, using country X as an example: F_{in} (solid line) shows the total flow of carbon into the atmosphere due to emissions from the sectors energy and industry as well as other sources (as listed in Annex A of the Protocol); and F_{out} (dashed line) shows the total net flow of carbon out of the atmosphere resulting from biological sources and sinks restricted to areas of Kyoto compliant activities, on the assumption that they are not realized (post-t_0 baseline scenario). Here F_{in} and F_{out} may increase, without restricting generality. The implementation of Kyoto compliant projects at time t_0 results in F_{out}^{K} (solid line), which may reflect an increase in the total net flow of carbon out of the atmosphere, that is, a gradual increase over F_{out} over time. As a matter of principle, the post-t_0 baseline scenario $F_{out}(t)$ needs to be known at any time t $(t > t_0)$ in order to determine the carbon that is claimed additional, e.g.,

at time t_2
and
at time t_2 relative to time t_0 $\Bigg\}$ $\left[F_{out}^{K}(t_2) - F_{out}(t_2)\right]$

or

at time t_2 relative to time t_1 $\Big\}$ $\left\{\left[F_{out}^{K}(t_2) - F_{out}(t_2)\right] - \left[F_{out}^{K}(t_1) - F_{out}(t_1)\right]\right\}$

where $t_0 < t_1 < t_2$.

Problem 2: Without a post-t_0 baseline scenario, it is not possible to prove that the carbon claimed has been sequestered additionally and is the result of one or more Kyoto compliant activities. Additionality may or may not be given. As an example, we consider the following situation: Prior to 1990, country X may have decided to make use of its total abandoned agricultural and fallow land only for natural forest regeneration purposes, say, from the early 1990s on. After having found out about the incentives given under the Kyoto Protocol, country X may have changed its decision and decided to afforest this land by fast growing, single-species tree cultures, which in the medium to long term may be less effective in sequestering carbon than naturally regrowing forests. Thus, although carbon is sequestered, additionality may not be given in the medium to long term.[9] Concomitantly, the example shows that post-t_0 baseline scenarios can only be defined in an arbitrary fashion.

In essence, maintaining compliance with the additionality concept creates the challenge to provide instructions on how to implement it, including post-t_0 baselines, in some agreed, 'standard-arbitrary' fashion. In contrast, in the case that compliance with the additionality concept is not maintained, the challenge is to agree on a set of Kyoto compliant activities that are believed (or known) to meet the carbon-sequestration objective to the best of our knowledge (also see Problem 3 below).

<u>What are the Requirements in Following the Concept of Additionality?</u>

The characteristic time scale underlying the concept of additionality, i.e., the dynamics underlying long-term (and nonlinear) biological sources and sinks, is not compatible with the time scale given by the commitment periods of the Kyoto Protocol.

Example 1: In the example mentioned under Problem 2 above, we may face the situation that, in the short term, the fast growing, single-species tree cultures may sequester more carbon than the naturally regrowing forests — in contrast to sequestration conditions prevailing in the medium to long term. Thus, the crucial question is: How meaningful is the concept of additionality on a short time scale?

Example 2: Afforesting some abandoned agricultural land with exotic (non-domestic), carbon-rich tree species may prove not sustainable, say, after two or three rotation periods — in contrast to afforesting domestic tree species, albeit not as carbon-rich. This leads us to another crucial question, beyond the one posed in Example 1: Which criteria, in addition to the additionality concept, must be followed in implementing Kyoto compliant projects? Criteria that support the proper functioning of ecosystems and maintain their amenities may be considered.

Problem 3: The scientific challenge prior to using PCA within the framework of the Kyoto Protocol (i.e., under partial inclusion of biological sources and sinks, resulting from direct human-induced land-use change and forestry activities) is to ensure that additionality is considered (in this case, quantitatively considered) on a long-term basis and to put incentives in place which reflect the entire set of objectives to be met by Kyoto compliant activities, not simply the long-term carbon-sequestration objective.[10]

This challenge is also valid if carbon sequestration is practiced in a 'to-the-best-of-our-knowledge' fashion (see Problem 2 above) rather than in a 'standard-arbitrary' fashion by applying the additionality concept (i.e., post-t_0 baseline scenarios).

Table 2-1 summarizes our discussion under Section 2. It lists the scientific problems COP/MOP is facing in its decisions on how to account for carbon (PCA versus FCA) and whether or not to implement the concept of additionality. It is important to note that FCA takes into account the issue of land indirectly affected by human activities, but faces the same problems as PCA in dealing with the issue of additionality.

Table 2-1: Table summarizing the scientific problems underlying COP/MOP's decision options in regard to carbon accounting (PCA versus FCA) and complying or not with the concept of additionality. The bold numbers **1**, **2** and **3** refer to the problems discussed in the text.

	Case		Scientific Problem
PCA	**I**	**No compliance with additionality** Articles 3.3 and 3.4 as well as Articles 6.1(b) and 12.5(c) will not follow the additionality concept.	**Articles 3.3, 3.4, 6.1(b) and 12.5(c):** **1:** Land indirectly affected by human activities is disregarded. **2:** Kyoto compliant activities must be agreed on that are believed to meet the carbon sequestration objective to the best of our knowledge. Additionality may or may not be given. **3:** Carbon sequestration must be long-term. Kyoto compliant activities must meet environmental protection objectives, in addition to the carbon sequestration objective.
	II	**Partial compliance with additionality** Articles 3.3 and 3.4 will not follow the additionality concept Articles 6.1(b) and 12.5(c) will follow the additionality concept.	**A) Articles 3.3 and 3.4:** See PCA, Case I. **B) Articles 6.1(b) and 12.5(c):** **1:** Land indirectly affected by human activities is disregarded. **2:** 'Standard-arbitrary' instructions how to implement the additionality concept, including post-t_0 baseline scenarios, must be agreed on. **3:** Additionality must be measured on a long-term basis. Kyoto compliant activities must meet environmental protection objectives, over and above the carbon sequestration objective.
	III	**Compliance with additionality** Articles 3.3 and 3.4 as well as Articles 6.1(b) and 12.5(c) will follow the additionality concept.	**Articles 3.3, 3.4, 6.1(b) and 12.5(c):** See PCA, Case II, Point B.
FCA	**I**	**No compliance with additionality** Articles 3.3 and 3.4 as well as Articles 6.1(b) and 12.5(c) will not follow the additionality concept.	**Articles 3.3, 3.4, 6.1(b) and 12.5(c):** **2:** Kyoto compliant activities must be agreed on that are believed to meet the C-sequestration objective to the best of our knowledge. Additionality may or may not be given. **3:** Carbon sequestration must be long-term. Kyoto compliant activities must meet environmental protection objectives, over and above the carbon sequestration objective.
	II	**Partial compliance with additionality** Articles 3.3 and 3.4 will not follow the additionality concept. Articles 6.1(b) and 12.5(c) will follow the additionality concept.	**A) Articles 3.3 and 3.4:** See FCA, Case I. **B) Articles 6.1(b) and 12.5(c):** **2:** 'Standard-arbitrary' instructions how to implement the additionality concept, including post- t_0 baseline scenarios, must be agreed on. **3:** Additionality must be measured on a long-term basis. Kyoto compliant activities must meet environmental protection objectives, over and above the carbon sequestration objective.
	III	**Compliance with additionality** Articles 3.3 and 3.4 as well as Articles 6.1(b) and 12.5(c) will follow the additionality concept.	**Articles 3.3, 3.4, 6.1(b) and 12.5(c):** See FCA, Case II, Point B.

3. Methodology

Section 3 demonstrates the method for determining the verification time for a dynamical system. This leads to Section 4, where we calculate the verification times for several global-scale examples.

Let us assume that either full carbon accounting or some form of partial source-sink (i.e., net) carbon accounting is applied to the entire globe. The net carbon emissions reported require verification (irrespective of whether or not emission reduction measures have been applied). We pose the following two questions:

1. What are the verification times arising from the different methods of carbon accounting, and can they be expected to be compatible with the commitment periods foreseen by the Kyoto Protocol?
2. How do verification times change depending on changes in our knowledge of the underlying uncertainties?

To address these questions, we distinguish between favorable and unfavorable verification conditions, explained below, and apply — without restricting generality — simple first-order (i.e., linear) approximations to project changes in net carbon emissions and our knowledge of the underlying uncertainties. By doing so, we:

- restrict our approach to large spatial (global) and long temporal (at least decadal) scales, considering that averaging conditions (smoothing) are more favorable at larger spatial/longer temporal scales than at smaller spatial/shorter temporal scales.
- acknowledge that the verification problem is more than a purely statistical problem[11] by not neglecting the characteristic time scales of the dynamic system under investigation.

To begin with, we discuss what we consider a reasonable standard condition for verification. This condition states that the absolute change in the country's net carbon emissions, $|\Delta F_{net}(t_2)|$ at time t_2, with reference to time t_1 ($t_1 < t_2$), is greater than the uncertainty in the reported net carbon emissions at time t_2. This condition permits favorable verification, that is, verification that is compatible with the reported change in net carbon emissions:

$$|\Delta F_{net}(t_2)| > \varepsilon(t_2) \ , \qquad (3\text{-}1)$$

or, under the non-restrictive assumption that first-order (i.e., linear) approximations are applicable,

$$\left|\frac{dF_{net}}{dt}\right|_{t_1} \Delta t > \varepsilon(t_2) \qquad (3\text{-}2)$$

(cf. Figure 3-1), where F_{net} describes the net carbon emissions and $\pm\varepsilon$ (defined via F^+ and F^-, the upper and lower uncertainty limits of the net carbon emissions) the uncertainty in F_{net}. We call Δt the verification time for the dynamical system considered under equations (3-1) and (3-2).[12]

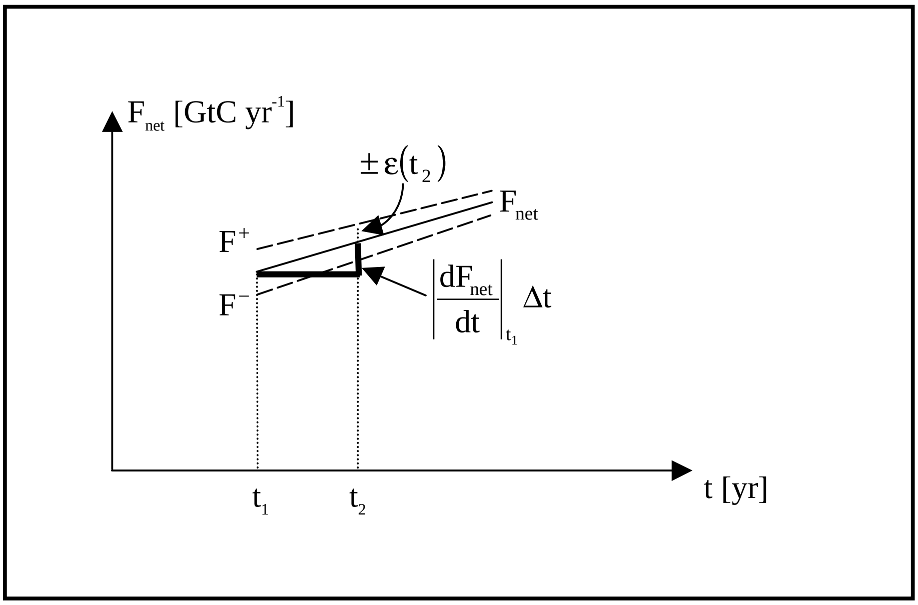


Figure 3-1: Favorable verification: Simplified linear graphical representation of equation (3-1) for increasing net carbon emissions (F_{net}) and a decrease in their uncertainty ($\pm\,\varepsilon$).

Equation (3-2) informs us that

a) the smaller the projected uncertainty ε in F_{net} for a given Δt, the smaller can be the change in F_{net} that can be agreed upon and favorably verified; or, equivalently,

b) the smaller the projected uncertainty ε in F_{net} for a given (i.e., agreed) change in F_{net}, the smaller is Δt after which the change in F_{net} can be favorably verified.

We will employ equation (3-2) according to option b below. The case of stabilizing net carbon emissions (resulting in unfavorable verification conditions) requires further discussion (see below).

With the help of

$$2\varepsilon(t_1) = F^+(t_1) - F^-(t_1) \tag{3-3}$$

and

$$2\varepsilon(t_2) = F^+(t_2) - F^-(t_2) \tag{3-4a}$$

$$= \left\{F^+(t_1) + \left(\frac{dF^+}{dt}\right)_{t_1} \Delta t\right\} - \left\{F^-(t_1) + \left(\frac{dF^-}{dt}\right)_{t_1} \Delta t\right\} \tag{3-4b}$$

$$= 2\varepsilon(t_1) + 2\left(\frac{d\varepsilon}{dt}\right)_{t_1} \Delta t \ , \tag{3-4c}$$

we can rewrite equation (3-2):

$$\left|\frac{dF_{net}}{dt}\right|_{t_1} \Delta t > \varepsilon(t_1) + \left(\frac{d\varepsilon}{dt}\right)_{t_1} \Delta t \ . \tag{3-5}$$

Therefore:

$$\Delta t > \frac{\varepsilon(t_1)}{\left|\frac{dF_{net}}{dt}\right|_{t_1} - \left(\frac{d\varepsilon}{dt}\right)_{t_1}} \ . \tag{3-6}$$

In this study we consider equation 3-6 for the case $\left|\frac{dF_{net}}{dt}\right|_{t_1} > \left(\frac{d\varepsilon}{dt}\right)_{t_1}$. Note that a probabilistic approach may lead to an even greater verification time. In Appendix III, we describe how to generalize our linear-averaging approach and improve its applicability in terms of space and time.

In the case of stabilizing net carbon emissions, we face the situation of $\left|\frac{dF_{net}}{dt}\right|$ approaching zero in equation (3-6), while $\varepsilon(t)$ may still be far away from approaching a constant value that is sufficiently small and $\left(\frac{d\varepsilon}{dt}\right)$ may still be far away from approaching zero. We term this situation "unfavorable verification". The concept of favorable verification must be given up, as the notion of verification time becomes impractical to apply, and the concept of favorable verification must be replaced by another (e.g., statistical[11]) concept. A wide uncertainty range remains extremely unsatisfying for any verification procedure as long as ε stays large and decreases only slowly in time.

In Section 4, we apply the concept of favorable verification to full and partial source-sink (i.e., net) carbon accounting on the global scale. We are interested in the verification times involved and how they change depending on changes in our knowledge of the underlying uncertainties. Currently, we do not deal with unfavorable verification conditions, although this may receive our attention in a follow-up study.

4. Global Verification Times

In Section 4 the verification times for four global-scale examples are calculated. As in Section 3, let us assume that either full carbon accounting or some form of partial source-sink (i.e., net) carbon accounting is applied to the entire globe. We are interested in answering the two questions posed at the beginning of Section 3, presupposing favorable verification conditions:

1. What are the verification times arising from the different methods of carbon accounting and can they be expected to be compatible with the commitment periods foreseen by the Kyoto Protocol?
2. How do verification times change depending on changes in our knowledge of the underlying uncertainties?

We apply – without restricting generality – first-order (i.e., linear) approximations to project changes in net carbon emissions and our knowledge of the underlying uncertainties. In doing so, we assume that the combination of global-decadal space-time scales is appropriate. For reasons of data availability, we select the decade of 1980-1989 as the basis for our calculations.

4.1 FCA: Business-as-Usual Case (BaU)

In Section 4.1, we consider FCA under business-as-usual conditions.

From Schimel *et al.* (IPCC, 1996a, p. 79, Table 2.1) and Tans and Wallace (1999, p. 563), we can infer, for 1980 to 1989, the average annual carbon flows into and out of the atmosphere, the atmospheric carbon storage, and the error limits involved (which correspond to an estimated 90% confidence interval) (cf. Figure 4-1). The overall uncertainty of the total carbon flow into/out of the atmosphere, arising from the combination of the carbon sub-flows into/out of the atmosphere, is calculated (similar to the standard deviation) as the square root of the sum of the squares of the individual uncertainties in accordance to the procedure applied by Schimel *et al.* (IPCC, 1996a) and Tans and Wallace (1999) as well as other authors (e.g., Heimann *et al.*, 1999).[13]

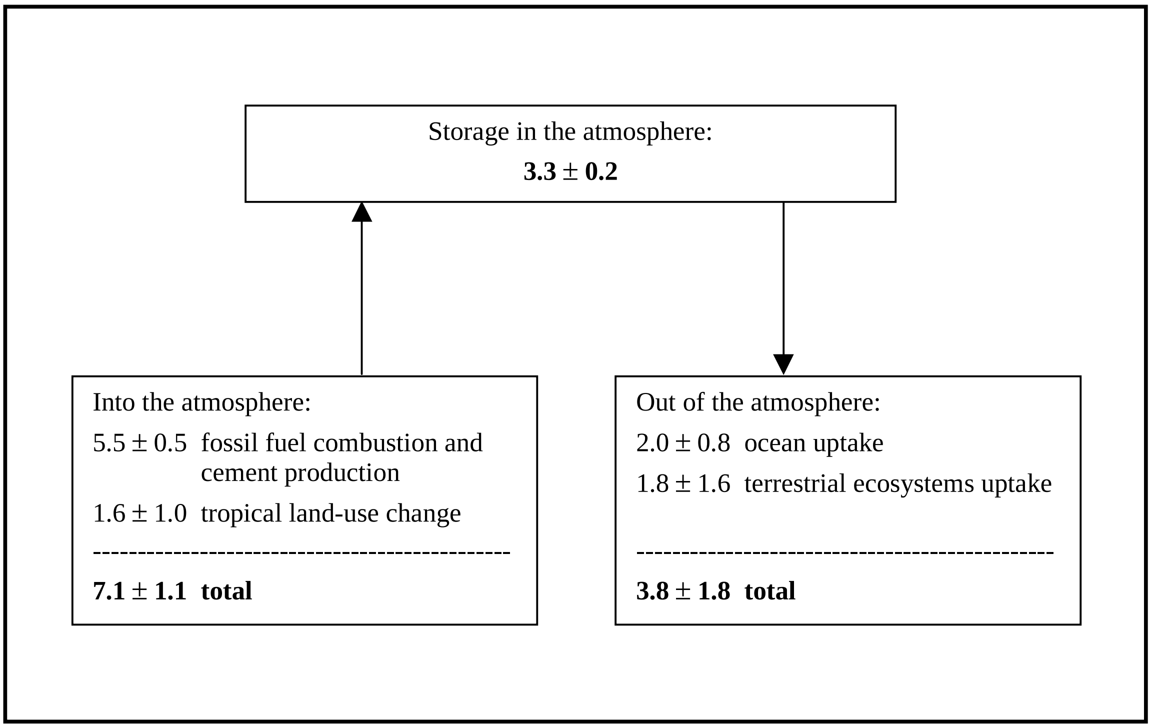


Figure 4-1: Average annual budget of CO_2 perturbations for 1980 to 1989 (IPCC, 1996a; Tans and Wallace, 1999). Flows and reservoir changes are expressed in GtC yr^{-1}; error limits correspond to an estimated 90% confidence interval.

If we specify:

- t_1 = 1 Jan. 00GMT, 1985 (i.e., the exact middle of the decade)

  as the mean over the period 1980 to 1989;

- $$\left|\frac{dF_{BaU}}{dt}\right|_{t_1} \approx \frac{0.184\,\text{ppmv yr}^{-1}}{(1\,\text{Jan.00GMT,1990} - 1\,\text{Jan.00GMT,1980})\,\text{yr}} \frac{3.2\,\text{GtC yr}^{-1}}{1.53\,\text{ppmv yr}^{-1}} \approx 0.039\frac{\text{GtC yr}^{-1}}{\text{yr}},$$ [14]

  as the rate of change in $F_{BaU}(t_1)$, the net carbon emissions into the atmosphere, which can be inferred from Figure 2.2 in IPCC (1996a, p. 81) [or Figure 1(b) in IPCC (1996a, p. 16;][15] (cf. Appendix IV) and from Section 1.3.3.2 in IPCC (1995, p. 49);[16] and

- $\varepsilon_{BaU}(t_1) \approx 2.1\text{GtC yr}^{-1}$,

  as the uncertainty in $F_{BaU}(t_1)$, which can be derived from the uncertainties of the total carbon flows into and out of the atmosphere in Figure 4-1;[17]

equation (3-6) can be used in the form

$$\Delta t > \frac{\varepsilon_{BaU}(t_1)}{\left|\frac{dF_{BaU}}{dt}\right|_{t_1} - \left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1}} \qquad (3\text{-}6a)$$

and plotted as a function of $\left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1}$, the rate of change in ε_{BaU} (cf. Figure 4-2).

In consideration of the underlying assumptions, Figure 4-2 tells us that:

- it will take at least 54 years until full carbon net accounting can be favorably verified if the uncertainty in F_{BaU} cannot be decreased;
- it will take at least 23 years until full carbon net accounting can be favorably verified if the uncertainty in F_{BaU} can only be decreased by 25% over the next 10 years;
- it will take at least 15 years until full carbon net accounting can be favorably verified even if the uncertainty in F_{BaU} can be decreased by 50% over the next 10 years;
- the $\Delta t - \left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1}$ function will move upwards (that is, towards greater verification times), if $\left|\frac{dF_{BaU}}{dt}\right|$ decreases, and vice versa. [Equation (3-6a) depends sensitively upon the rate of change in F_{BaU}.][18]

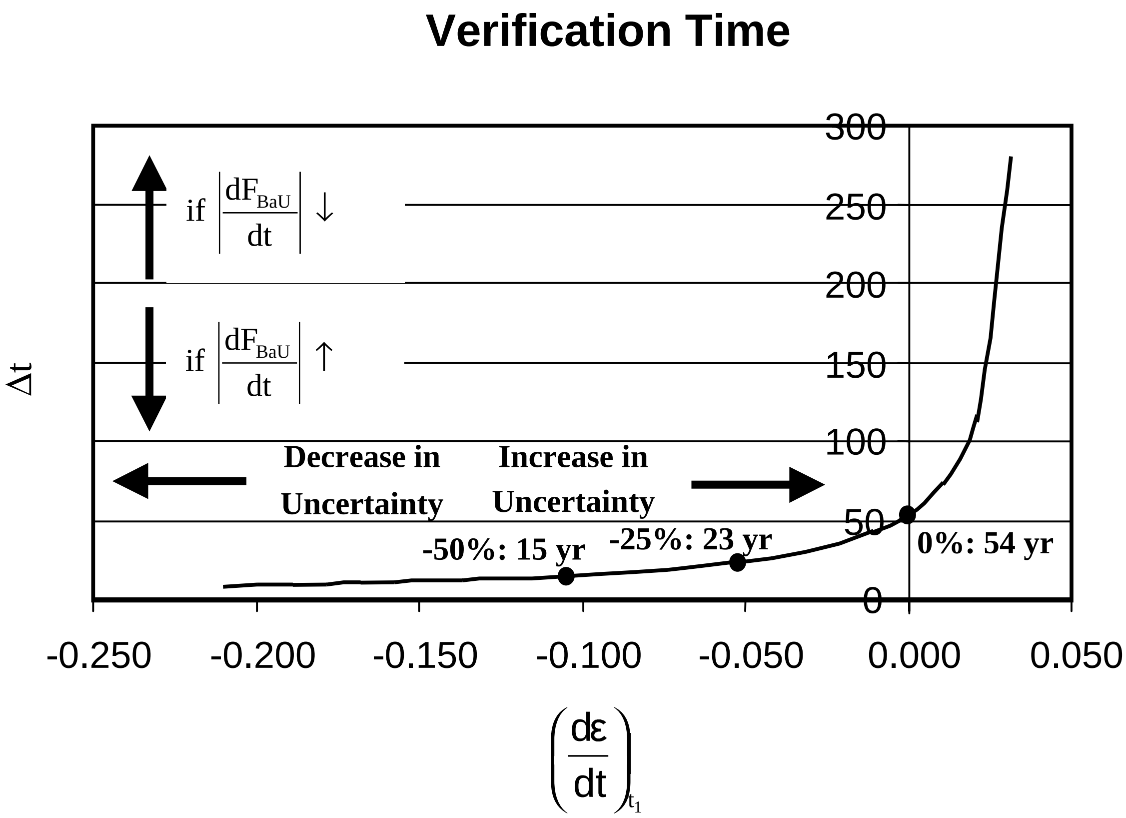


Figure 4-2: Verification time for FCA under business-as-usual conditions: Graphical representation of equation (3-6a). The ordinate gives the minimum time [in years] that is needed to favorably verify a change in the global net carbon emissions, given their today's rate of change. The abscissa permits assumptions on how the uncertainty that underlies the global net carbon emissions may change [in a first-order (linear) fashion] in the future [in (GtC yr^{-1}) / yr].

In the second and third statement above, we translated the question "*What does a specific value of* $\left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1}$ *, the rate of change in the uncertainty in* F_{BaU} *, mean?*" into understandable terms. To do so, we related a specific $\left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1}$ -value to a, e.g., 10-year basis, as follows:

$$\varepsilon_{BaU}(t_2) = R\varepsilon_{BaU}(t_1) = \varepsilon_{BaU}(t_1) + \left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1} \Delta t_{10} \ , \qquad (4\text{-}1a,b)$$

or, equivalently,

$$R = 1 + \frac{\left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1} \Delta t_{10}}{\varepsilon_{BaU}(t_1)} \ , \qquad (4\text{-}2)$$

where $\Delta t_{10} = 10 \text{ years}$ and the factor $(R-1)100\%$ describes the change of $\varepsilon(t_2)$ relative to $\varepsilon(t_1)$ in percent. We selected $\left(\frac{d\varepsilon_{BaU}}{dt}\right)_{t_1}$ -values that correspond to $[(R-1)100\%]$-values of -25% and -50%.

We proceed similarly in Sections 4.2, 4.3 and 4.4.

4.2 FCA: Global Afforestation Case (Aff)

In Section 4.2 we consider FCA and combine the business-as-usual case, discussed in Section 4.1, with the global afforestation program (Aff), described by Nilsson and Schopfhauser (1995). (For reasons of convenience, we refer to their afforestation program by ‘Aff’ hereafter.) Additionality may or may not be given.

The global afforestation program described in Nilsson and Schopfhauser (1995) covers only about 345 Mha that they regard as suitable for large-scale plantations for the sole purpose of sequestering carbon, 275 Mha for plantations and 70 Mha for agroforestry. They assumed that the program is implemented during the period of 1995 to 2050. (The implementation time varies for different regions.) In their calculations of the carbon-sequestration effects, Nilsson and Schopfhauser (1995) consider carbon uptake by above- and below-ground biomass for the period of 1995 to 2095 relative to the land-use/cover situation before planting. They do not consider the issue of additionality, i.e., post-planting baseline scenarios for the calculation of what would have happened to the initial carbon stocks had the afforestation projects not been implemented.[19]

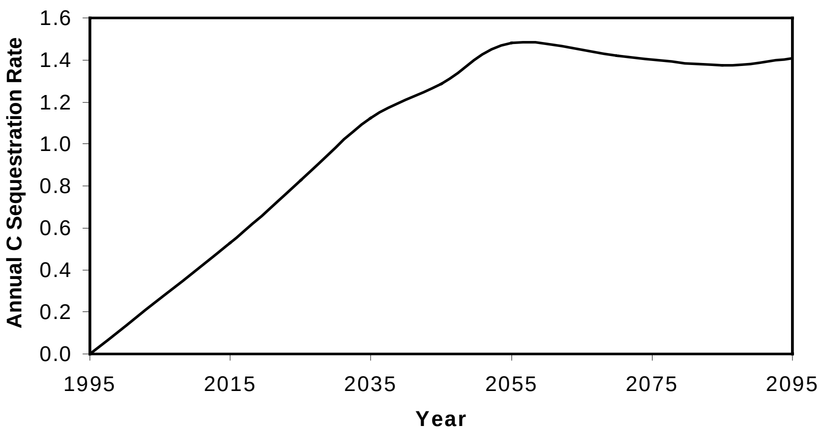


Figure 4-3: Nilsson and Schopfhauser's (1995) 1995-2095 global afforestation program: Estimates of annual carbon fixation rates (in GtC yr^{-1}).

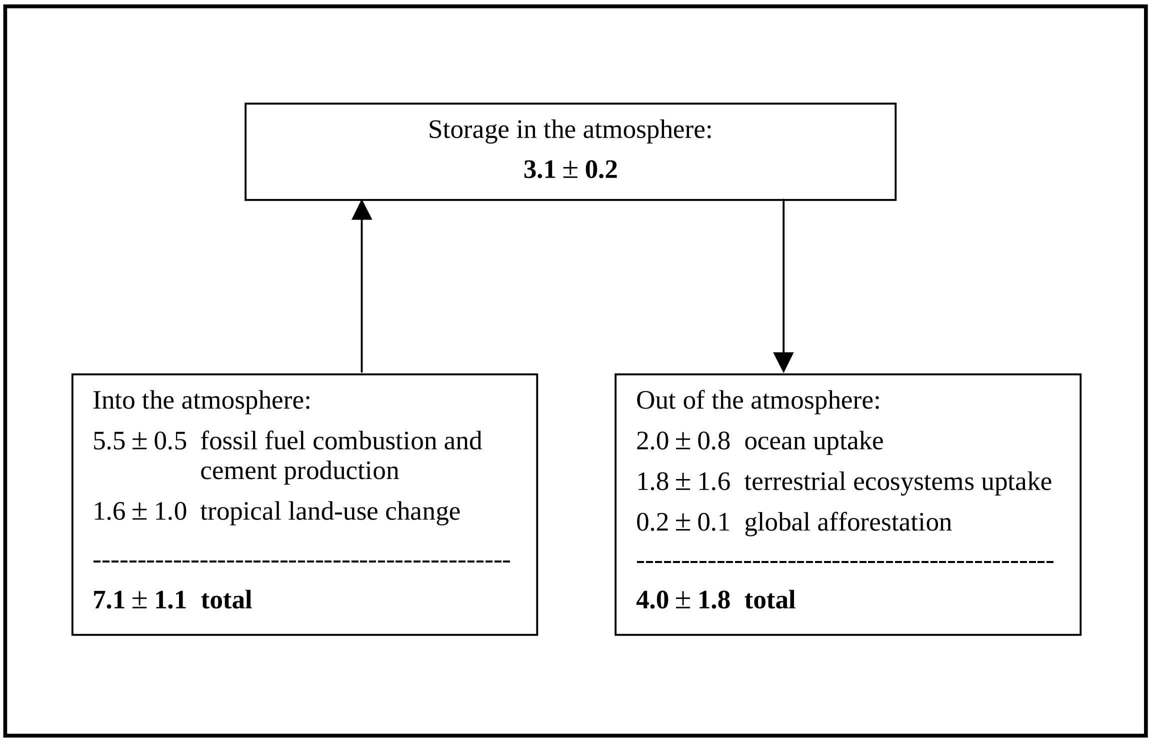


Figure 4-4: Average annual budget of CO_2 perturbations for 1980 to 1989 (business-as-usual case), as shown in Figure 4-1, on which is superimposed Nilsson and Schopfhauser's (1995) global afforestation program, the start of which is set at 1980 for the purposes of this study. Flows and reservoir changes are expressed in GtC yr^{-1}.

Nilsson and Schopfhauser (1995) report that the impact of the proposed plantation program on the carbon balance would become significant only after 40 to 50 years, and that the maximum carbon fixation rate of 1.48 GtC yr^{-1} would be reached about 60 years after the initiation of the plantation program (cf. Figure 4-3). Over the 100-year period studied, the proposed global plantation program would sequester a total of some 104 GtC.

For the purposes of our study, we let the global afforestation program start (without restricting generality) in 1980, instead of 1995, and assume that impacts upon the global carbon budget other than through afforestation (e.g., carbon losses due to deforestation or degradation from tropical fuelwood extraction) are included within the underlying business-as-usual case, as before. In addition, we assume that the global afforestation program does not result in any negative or positive effects that may indirectly affect the global carbon balance, due to our inability to quantify such effects. As already noted earlier (cf. Section 2), this assumption is crucial.

To superimpose the global afforestation program on the underlying business-as-usual case, it is sufficient to consider the initial 60 years of the program in a first-order (linear) fashion.[20] By applying linear regression, we find 0.037 GtC yr^{-1} for the intercept (in year 0 = 1980), 0.025 (GtC yr^{-1}) / yr for the rate of change in the sequestration rate, 0.996 for the correlation coefficient, and 0.162 GtC yr^{-1} for the average annual sequestration effect during the first decade, i.e., the period of 1980 to 1989. In consideration of the multiple assumptions and data limitations underlying their calculations, Nilsson and Schopfhauser (1995) estimate the uncertainty in the calculated sequestration rates roughly to be in the order of ± (30-50)%. For lack of better knowledge, we select an uncertainty of ± 40%.

Figure 4-4 shows the superposition of the global afforestation program on the average annual budget of CO_2 perturbations for 1980 to 1989 business-as-usual case shown in Figure 4-1. It is important to note that the overall uncertainty of the total carbon flow out of the atmosphere (and, thus, of the net carbon flow into the atmosphere) practically remains unchanged. We continue to apply a rounding procedure to the first decimal place.

To calculate the verification time for the Aff case, we use equation (3-6) in the form

$$\Delta t > \frac{\varepsilon_{Aff}(t_1)}{\left|\frac{dF_{Aff}}{dt}\right|_{t_1} - \left(\frac{d\varepsilon_{Aff}}{dt}\right)_{t_1}} \approx \frac{\varepsilon_{BaU}(t_1)}{\left|\left(\frac{dF_{BaU}}{dt}\right)_{t_1} - m_{Aff}(t_1)\right| - \left(\frac{d\varepsilon_{Aff}}{dt}\right)_{t_1}}, \qquad (3\text{-}6b)$$

where

- $m_{Aff}(t_1) \approx 0.025 \frac{\text{GtC yr}^{-1}}{\text{yr}}$

  describes the rate of change in the sequestration rate,

- $\left|\frac{dF_{Aff}}{dt}\right|_{t_1} = \left|\left(\frac{dF_{BaU}}{dt}\right)_{t_1} - m_{Aff}(t_1)\right| \approx (0.039 - 0.025)\frac{\text{GtC yr}^{-1}}{\text{yr}} = 0.014\frac{\text{GtC yr}^{-1}}{\text{yr}}$

  the rate of change in $F_{Aff}(t_1)$, the net carbon emissions into the atmosphere, and

- $\varepsilon_{Aff}(t_1) \approx \varepsilon_{BaU}(t_1) \approx 2.1\text{GtC yr}^{-1}$

  their uncertainty.

Other specifications are as in Section 4.1.

Figure 4-5 represents equation (3-6b) graphically (the upper curve). For purposes of comparison, we also represent equation (3-6a) from Figure 4-2 (the lower curve). Note that, for the reasons pointed out above, equation (3-6b) should be applied only for the period of 1980 to 2040 and not be extended beyond 2040.[20]

Considering FCA under business-as-usual conditions in combination with the global afforestation program, the upper curve in Figure 4-5 tells us that:

- the carbon-accounting of the Aff system is less easy to verify. The verification time increases, relative to the same, fully carbon-accounted system under business-as-usual conditions only (lower curve in Figure 4-5). This is the result of

$0 < \left| \frac{dF_{BaU}}{dt} - m_{Aff} \right| < \left| \frac{dF_{BaU}}{dt} \right|$ [cf. denominators in equations (3-6b) and (3-6a)]. In other words, net carbon emissions into the atmosphere increase, under the combination of business-as-usual conditions and the global afforestation program, at a smaller rate than under business-as-usual conditions only. The uncertainties in the net carbon emissions remain practically indiscernible from each other. Under the global afforestation program (or any other carbon sequestration program with similar characteristics), verification approaches a situation that we term "unfavorable verification under unsatisfying boundary conditions" (cf. Section 3).

- it will take considerably more than 60 years until full carbon net accounting can be favorably verified if the uncertainty in F_{BaU} cannot be decreased. (We recall that the uncertainty in m_{Aff}, the rate of change in the sequestration rate, does not matter.)
- it will take at least 32 years until full carbon net accounting can be favorably verified if the uncertainty in F_{BaU} can only be decreased by 25% over the next 10 years.
- it will take at least 18 years until full carbon net accounting can be favorably verified even if the uncertainty in F_{BaU} can be decreased by 50% over the next 10 years.

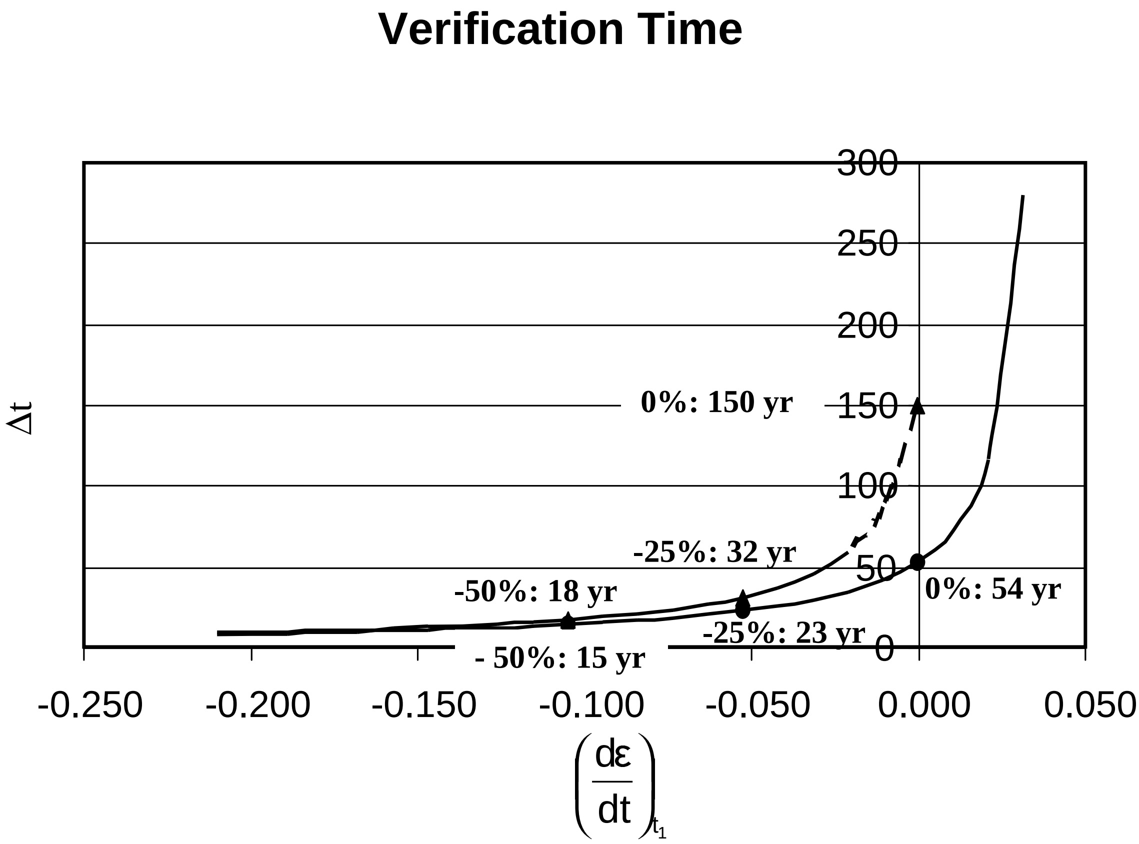


Figure 4-5: Verification time for FCA under business-as-usual conditions in combination with Nilsson and Schopfhauser's (1995) global afforestation program (upper curve): Graphical representation of equation (3-6b). Note that our approach, which is based on first-order (linear) approximations and which underlies equation (3-6b), should be applied only for the period of 1980 to 2040, and not be extended beyond 2040. (The dashed right end of the upper curve represents a verification time that extends beyond 2040.) For comparison, the verification time for FCA under business-as-usual conditions only, as shown in Figure 4-2, is included in the figure (lower curve).

4.3 PCA: Fossil Fuel Case (FF)

In Section 4.3 we consider PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production (FF emissions hereafter) — i.e., excluding CO_2 emissions from changes in tropical land-use and CO_2 uptake by oceans and terrestrial ecosystems — under business-as-usual conditions. Figure 4-6 shows the PCA approach that we follow. It forms a logical and consistent subset of the FCA approach shown in Figure 4-1.

We make use of the FF emissions data reported by the Carbon Dioxide Information Analysis Center at the Oak Ridge National Laboratory (Marland *et al.*, 1999); they are shown in Figure 4-7 below. [See also Figure 1.7 in IPCC (1995, p. 47) and Figure 1(a) in IPCC (1996a, p. 16).]

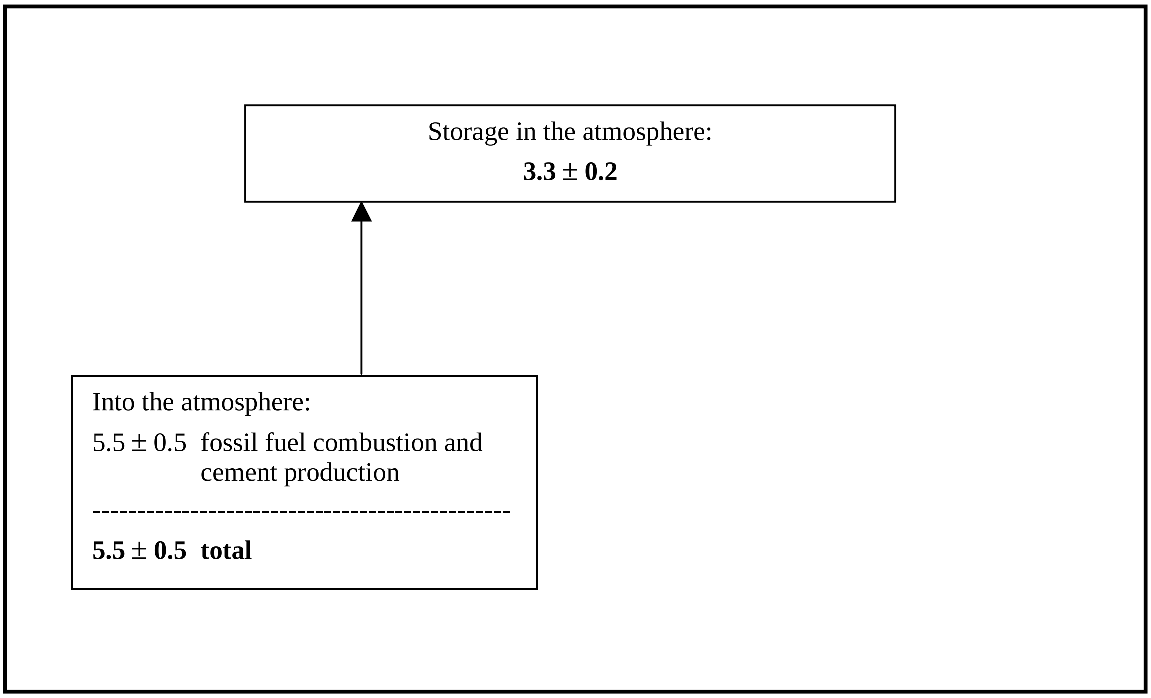


Figure 4-6: Average annual budget of CO_2 perturbations for 1980 to 1989 (business-as-usual case), as shown in Figure 4-1, restricted to CO_2 emissions from fossil fuel combustion and cement production. Flows and reservoir changes are expressed in GtC yr^{-1}.

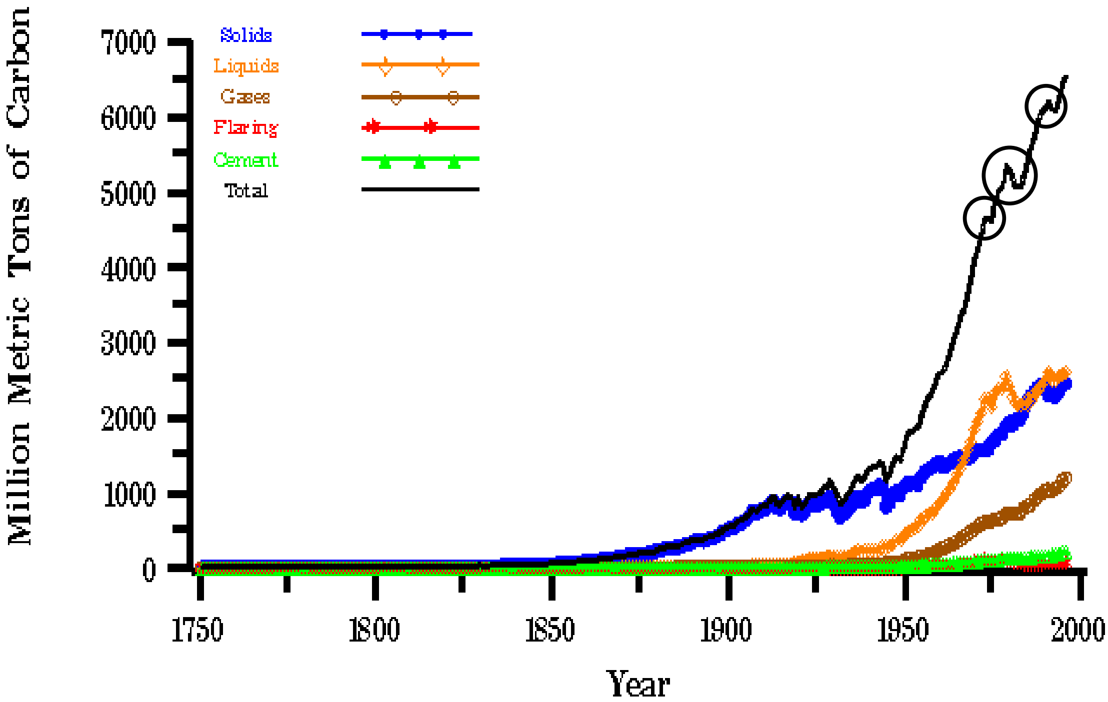


Figure 4-7: Global CO_2 emissions (in MtC yr^{-1}) from fossil fuel burning (including gas flaring) and cement production for 1751-1996. See text for explanations of circles.

Source: Marland *et al*. (1999); taken from http://cdiac.esd.ornl.gov/trends/emis/tre_glob.htm (modified).

For the purposes of our study, it is important to mention that we can characterize the FF emissions since 1960 in a simplified fashion, namely by (four) linear curves. These curves are displaced relative to each other (see the three circles in Figure 4-7, indicating the three displacements in time between 1973–1975, 1979–1983 and 1991–1993), but all demonstrate more or less the same steep increase. We recall that the verification time is determined by the increase in FF emissions stepwise in terms of time [cf. equation (3-6) above or equation (3-6c) below)], not by their lateral displacements to each other.[21]

We select the period of 1983-1991 (instead of the period 1980-1989, to which we refer) to capture the increase in FF emissions. We find 5.112 GtC yr^{-1} for the intercept (in year 0 = 1983), 0.146 (GtC yr^{-1}) / yr for the rate of change in the FF emissions, and 0.989 for the correlation coefficient.

To calculate the verification time underlying the FF case, we use equation (3-6) in the form

$$\Delta t > \frac{\varepsilon_{FF}(t_1)}{\left|\frac{dF_{FF}}{dt}\right|_{t_1} - \left(\frac{d\varepsilon_{FF}}{dt}\right)_{t_1}} , \qquad (3\text{-}6c)$$

where

- $\left|\frac{dF_{FF}}{dt}\right|_{t_1} \approx 0.146 \frac{\text{GtC yr}^{-1}}{\text{yr}}$

  describes the rate of change in $F_{FF}(t_1)$, the FF emissions into the atmosphere, and

- $\varepsilon_{FF}(t_1) \approx 0.5\,\text{GtC yr}^{-1}$

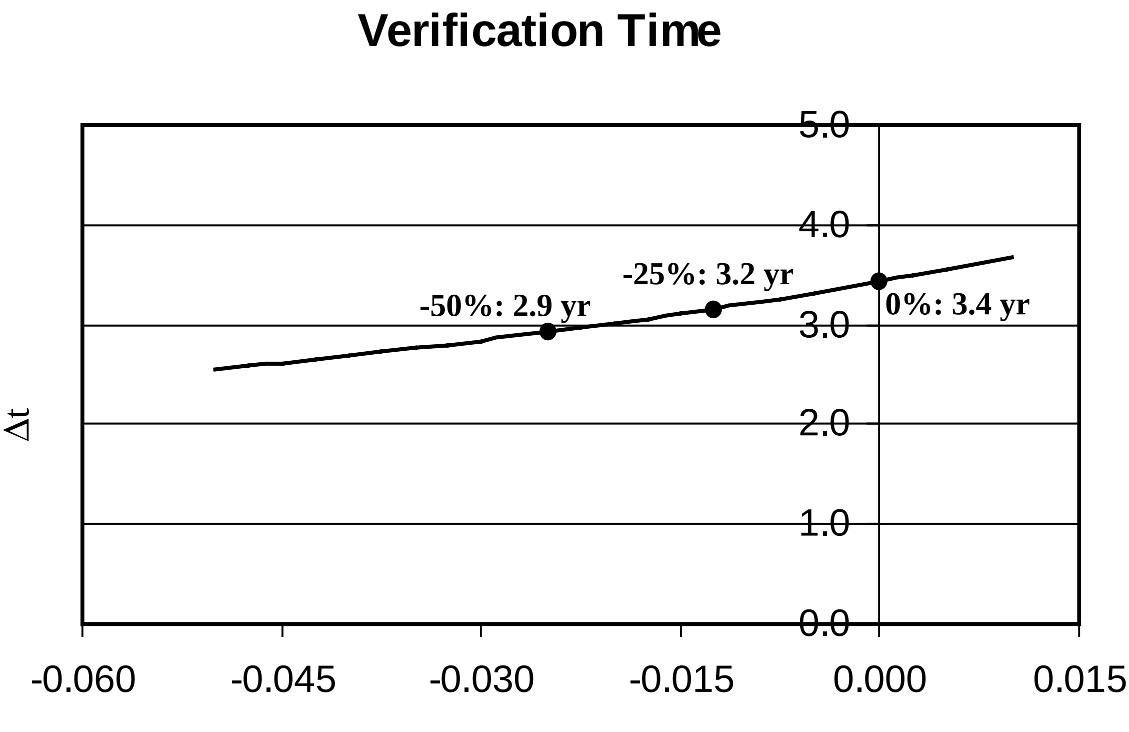
  their uncertainty.

Other specifications are as in Section 4.1.

Figure 4-8 shows the verification time as a function of $\left(\frac{d\varepsilon_{FF}}{dt}\right)_{t_1}$, the rate of change in ε_{FF}.

With reference to PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production under business-as-usual conditions, Figure 4-8 tells us that:

- it will take only about 3.4 years until partial carbon net accounting can be favorably verified, even if the uncertainty in F_{FF} cannot be decreased; and
- that a decrease in the uncertainty in F_{FF} (over the next 10 years) changes the verification time only insignificantly.



$$\left(\frac{d\varepsilon}{dt}\right)_{t_1}$$

Figure 4-8: Verification time for PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production (i.e., excluding CO_2 emissions from changes in tropical land-use, and CO_2 uptake by oceans and terrestrial ecosystems) under business-as-usual conditions: Graphical representation of equation (3-6c).

4.4 PCA: Fossil-Fuel-plus-Global-Afforestation Case (FF+Aff)

In Section 4.4, we consider PCA restricted to CO_2 emissions from fossil fuel combustion and cement production discussed in Section 4.3 in combination with the global afforestation program described in Section 4.2. As in Section 4-2, additionality may or may not be given.[22]

Figure 4-9 reflects the extended PCA approach that we follow. [See Figures 4-6 and 4-4 for comparison.] As in Section 4.2, the overall uncertainty of the total carbon flow out of the atmosphere (and, thus, of the net carbon flow into the atmosphere) remains practically unchanged. We continue to apply a rounding procedure to the first decimal place. In addition, we continue to assume that the global afforestation program does not reveal any negative or positive effects that may indirectly affect the global carbon balance, due to our inability to quantify such effects. As already noted earlier (cf. Section 2), this assumption is crucial.

To calculate the verification time underlying the FF+Aff case, we use equation (3-6) in the form

$$\Delta t > \frac{\varepsilon_{FF+Aff}(t_1)}{\left|\frac{dF_{FF+Aff}}{dt}\right|_{t_1} - \left(\frac{d\varepsilon_{FF+Aff}}{dt}\right)_{t_1}} \approx \frac{\varepsilon_{FF}(t_1)}{\left|\left(\frac{dF_{FF}}{dt}\right)_{t_1} - m_{Aff}(t_1)\right| - \left(\frac{d\varepsilon_{FF+Aff}}{dt}\right)_{t_1}} \quad , \qquad \text{(3-6d)}$$

where

- $m_{Aff}(t_1) \approx 0.025 \frac{GtC\ yr^{-1}}{yr}$

  describes the rate of change in the sequestration rate (as before),

- $\left|\frac{dF_{FF+Aff}}{dt}\right|_{t_1} = \left|\left(\frac{dF_{FF}}{dt}\right)_{t_1} - m_{Aff}(t_1)\right| \approx (0.146 - 0.025)\frac{Gt\ C\ yr^{-1}}{yr} = 0.121 \frac{Gt\ C\ yr^{-1}}{yr}$

  the rate of change in $F_{FF+Aff}(t_1)$, the net carbon emissions into the atmosphere, and

- $\varepsilon_{FF+Aff}(t_1) \approx \varepsilon_{FF}(t_1) \approx 0.5\, GtC\ yr^{-1}$

  their uncertainty.

Other specifications are as in Section 4.1.

Figure 4-10 represents equation (3-6d) graphically (the upper curve). For purposes of comparison, we also represent equation (3-6c) from Figure 4-8 (the lower curve).

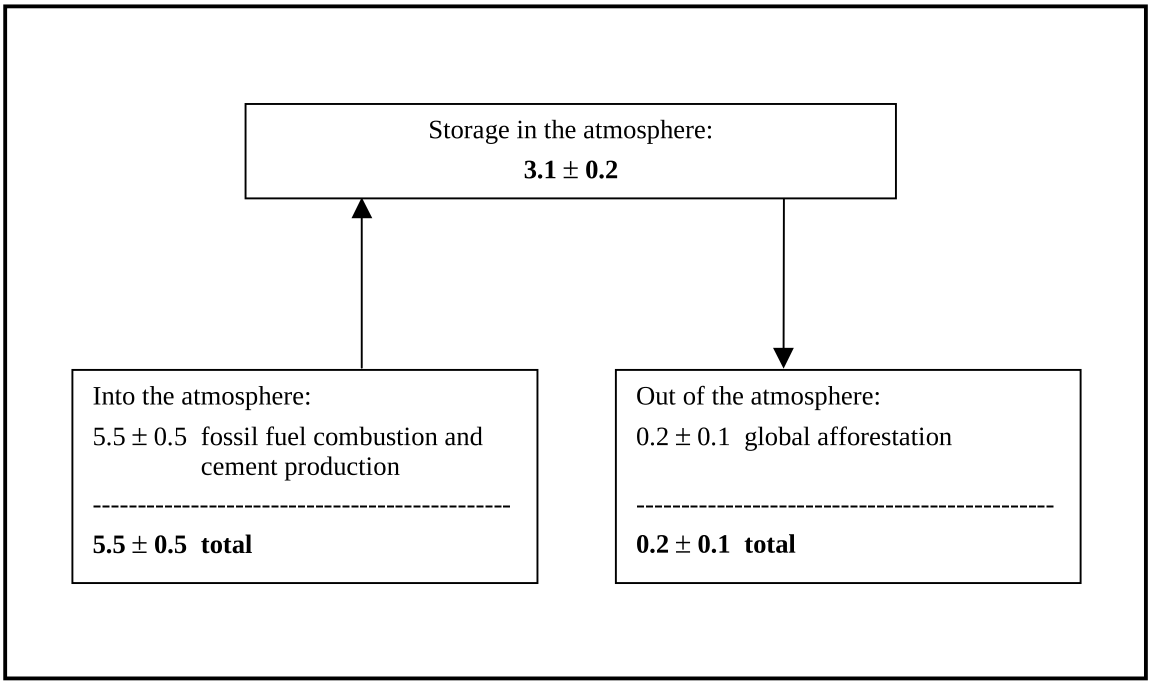


Figure 4-9: Average annual budget of CO_2 perturbations for 1980 to 1989, restricted to CO_2 emissions from fossil fuel combustion and cement production (business-as-usual case), as shown in Figure 4-6, and combined with Nilsson and Schopfhauser's (1995) global afforestation program, as shown in Figure 4-4. The start of the afforestation program is set at 1980 for the purposes of this study. Flows and reservoir changes are expressed in GtC yr^{-1}.

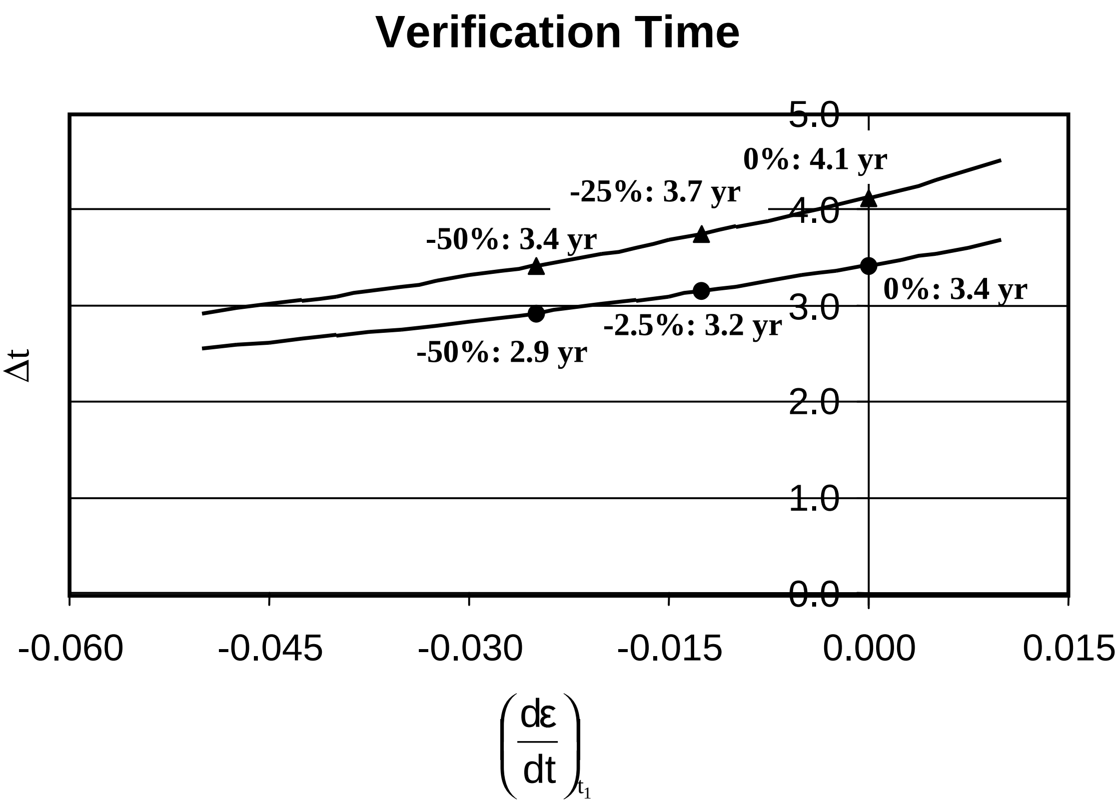


Figure 4-10: Verification time for PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production, under business-as-usual conditions in combination with Nilsson and Schopfhauser's (1995) global afforestation program (upper curve): Graphical representation of equation (3-6d). For comparison, the verification time for PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production under business-as-usual conditions only, as shown in Figure 4-8, is included in the figure (lower curve).

With reference to PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production under business-as-usual conditions and in combination with the global afforestation program, the upper curve in Figure 4-10 tells us that:

- it will still take only a short time, about 4.1 years, until partial carbon net accounting can be favorably verified if the uncertainty in F_{FF} cannot be decreased. We recall that the uncertainty in m_{Aff}, the rate of change in the sequestration rate, does not matter.
- that a decrease in the uncertainty in F_{FF} (over the next 10 years) changes the verification time only insignificantly.

5. Conclusions: Implications for the Kyoto Protocol

Section 5 combines our findings of Sections 2 (discussion of land indirectly affected by human activities and the concept of additionality) and 4 (verification-time calculations) and examines the implications for the Kyoto Protocol.

Table 5-1 summarizes the problems underlying our global-scale verification time calculations in Section 4 with consideration of our findings in Section 2 with respect to the issue of land indirectly affected by human activities (in contrast to the issue of land directly impacted by human activities) and the issue of additionality. This summary leads directly to the identification of implications for the Kyoto Protocol. From this summary we conclude that PCA restricted to CO_2 emissions from fossil fuel combustion and cement production (FF case) represents the only 'clean' global-scale carbon accounting approach for implementing the Kyoto Protocol that does not build upon crucial assumptions and does not result in unfavorable verification conditions. This statement is also valid if the FF emissions refer to conditions other than the business-as-usual conditions that we employed in Section 4.3.

From this summary, one may conclude that PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production in combination with a global afforestation program (FF+Aff case), can also be be implemented under the Kyoto Protocol — if it can be shown that indirect human effects are negligible. (Additionality may be met by applying today's best-available expertise, i.e., by proceeding in a 'to-the-best-of-our-knowledge' fashion.) This conclusion, however, is not valid, as demonstrated in the following.

Table 5-2 translates the global-scale scientific problems identified in Table 5-1 to sub-global (e.g., national) scales. With the exception of Points 3 and 4 mentioned under the FF+Aff case (where 'Aff' serves as a substitute for any other Kyoto compliant LUCF activity), this translation works on a 1:1 basis and is straightforward. By way of contrast, Points 3 and 4 under the FF+AFF case require further discussion.

<u>PCA: FF+Aff Case — Point 3:</u>

Implementing Kyoto compliant LUCF projects on sub-global scales may result in verification conditions that are unfavorable, in contrast to our global-scale results. For the purposes of illustration, let us look at equation (3-6d), which we used in connection with the afforestation program on the global scale. On sub-global scales, parameter combinations resulting from the combination of Kyoto compliant LUCF projects with FF emissions are conceivable that may let the fraction on the right side of equation (3-6d), and therefore the verification time Δt, become very great as a consequence of a great numerator and/or a small denominator.

Therefore, the scientific challenge prior to using PCA within the framework of the Kyoto Protocol (i.e., under partial inclusion of biological sources and sinks resulting from direct human-induced land-use change and forestry activities) is to demonstrate that no country can position itself under unfavorable verification conditions by implementing Kyoto compliant LUCF projects. By doing so, these countries would gain an advantage over other countries, such as those that manage only FF emissions that can be verified favorably.

Table 5-1: Table summarizing the problems underlying the global-scale verification-time calculations in Section 4, in consideration of the findings in Section 2 with respect to the issue of land indirectly affected by human activities (in contrast to the issue of land directly impacted by human activities) and the issue of additionality.

Case **(Referring to the Global Scale)**	**Section**	**Carbon Accounting**	**Scientific Problem (Implication)**
Business-as-Usual Case (BaU)	4.1	FCA	**1.** The verification time is not compatible with the commitment periods foreseen by the Kyoto Protocol.
Global Afforestation Case (Aff)	4.2	FCA	**1.** The verification time is not compatible with the commitment periods foreseen by the Kyoto Protocol. Implementing the global afforestation program described in Nilsson and Schopfhauser's (1995) results in verification conditions that are significantly less favorable than in the BaU case. **2.** Indirect (negative or positive) effects of the global afforestation program on the full carbon balance are disregarded. **3.** Additionality may or may not be given.
Fossil Fuel Case (FF)	4.3	PCA	
Fossil-Fuel-plus-Afforestation Case (FF+Aff)	4.4	PCA	**1.** Indirect (negative or positive) effects of the global afforestation program on the underlying full carbon balance are disregarded. **2.** Additionality may or may not be given.

Table 5-2: Table following up Table 5-1: Translation of global-scale scientific problems (implications) to sub-global (e.g., national) scales.

Case **(Referring to Sub-global Scales)**	**Carbon Accounting**	**Scientific Problem/Underlying Assumption (Implication)**
Business-as-Usual Case (BaU)	FCA	**1.** The verification time may not be compatible with the commitment periods foreseen by the Kyoto Protocol. Example: Austria (Jonas *et al.*, 1998; Jonas *et al.*, 1999)
Afforestation Case (Aff) (where 'Aff' serves as a substitute for any other Kyoto compliant LUCF activity)	FCA	**1.** The verification time may not be compatible with the commitment periods foreseen by the Kyoto Protocol. Implementing Kyoto compliant LUCF projects may result in verification conditions that are less favorable than in the BaU case. **2.** Indirect (negative or positive) effects of the Kyoto compliant LUCF activities on the full carbon balance are negligible. [Assumption: This can be proven.] **3.** Additionality need not be met. [Assumption: Additionality may be met by applying today's best-available expertise.]
Fossil Fuel Case (FF) (where 'FF' refers also to conditions other than BaU conditions)	PCA	
Fossil-Fuel-plus-Afforestation Case (FF+Aff) (where 'Aff' serves as a substitute for any other Kyoto compliant LUCF activity)	PCA	**1.** Indirect (negative or positive) effects of the Kyoto compliant LUCF activities on the underlying full carbon balance are negligible. [Assumption: This can be proven.] **2.** Additionality need not be met. [Assumption: Additionality may be met by applying today's best-available expertise.] - - - - - - - - - - **3.** Implementing Kyoto compliant LUCF projects may result in verification conditions that are unfavorable. **4.** Implementing Kyoto compliant projects on sub-global levels impedes FCA on large spatial scales.

The counter-argument that unfavorable verification conditions may also be possible in the absence of Kyoto compliant LUCF activities (i.e., under the FF case) is not valid. In contrast to the case $\left|\frac{dF_{FF}}{dt}\right| \approx 0$ [cf. equation (3-6c)], the case $\left|\frac{dF_{FF+Aff}}{dt}\right| \approx 0$ [cf. equation (3-6d)] reveals weaknesses that may be significant:

- ε_{FF}, the uncertainty in F_{FF}, is smaller than ε_{FF+Aff}, the uncertainty in F_{FF+Aff}. That is, the uncertainty band surrounding F_{FF} is not as wide as the uncertainty band surrounding F_{FF+Aff}. Or,
- if ε_{FF} is not yet sufficiently small, it can be made small (i.e., $\left(\frac{d\varepsilon_{FF}}{dt}\right)$ approaching zero) within a period of time that is compatible with the commitment periods foreseen by the Kyoto Protocol, while this is not as easily possible with ε_{FF+Aff}; and
- changing $\left|\frac{dF_{FF}}{dt}\right| \approx 0$ to $\frac{dF_{FF}}{dt} < 0$ can be realized more easily than changing $\left|\frac{dF_{FF+Aff}}{dt}\right| \approx 0$ to $\frac{dF_{FF+Aff}}{dt} < 0$.

PCA: FF+Aff Case — Point 4:

Implementing Kyoto compliant projects on sub-global scales would impede FCA research at large spatial scales. For the purposes of illustration, it is sufficient to compare the PCA-based cases 'FF' and 'FF+Aff' (lower and upper curve, respectively, in Figure 4-10) and the FCA-based cases 'BaU' and 'Aff' (lower and upper curve, respectively, in Figure 4-5) on the global scale. Under PCA, the verification time for some 'mean' country (or, equivalently, the sum of all countries including those that implemented the global afforestation program nationally in the form of Kyoto compliant projects), is insignificantly greater than the verification time for the FF case alone (as seen in Figure 4-10). This is not so under FCA. The verification time for a global afforestation program is significantly greater than the verification time for the business-as-usual case (as seen in Figure 4-5). Flux based FCA on large spatial scales (such as on a continental or hemispheric scale), as a tool for validating sub-global Kyoto compliant carbon reporting, would be more difficult if Kyoto compliant LUCF projects were implemented. This is due to the extremely long verification times involved in FCA. Today's primary FCA-related research objectives, i.e., the global-scale quantification of carbon sources and sinks and their combination in a closed budget, as well as the understanding how the budget changes with time as a function of natural and anthropogenic perturbations, will become more difficult endeavors. In essence, FCA-based carbon accounting research would be impeded.

The counter-argument that under FCA on large spatial scales one can make use of the much smaller uncertainty that refers to "storage in the atmosphere" in Figure 4-1 (see also Footnote 17) is only partly valid. FCA-based carbon research requires global and sub-global verification. As discussed in Footnote 17, sub-global FCA requires flux-based accounting. The small uncertainty referring to "storage in the atmosphere" is associated with stock-based accounting. Only at the fully global scale may this smaller uncertainty be used, since stock based atmospheric carbon accounting can only be applied to the entire globe. In this sense, global FCA is an exceptional case.

Based on our findings, we conclude that:

- PCA, restricted to CO_2 emissions from fossil fuel combustion and cement production (FF case), represents the only 'clean' scale-independent carbon accounting approach for implementing the Kyoto Protocol that does not build upon crucial assumptions. It is also characterized by the most feasible verification conditions.
- In the case that the Kyoto Protocol is based on PCA under partial inclusion of biological sources and sinks, countries may position themselves under unfavorable verification conditions by implementing Kyoto compliant LUCF projects. By doing so, these countries would gain an advantage over other countries, which manage, for example, only FF emissions that can be verified favorably.
- In the case that the Kyoto Protocol is based on PCA under partial inclusion of biological sources and sinks, FCA-based carbon research is impeded. Flux based FCA on large spatial scales, as a tool for validating sub-global Kyoto compliant carbon reporting, would be more difficult if Kyoto compliant LUCF projects were implemented.

In light of these conclusions, we recommend to use PCA restricted to CO_2 emissions from fossil fuel combustion and cement production (FF case) as the Kyoto eligible carbon accounting approach and to disqualify all LUCF activities for carbon emission reduction purposes under the Kyoto Protocol. Biological sources and sinks, resulting from direct human induced LUCF activities, need to be treated outside the Protocol — ideally within a globally harmonized environmental protection context — under verification conditions that are appropriate for these activities. The present global increase in the FF emissions must be stopped and turned around without carbon-accounting (not disregarding) LUCF measures. Combining a FF-emissions-only Kyoto Protocol with a 'biological source-sink protocol' will face, in principle, more favorable conditions if FF emissions decline and the addition of LUCF activities decreases the verification time.

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Appendices

Appendix I

The following definition of FCA is based on that presented in Jonas *et al.* (1999):

FCA follows — in a consistent fashion — the full carbon-system concept. 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, presence, future). It is assumed that the components can be described by adopting the concept of pools (also termed reservoirs or stocks) and fluxes (also termed flows) to capture their functioning. The carbon pools may be directly human-impacted or indirectly human-affected, and internally or externally linked by the exchange of carbon (as well as other matter and energy). [See also Steffen *et al.* (1998) and Nilsson *et al.* (1999).]

Appendix II:

Articles 3.3, 3.4, 6.1(b), and 12.5(c) of the Kyoto Protocol (UNFCCC, 1998) are given below:

Article 3.3 *The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8.*

Article 3.4 *Prior to the first session of the Conference of the Parties serving as the meeting of the Parties to this Protocol, each Party included in Annex I shall provide, for consideration by the Subsidiary Body for Scientific and Technological Advice, data to establish its level of carbon stocks in 1990 and to enable an estimate to be made of its changes in carbon stocks in subsequent years. The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session or as soon as practicable thereafter, decide upon modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I, taking into account uncertainties, transparency in reporting, verifiability, the methodological work of the Intergovernmental Panel on Climate Change, the advice provided by the Subsidiary Body for Scientific and Technological Advice in accordance with Article 5 and the decisions of the Conference of the Parties. Such a decision shall apply in* *the second and subsequent commitment periods. A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided that these activities have taken place since 1990.*

Article 6.1 *For the purpose of meeting its commitments under Article 3, any Party included in Annex I may transfer to, or acquire from, any other such Party emission reduction units resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gases in any sector of the economy, provided that:*

. . .

(b) Any such project provides a reduction in emissions by sources, or an enhancement of removals by sinks, that is additional to any that would otherwise occur;

. . .

Article 12.5 *Emission reductions resulting from each project activity shall be certified by operational entities to be designated by the Conference of the Parties serving as the meeting of the Parties to this Protocol, on the basis of:*

. . .

(c) Reductions in emissions that are additional to any that would occur in the absence of the certified project activity.

. . .

Appendix III

In this appendix we describe how to generalize our linear-averaging approach of Section 3 and improve its applicability in terms of space and time. It must be realized, however, that there are several ways to handle the intricate (according to our knowledge still unresolved) problem of matching spatial and temporal resolution scales appropriately in quantitative terms in global change (including climate change and carbon cycle) research. These include, among others, the use of expert knowledge and probabilistic-based approaches.

The generalization that we describe here continues to make use of averages but involves the application of approximations higher than first order to project changes in net carbon emissions (while we continue to project changes in our knowledge of the underlying uncertainties in a first-order, i.e., linear, fashion for reasons of data availability). Hence, in the case of a second-order approximation for projected changes in net carbon emissions:

$$F_{net}(t_2) - F_{net}(t_1) > \varepsilon(t_2) \qquad \text{(AIII-1)}$$

$$\Rightarrow \left(\frac{dF_{net}}{dt}\right)_{t_1} \Delta t + \frac{1}{2}\left(\frac{d^2F}{dt^2}\right)_{t_1} \Delta t^2 > \varepsilon(t_1) + \left(\frac{d\varepsilon}{dt}\right)_{t_1} \Delta t \quad . \qquad \text{(AIII-2)}$$

The verification time is given by

$$\Delta t > \frac{b_1 - a_1}{a_2} + \sqrt{\left(\frac{b_1 - a_1}{a_2}\right)^2 + 2\frac{b_0}{a_2}} \quad , \qquad \text{(AIII-3)}$$

where the coefficients a_i (i = 1, 2) and b_j (j = 0, 1) are given in Table AIII-1.

Table AIII-1: Coefficients a_i (i = 1, 2) and b_j (j = 0, 1) to equation (AIII-3).

a_i	b_i	Unit	Equation No.
not required	$b_0 = \varepsilon(t_1)$	$GtCyr^{-1}$	(AIII-4)
$a_1 = \left(\frac{dF_{net}}{dt}\right)_{t_1}$	$b_1 = \left(\frac{d\varepsilon}{dt}\right)_{t_1}$	$\frac{GtCyr^{-1}}{yr}$	(AIII-5), (AIII-6)
$a_2 = \left(\frac{d^2F_{net}}{dt^2}\right)_{t_1}$	. . .	$\frac{GtCyr^{-1}}{(yr)^2}$	(AIII-7)
. . .	. . .	. . .	

Appendix IV

Figure 2.2 from IPCC (1996a, p. 81), renamed into Figure AIV-1 here:

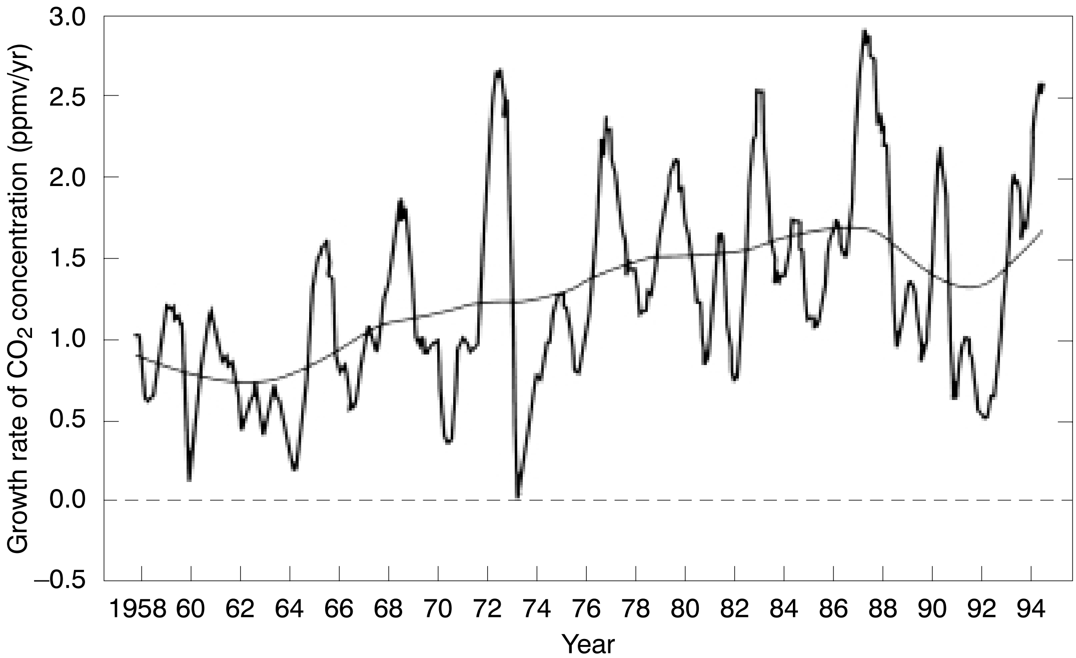

Figure AIV-1: Growth rate of CO_2 concentrations since 1958 in ppmv yr^{-1} at the Mauna Loa, Hawaii station. The high growth rates of the late 1980s, the low growth rates of the early 1990s, and the recent upturn in the growth rate are all apparent. The smoothed curve shows the same data but filtered to suppress variations on time scales less than approximately 10 years. (Sources: C.D. Keeling and T.P. Worf, Scripps Institute of Oceanography, and P. Tans, NOAA CMDL. The Keeling and NOAA results are in close agreement. The Mauna Loa Observatory is operated by the NOAA.)

Source: IPCC (1996a).

Note that we make use of the Mauna Loa data here, for the following two reasons: 1) The data have already been processed according to our needs; 2) we did not find other sources for data on globally averaged CO_2 concentration growth rates that had been processed similarly. The alternative of using Mauna Loa data, however, can be assumed to be sufficiently accurate for our first-order calculations presented in this study, since we are interested only in the temporally (≥ decadally) averaged CO_2 concentration growth rates; they agree sufficiently well across latitudes. See, for example, IPCC (1995, p. 43, Figure 1.4) or Globalview-CO_2 (1999).

Notes

[1] As of 14 June 1999, the Convention had received 179 instruments of ratification and, as of 27 August 1999, 84 Parties have signed the Kyoto Protocol (UNFCCC, 1999).

[2] The issue of compliance, however, is under discussion. A Joint Working Group on Compliance (JWG), formed by the Subsidiary Body for Implementation (SBI) and the Subsidiary Body on Scientific and Technological Advice (SBSTA), discusses issues such as identification of compliance-related elements, including gaps and suitable forums to address them; design of a compliance system; and consequences of non-compliance (IISD, 1999).

[3] The COP/MOP will take decisions on the issue of commitment periods after the first commitment period (2008-2012) at its first session (UNFCCC, 1998). It is appropriate to state, however, that the 'current thinking' of policy makers as well as scientists is short-term rather than long-term. In other words, the current thinking is in terms of continuous or close-to-continuous commitment periods [see, e.g., Decision 1/CP.3 in UNFCCC (1998); Steffen *et al.* (1998); WBGU (1998)].

[4] There are indirect human effects (e.g., CO_2 and nitrogen fertilization), which are global in scale. Therefore, we do not identify 'natural land' as a separate category.

[5] Article 3.4 refers simply to 'human-induced activities' rather than to 'directly human-induced activities' as in Article 3.3. For the following two reasons, however, we interpret 'human-induced' as 'directly human-induced' in the context of Article 3.4: 1) Article 3.4 follows up Article 3.3; and 2) the human-induced activities are specified by 'related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories'.

[6] Articles 3.3, 3.4, 6.1(b) and 12.5(c) of the Kyoto Protocol are given in Appendix II.

[7] The Kyoto Protocol mentions only the term 'base year' (in its Articles 3.5, 3.7, 3.8 and Annex B).

[8] For reasons of completeness, we note that in the context of the Kyoto Protocol three different reference standards for carbon emissions are presently discussed by the scientific community: 1) 1990-baselines for carbon emissions from the energy-industry sector as well as other sources; 2) in essence, 2008-baselines for net emissions from Kyoto-compliant activities falling under Article 3.3 (and most likely under Article 3.4); and 3) post-implementation baseline scenarios for net emissions from Kyoto-compliant activities falling under Articles 6 and 12. Here we do not comment on the scientific need or usefulness in complying with different reference standards. In addition, we do not comment on how reference standards are derived in practice.

[9] Many similar examples can be given. They are not at all far-fetched. The greater the commitment of country X to reduce emissions and the more expensive to do this by introducing appropriate measures in the energy-industry sector, the greater the incentive to implement short-term Kyoto-compliant projects with maximal potential for carbon-sequestration per unit of time.

[10] A thorough investigation on the extent to which the Kyoto Protocol creates incentives running counter to the objectives of the other Rio conventions (Biodiversity Convention, Desertification Convention), and on the extent to which 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).

[11] In referring to statistics, consideration should be given to the fact that there are only a very limited number of independent measurement (including modeling) methods available to derive carbon-related data sets (Jonas *et al.*, 1999).

[12] The verification time Δt is reported correctly in 'greater than . . . (number of) years'.

[13] The IPCC (1997a, Annex 1), however, cautions against the use of this rule, if the individual uncertainties become too great (e.g., if they are greater than 60%, presupposing that the individual ranges of the underlying data are regarded as estimates of the 95% confidence interval).

[14] In order to minimize the use of indices, we neglect the index 'net' from now on and replace it by an index that refers to the case under investigation (i.e., the BaU case here).

[15] We used Figure 2.2 in IPCC (1996a, p. 81) because of its slightly better graphical resolution for linear regression purposes. From this figure we could reproduce a mean CO_2 concentration growth rate of 1.57 ppmv yr^{-1} for 1980 to 1989, in slight contrast to 1.53 ppmv yr^{-1} reported by the IPCC (1995). Here we made use, however, only of the change in the 1980-89 growth rate of CO_2 concentration [$\approx$ 0.0184 (ppmv yr^{-1}) / yr = 0.184 (ppmv yr^{-1}) / (10 yr)], which we took from our linear regression and which we assumed to be sufficiently well reproduced (i.e., only a parallel shift).

[16] The globally averaged CO_2 concentration, as determined through analysis of NOAA/CMDL data (Boden *et al.*, 1991; Conway *et al.*, 1994), increased by 1.53 ± 0.1 ppmv yr^{-1} over the period from 1980 to 1989. This corresponds to an annual average rate of change in atmospheric carbon of 3.2 ± 0.2 GtC yr^{-1}.

[17] It is this greater combined uncertainty, derived from the addition of the uncertainties in individual fluxes into and out of the atmosphere, which must be applied to sub-global scales. The smaller uncertainty — referring to "storage in the atmosphere" in Figure 4-1 — is exceptional in the sense that it not available to us on sub-global scales, since there is no such thing as sub-global atmospheres that belong to individual countries or regions. In drawing conclusions on sub-global scales, we must therefore proceed with this greater combined uncertainty.

[18] This is an important remark because, on average, $\left|\frac{dF_{BaU}}{dt}\right|$ decreased between 1989 and 1994 (cf. Figure AIV-1). Note that $\left|\frac{dF_{BaU}}{dt}\right|$ depends on the temporal averaging procedure that is applied.

[19] Identifying the (linearly projected) BaU case as the (overall) post-planting baseline scenario is an arbitrary decision, which we do not take here.

[20] To linearize Figure 4-3 over the entire period from 1980 to 2080, a two-range linearization procedure should be considered, for the period of 1980 to 2040 and the period of 2040 to 2080, respectively. This procedure, however, must be combined with a generalized approach (at least up to the second order) to calculate the verification time, as described in Appendix III. For the purposes of our study, it is sufficient to limit our verification-time calculations to the initial 60-year period, i.e., to the period of 1980 to 2040, and to continue applying first-order approximations, as described in Section 3.

[21] Note, however, that we encounter unfavorable verification conditions if the lateral dislocations that we are facing here would be greater in terms of time (a situation that we do not investigate).

[22] Identifying the (linearly projected) FF case as the (overall) post-planting baseline scenario is an arbitrary decision, which we do not take here.