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If You Act Locally and Compute Globally What is the Optimal Comprehensiveness of the Reference Carbon System?

A note on decision making under changing properties of total system errors of full carbon accounting (FCA) and partial carbon accounting (PCA)

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Abstract

Kyoto fails to recognize the institutional vacuum to verify countries' uncertain carbon accounts and there is a strong debate on the potentials of carbon systems other than fossil fuels to contribute to curbing the increases in the atmospheric carbon content. In this paper we develop an analytical framework to address the issue of 'how comprehensive should a country's reference carbon system be (not) ignoring the interaction of the particular system with the rest of the global carbon system under the clause of (non-) verification?' To solve this problem we first develop a concept to understand the trade-off between the range of potential carbon emission reduction/carbon sequestration and the degree of uncertainty under Full Carbon Accounting (FCA) and Partial Carbon Accounting (PCA). We then provide a formal description of the properties of uncertainty under FCA and PCA. Finally, we suggest a model that allows us to compute the optimal degree of comprehensiveness of a reference carbon system that should be eligible for the mutual recognition of emission reductions. The model is general enough to be applicable on both the project level as well as on global scales.

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Background

Modeling global or sub-global carbon systems involves the treatment of highly complex systems. Models play an important role in understanding the causes and consequences of climate change and policies to alleviate negative effects. In order to make full use of these models, it is necessary to establish the magnitude and source of uncertainty associated with their prediction. This information can be used to achieve a better understanding of the simulated systems, to increase the reliability of model prediction, to guide field surveys and laboratory experiments, and to define realistic values that should be used in scientific, economic, and political discussions of the future. The degree of uncertainty will also sooner or later influence climate change politics in the sense that carbon emission reduction will be required to be verifiable. The uncertainties of large-scale carbon accounts may be too large for Kyoto measures to be globally verifiable in the twenty year period from 1990 to 2010 (see Jonas *et al*., 1999; Rypdal and Zhang, 2000).

The Intergovernmental Panel on Climate Change (IPCC, 1996) identifies an uncertainty of fossil fuel emissions to be in the range of ±10% for Annex I countries, which is larger than the committed reduction of many of those countries. The uncertainty of biological systems is believed by most reseachers to be larger than those of fossil fuel systems (see, e.g., IPCC, 1996; Houghton, 1999; Schimel *et al*., 2000). Although *The 2nd Precautionary Principle* can be applied here, it seems to be perfectly legitimate for critics to scrutinize the very existence of the Kyoto Protocol on the grounds of the non-verifiability of Kyoto measures. Verifiability is intimately linked to the quantification of uncertainties. On the project level uncertainties are not only linked to internal uncertainty, but are also linked to negative spill-over effects (leakages) with the rest of the system. Therefore, the nature of uncertainty depends upon the type and comprehensiveness of carbon accounting underlying the evaluation of a project or reported emission reduction for a country. We, thus, propose to distinguish between a weak and a strong verification concept, where under PCA the weak verification and under FCA the strong verification concept applies. This is due to the fact that if we consider PCA[1] as the chosen accounting method we find small random errors, but potential large biases due to spill-over effects remain unknown under PCA. It is hoped that under PCA the concept of additionality by establishing base-line scenarios could eliminate some biases but, as we argue in this paper, unless a system of FCA is established the additionality problem cannot be solved due to methodological limitations. In addition, under PCA parties will not be able to maximize emission reductions due to foregone least cost measures of a restricted choice set, which are not included under PCA. On the other hand, under FCA we can, in principle, be able to maximize emission reduction and participating parties will be able to reduce biases as claimed earlier. However, large system internal errors under FCA might bring a number of countries (regions, projects) under unfavorable verification conditions. For such countries a reduction of uncertainty based on improved inventories might turn out to be a cheap way to gain verifiability — at least in a post-Kyoto period.

The evaluation of greenhouse gas (GHG) reduction is a rather problematic undertaking, especially with respect to the reliability of the reduction estimates and the credibility of the institutional set-up of ruling, monitoring, evaluating, reporting, and verifying. Doubts about reliability arise due to (1) differing interpretations of sources and sink categories or other definitions, assumptions, units, etc., (2) use of simplified representations with averaged values (e.g., emission factors), (3) inherent uncertainty in the scientific understanding of the basic processes leading to emissions and removals, (4) operational risk (e.g., if energy-consuming equipment is not used as projected), and (5) performance risk (engineering, systems design and equipment performance) (Vine and Sathaye, 1997). With respect to uncertainty, there is still a lack of mutual understanding among carbon researchers not only on the methodology of how to estimate uncertainties but also about the uncertainty concept *per se*. Given the problems of *inter alia* artificial system boundaries, imperfect experimental design and measurement, up to the use of borrowed conversion factors and guessed parameter estimates we need to ask questions like: "What do reported uncertainties say and not say?" Or, another question is whether it is necessary to always model entire systems or is it enough to study isolated subsystems and what can we say about the total system errors of both approaches?

In order to address these questions we need to reflect on the systems properties of carbon models with respect to how much they can tell us about the uncertainty and potential emission reduction. From a general modeling point of view, it is generally known that the simplest models (e.g., non-structural time series analysis) create the smallest prediction error, where in contrast very complex structural models can exhibit vast internal errors making meaningful projections almost impossible. When modelers

[1] The Kyoto Protocol foresees a system of partial carbon accounting (PCA) where biological sources and sinks are only partially included. Partial carbon accounting, however, means that only a restricted set of actions are allowed to reduce carbon emissions, which are mainly related to the reduction of fossil fuel emissions. It should also be acknowledged, however, that over $2 * 10^{15}$ G Cyr^{-1} arise from net fluxes from the destruction of vegetation (not taking into account the foregone loss of sink strength), where $5 * 10^{15}$ G Cyr^{-1} are due to FF emissions.

design models they *a priori* determine the level of uncertainty the model will generate and the degree of insight they gain in the functioning of the system by using models. Thus, a researcher has to consider an uncertainty/systems insight trade-off. This paper is about trying to define some systems theoretic framework to improve the understanding concerning this trade-off in order to be able to work towards a more general decision theory.[2]

Defining Uncertainties

Uncertainties arise due to the stochastic nature of the underlying system and from knowledge gaps and imperfect measurability of the carbon system processes. The research community must admit that mankind still knows very little about the true global and (sub-)global greenhouse gas exchange budgets of the earth's ecosystems (including all human activities) with the atmosphere. Before we start to quantify uncertainties we need to define the uncertainty concept as such and analyze its role under FCA and PCA. Discussion with many colleagues has shown that the interpretation of uncertainty depends on how researchers view the system they are looking at and whether they have a 'statistical' or 'physical' mind. As a consequence, the method of carbon modeling and the team mix somehow also dictates the way uncertainties are interpreted. There have been a number of attempts to classify uncertainties relating to the use of greenhouse gas guidelines, which mainly refer to PCA types of accounting (e.g., Shvidenko *et al*., 1996; Vine and Sathaye, 1997; Jonas *et al*., 1998; SBSTA, 1998; Nabuurs *et al*., 1999; Vine *et al*., 1999). However, little work has been done to understand uncertainties from a FCA perspective and to try to put uncertainties into a comparative picture with PCA (see also Jonas *et al*., 1999).

Figure 1 provides an overview of the levels of uncertainty components in the context of different accounting methods and feasible ranges of potential emission reduction. An analysis of the economic interpretation of the interplay of emission reduction and uncertainty with respect to verification is provided in Obersteiner *et al*. (2000a). In Figure 1 we distinguish three different carbon accounting systems.

The first accounting system is recommended by the IPCC (1996, 1999), which is based on PCA comprising almost the entire fossil fuel system with only partial inclusion of biological sources and sinks. The second carbon accounting system is FCA. According to Jonas *et al*. (1999), FCA is a full carbon budget that encompasses and integrates all carbon related components of all terrestrial (and aquatic) ecosystems (including the technosphere) and is applied continuously in time. The concept of FCA involves uncertainties as an integral part as illustrated in Jonas *et al*. (1999). Since FCA involves a larger set of subsystems (a larger set of variables describing the states of a larger system) the summarized or total system error (measured by random errors) are larger than under PCA.[3] Moreover, under the current reporting schemes uncertainties do not

[2] In a decision theoretic setting, the purpose of estimating the parameter is to use the data to formulate a decision. In a statistical setting, the decision depends on the estimated parameter and will be erroneous if the empirical parameter does not equal the true parameter. The concept of the quadratic loss functions supposes that the cost associated with a decision is proportional to the square of the difference between the estimate and the true parameter.
[3] This point is treated later in a more formal way.

play a meaningful role under the PCA reporting prescriptions. However, there is an IPCC process underway to at least try to fully quantify uncertainties in a consistent way. However, under such a PCA_U (Partial Carbon Account involving uncertainties, which is the third carbon accounting system) uncertainties are only documented, but the parties still fail to include uncertainties in the process of the mutual recognition of binding legal commitments. This IPCC process still takes on an anthropogenic systems view, which proved to be insufficient to quantify total system errors of biological systems (see Nilsson *et al*., 2000 for a discussion of errors in biological systems).

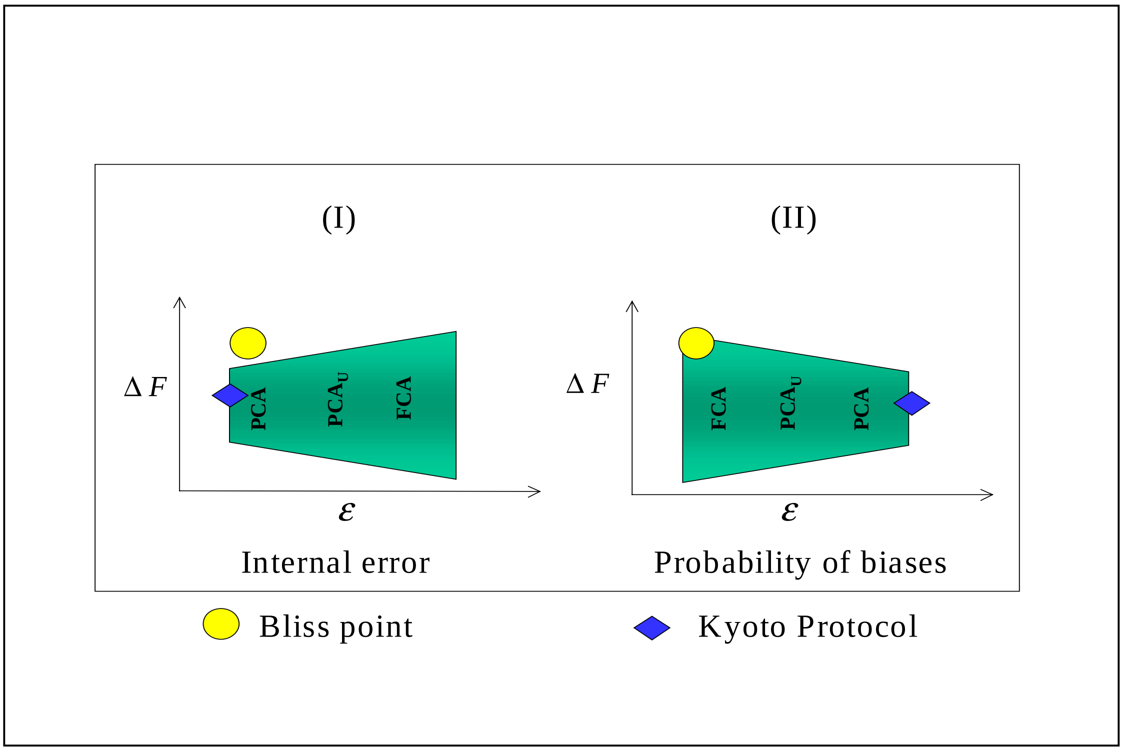

Figure 1: Uncertainty levels and potential emission reduction under PCA, PCA_U and FCA.[4] From the left Chart (I) we see that the internal error increases with the comprehensiveness of the system (i.e., PCA systems exhibit smaller internal errors (summarized random errors) than the larger FCA system). With respect to the probability of the occurrence of biases (Chart (II)) there is an inverse relationship between the comprehensiveness of the system and the error. The possibility set of emission reduction always increases with the comprehensiveness of the system.

In Figure 1 we distinguish between two types of errors which are related to the potential emission reductions in the three carbon accounting systems. Figure 2 provides a graphical representation of the different error components. The random error is used here in the sense of the statistical definition of white noise (signal without information content) and for simplicity we assume that the summarized random error equals the internal error. This assumption seems to be justified due to the fact that biases are hard

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[4] ΔF stands for the potential emission reduction induced by Kyoto measures and ε stands for the involved error. We distinguish random errors and systematic errors (biases).

to assess within a closed system in the absence of reference points and benchmarks. *Random errors* are errors that affect the precision of a set of measurements or, under some restrictions, the precision of any continuous function of random variables. Random errors scatter measurements above and below the empirical mean of various distributions, with small random errors being more likely than large. *Precision* is reproducibility or a measure of the random error. Precision is measured by the standard deviation or the standard deviation of the mean value, where the latter is an inverse function of the square root of the number of observations.

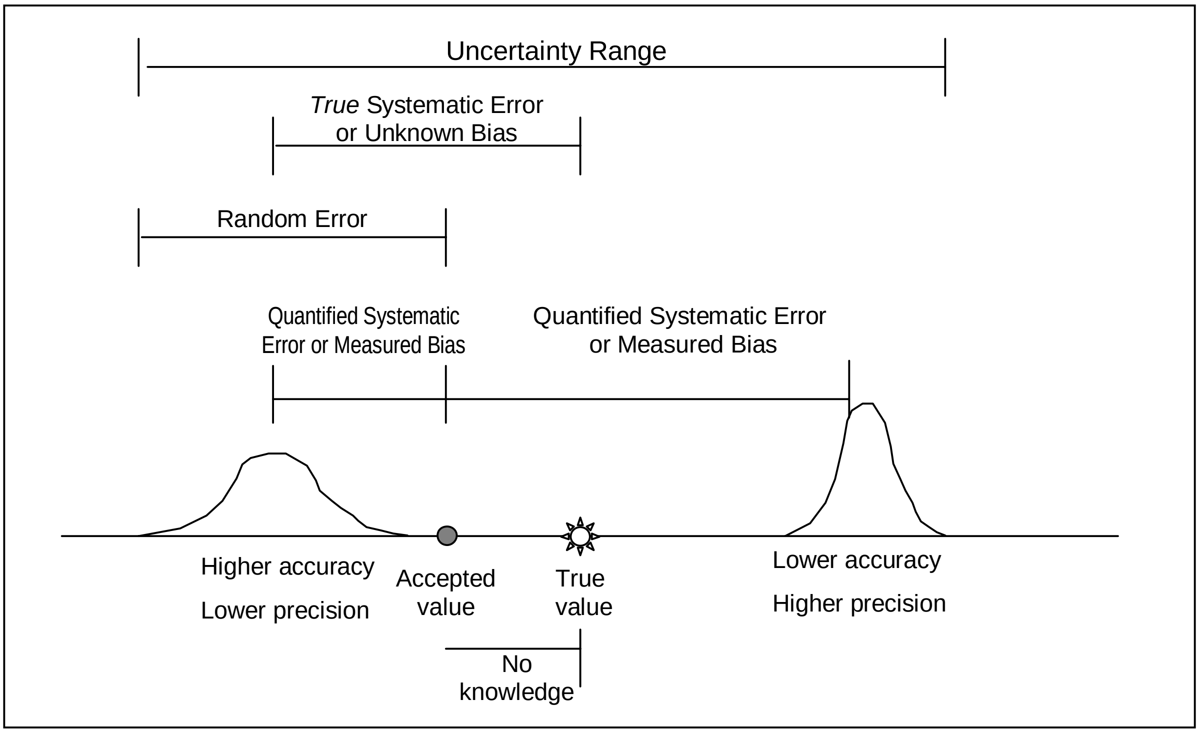

Figure 2: A hypothetical uncertainty range for two set of measurements of the same phenomenon.

Biases are mainly related to white spots and fuzzy areas on the carbon knowledge landscape. *Systematic errors* (also called *bias*) affect the accuracy of the results. *Accuracy* is correctness or a measure of the systematic error. The accuracy of a measurement is assessed by comparing the measurement with the *accepted* value (the difference between the true and accepted value is unknown, in itself, perceiving this difference is *soft knowledge*), based on evidence independent of the measurement. However, in most subsystems of PCA, and more so of FCA, the true and accepted value is unknown and could be beyond the uncertainty range as indicated in Figure 2. Box 1 provides a classification of the sources of error according to two principally different types of sources — hard and soft knowledge (see Nilsson *et al.*, 2000 for more discussion).

Box 1: Classification of Sources of Errors

Hard knowledge (adapted from Shvidenko *et al*., 1996):

- Oversimplification
- Sampling
  - Definitions and classification schemes
  - Shortcomings of available data
  - Imperfect and incomplete measurement
  - Extrapolation
  - Up-scaling
  - Time series models
  - Sampling scheme
- Leakage (Jonas *et al*., 1999)
  - Spatial
  - Temporal

Soft knowledge (Expert judgement (IPCC, 1999)):

- Unconscious biases
  - Process understanding
  - Availability bias
  - Representativeness bias
  - Anchoring and adjustment bias
- Conscious biases
  - Motivational bias
  - Overconfident estimate of unqualified expert
  - Managerial bias
  - Selection bias

Coming back to the basic message contained in Figure 1: From the left plot (I) we see that the larger the carbon accounting system becomes the larger the random error and the larger the range of possible emission reduction.[5] This is due to the fact that under current conditions biological systems exhibit a larger random error. In addition, as we will formally show later, due to the law of error propagation by nature larger systems exhibit larger total random errors. It should be noted here that smaller countries are disadvantaged to report small random errors. This is due to the fact that (1) the standard error of the mean value is an inverse function of the square root of the number of observations, which means that smaller countries would need more observations for a carbon unit than a larger country to reach the same precision; and (2) thus, also the costs per unit carbon would become larger on a comparative basis. This means that reporting on biological carbon systems on a national level is sub-optimal.

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[5] The notion of size or largeness refers to the number of variables needed to describe the system of interest (e.g., PCA versus FCA), i.e., the dimensionality of the system increases the more the collection of subsystems describes the full carbon system.

With respect to systematic errors (biases) we conjecture that the probability of biases decreases with the completeness of the system. This is, of course, a working hypothesis, since in both PCA and FCA the true value is unknown. Without a benchmark no meaningful ranking can be established on a comparative basis.[6] Nonetheless, it is fair to assume that under FCA biases are minimized based on the following arguments:

1. Due to more consistent, complete and comprehensive analysis an improved understanding of the processes will lead to the elimination of some possible biases. This is especially true if an entire system or subsystem is analyzed separately using different models (e.g., ground inventory and remote sensing of biological and technospheric processes) or if competing research networks are able to pin down uncertainty boundaries and establish accepted true values as benchmarks.
2. FCA might eliminate biases through a top-down verification if the geographic coverage is of a sufficiently large scale. Top-down verification is not possible under PCA.
3. In a dynamic system of FCA, temporal and spatial spillovers are more likely to be detected.

We argue that in reality also the total error of an individual variable is the sum of a pure random error and a bias, i.e., $s^2 = s_B^2 + s_r^2$. Thus, there are two sources of error associated with each variable within a subsystem. We conjecture that an increase in the number of subsystems decreases the probability of uncorrected biases. Under the condition that the difference in the biases between FCA (larger system) and PCA (smaller system) is larger than the difference in the summarized random error between FCA and PCA, the total error of FCA would turn out to be smaller than that of the PCA, i.e., $s_i^2 = P(B_i)s_B^2 + s_{r_i}^2 > s_{i+1}^2 = P(B_{i+1})s_{B_{i+1}}^2 + s_{r_{i+1}}^2$ (here i stands for the number of subsystems and it is assumed that $i+1$ system was the final complement to establish the FCA). This is another reason why under FCA the total system error could turn out to be smaller than the total system error under PCA.

Spatial and temporal spillovers arise from spatial or temporal correlation between variables. A simple example would be where emission reduction measures lead to decreased consumption of fossil fuels (FF), with the result that the underlying global commodity markets face falling prices due to supply slacks. Reduced fossil fuel prices will lead to an increased consumption of FF in less developed countries outside the Kyoto agreement, such as future key players such as China and India. Such compensatory effects could neutralize the emission reduction in the commitment country in the short run (spatial correlation), but technological lock-ins in developing countries could lead to increased global FF emissions in the long-run (spatial and temporal correlation). In addition, falling prices increase the time of amortization of the large sunk costs related to resource extraction and distribution networks causing a temporal extension of the supply slack (temporal correlation). Spatial spillovers could also arise from plantations if they are established on agricultural sites that are more

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[6] Gödel's "imperfectness principle" in its strongest possible form asserts that a fundamental theory cannot be perfect — either it is inconsistent, or it is insufficient to solve some of its problems (Gödel, 1931). To our knowledge there is, however, no theorem on the relation of completness and degree of inconsistency or insufficiency, which would be of special interest in our context.

needed to satisfy soaring food demand, thereby resulting in soil carbon depletion due to intensive agricultural practices and deforestation elsewhere.[7]

Comparing (I) and (II) in Figure 1, we see that the bliss point can not be reached under PCA. The bliss point would be defined by the combination of the lowest possible error and the highest feasible emission reduction potential. Under FCA the feasible range of emission reduction potentials is larger compared to PCA due to the fact that under a fixed budget a wider set of mitigation measures can be applied. A wider choice set makes it more likely that lower cost strategies can be implemented leading to increased emission reduction or increased sink strength on the country level. Emission reduction could, however, also be smaller under FCA compared to PCA if the cost of uncertainty reduction outweighs the 'choice set advantage' — on a relative scale, despite lower costs for carbon flux reduction, there are fewer resources left to reduce carbon emissions under FCA due to higher expenditures to eliminate uncertainties. Under this scenario the emission reduction is smaller in FCA since uncertainties come at a cost as discussed in the model below. Thus, if in FCA the relative share of uncertainties is sufficiently larger than in PCA and verification is a binding condition, higher average costs per unit of carbon emission reduction leads to less carbon emission reduction in FCA. However, this is also in part due to the fact that under PCA some biases are ignored and the verification is weaker. Considering these points, hereafter we call verification under PCA weak verification and verification under FCA strong verification.[8]

Mathematical Description of the Properties of Uncertainty Under FCA and PCA

Proposition 1: Perfectly Separable and Independent Subsystems

FCA can be derived from a set of perfect and perfectly separable PCAs ($F^{FCA} = \sum_i F_i^{PCA}$). If F is a function describing the net flux form, a PCA carbon system using the two random variables x_1 (fossil fuel system) and x_2 (Article 3.3 LUF measures) with the associated second moments $s_{x_1}^2, s_{x_2}^2$ and, in addition, x_3 (complement of the PCA carbon system with respect to FCA system), ($s_{x_3}^2$) are needed to describe the entire system of the FCA, it follows that:

$$\varepsilon_{PCA} < \varepsilon_{FCA} \Leftrightarrow \sqrt{\left(\frac{\partial F}{\partial x_1}\right)^2 s_{x_1}^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 s_{x_2}^2} < \sqrt{\left(\frac{\partial F}{\partial x_1}\right)^2 s_{x_1}^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 s_{x_2}^2 + \left(\frac{\partial F}{\partial x_3}\right)^2 s_{x_3}^2}$$

$$for \left(\frac{\partial F}{\partial x_3}\right)^2 s_{x_3}^2 > 0 .$$

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[7] Here we ignore the many other social welfare losses.

[8] The analysis in this paper ignores the difference between trend and level uncertainty and its implications for verification.

Proposition 2: Interacting Subsystems

FCA cannot directly be derived from a set of PCAs due to interactions between the PCA systems ($F^{FCA} \neq \sum_i F_i^{PCA}$). If F is again the function describing the fluxes of the perfect FCA described by the same variables, it follows that the total system errors are defined by:

$$\varepsilon_{PCA} = \sqrt{\left(\frac{\partial F}{\partial x_1}\right)^2 s_{x_1}^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 s_{x_2}^2 + 2\left\{\left[\left(\frac{\partial F}{\partial x_1}\right)\left(\frac{\partial F}{\partial x_2}\right)s_{x_1}s_{x_2} + \left(\frac{\partial F}{\partial x1}\right)\left(\frac{\partial F}{\partial x_3}\right)s_{x_1}s_{x_3} + \left(\frac{\partial F}{\partial x_2}\right)\left(\frac{\partial F}{\partial x_3}\right)s_{x_2}s_{x_3}\right]\right\}}$$

$$\varepsilon_{FCA} = \sqrt{\left(\frac{\partial F}{\partial x_1}\right)^2 s_{x_1}^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 s_{x_2}^2 + \left(\frac{\partial F}{\partial x_3}\right)^2 s_{x_3}^2 + 2\left\{\left[\left(\frac{\partial F}{\partial x_1}\right)\left(\frac{\partial F}{\partial x_2}\right)s_{x_1}s_{x_2} + \left(\frac{\partial F}{\partial x1}\right)\left(\frac{\partial F}{\partial x_3}\right)s_{x_1}s_{x_3} + \left(\frac{\partial F}{\partial x_2}\right)\left(\frac{\partial F}{\partial x_3}\right)s_{x_2}s_{x_3}\right]\right\}}$$

From this follows again that $\varepsilon_{PCA} < \varepsilon_{FCA}$ since $\left(\frac{\partial F}{\partial x_3}\right)^2 s_{x_3}^2 > 0$. Since under PCA the interaction with the rest of the carbon system is ignored and interaction between carbon systems is usually also not taken into account (i.e., the covariances in the calculation of ε_{PCA} are assumed to be zero), it follows that $\varepsilon_{PCA|s_i s_j = 0} < \varepsilon_{FCA}$ holds

iff $\left(\frac{\partial F}{\partial x_3}\right)^2 s_{x_3}^2 > -2\left\{\left[\left(\frac{\partial F}{\partial x_1}\right)\left(\frac{\partial F}{\partial x_2}\right)s_{x_1}s_{x_2} + \left(\frac{\partial F}{\partial x1}\right)\left(\frac{\partial F}{\partial x_3}\right)s_{x_1}s_{x_3} + \left(\frac{\partial F}{\partial x_2}\right)\left(\frac{\partial F}{\partial x_3}\right)s_{x_2}s_{x_3}\right]\right\}$.

In words, this means that if the increase in total error from enlarging the PCA system is larger than the error from omitting error correction from interaction of the subsystems, then the total system error of PCA is smaller than the total error from FCA.

The law of error propagation allows us to consider only first order interactions, however, interactions are also possible of a higher order, which in our example would be defined by an interaction term as a function of x_1, x_2, x_3.

Formulation of the Decision Problem of Enlarging the Carbon System Under Weak and Strong Verification Conditions

Based on the concepts developed in Obersteiner *et al.*(2000a,b) we will develop, in this paper, a decision rule to allow for optimally choosing the size (comprehensiveness) of the carbon system under weak and strong verifiability. We will first describe the variables entering the decision problem and then set up the problem as such and then we will shortly discuss the implications of the model for implementation as a decision support for projects and for country strategies. In Obersteiner *et al.* (2000a,b) we have derived a decision rule that allows us to compute the optimal choice of emission reduction and uncertainty reduction within a Kyoto-type framework. Consider a Kyoto world where a country has to choose its path of emission reduction to meet an agreed emission target (*Kt*) (see Figure 3). In order to meet the terms of the contract the country must choose a certain rate of emission reduction, $\frac{dF}{dt}$, for each time period t.[9] Emission reduction involves a cost c_F to finance projects that reduce carbon emissions or induce increased carbon sequestration. Likewise, regulations, fees and carbon taxes that are targeted to decrease GHG emissions come at economic cost.[10] If the measures taken are not sufficient or if the cost of emission reduction in the country is too large, countries are allowed to reach the Kyoto target by carbon trading or other flexible arrangements. On the other hand, countries that shoot over the Kyoto target are allowed to sell their surplus on the carbon market or bank it for use in subsequent periods.

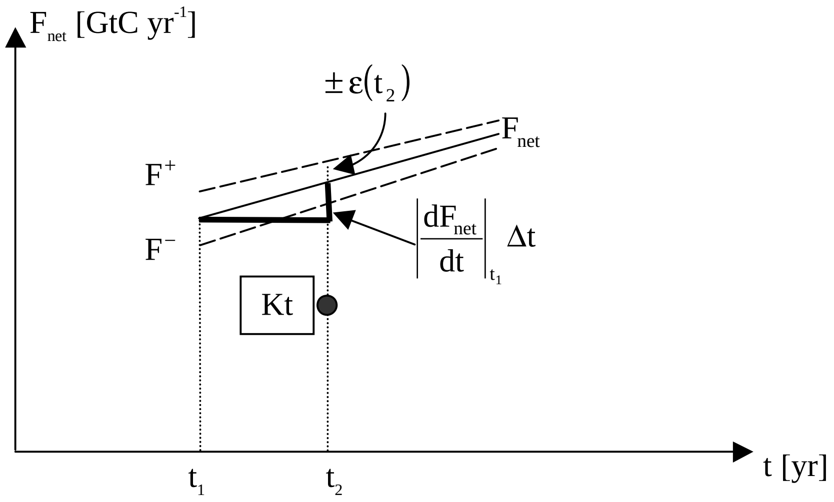

Figure 3: Simplified linear graphical representation of the key variables concerned. Illustration for increasing net carbon emissions ($F_t < F_{t+1}$) and decreasing in their uncertainty ($\varepsilon_t > \varepsilon_{t+1}$) (Source: Adapted from Jonas *et al*., 1999).

In principle there are two ways of dealing with uncertainties. First, countries could be penalized for uncertainties and second, countries are allowed to reduce this penalty by reducing the level of uncertainty. Both options are expressed as variables in the model set-up. Assume that a country starts with an initial degree of uncertainty $\varepsilon = \frac{1}{2}\varepsilon_{t_1} = \frac{1}{2}\left(F_{t_1}^+ - F_{t_1}^-\right)$ in t_1=1990. Uncertainties can be changed at a rate of $\frac{d\varepsilon}{dt}\Delta t = \varepsilon_t - \varepsilon_{t+1}$. Depending on the nature of uncertainty, as discussed in the previous section, the uncertainties refer to PCA taking or not taking interactions into account or refer to FCA, i.e., uncertainty can be defined as $\varepsilon_{PCA}, \varepsilon_{PCA|s_i s_j=0}, \varepsilon_{FCA}$. If uncertainties cannot be reduced, the country will be penalized for the remaining uncertainty.

A model needs to be constructed that provides a decision rule for a specific country to optimally reduce emissions and/or reduce uncertainties given a certain degree of

[9] For a list of the variables and units, see the Appendix.
[10] It is, of course, possible that energy cost savings and innovation triggered economic growth create positive externalities that compensate for such costs.

comprehensiveness of the reference system. To solve the problem of the optimal choice of emission reduction versus uncertainty reduction we formulate a profit maximization (loss minimization) for a certain commitment period for the particular reference carbon system. Profits are maximized by optimally choosing carbon emission reductions ($\Delta F = -\mathrm{sgn}\left(\frac{dF}{dt}\Delta t\right)\left|\frac{dF}{dt}\Delta t\right|$) and change of uncertainties ($\Delta\varepsilon = -\mathrm{sgn}\left(\frac{d\varepsilon}{dt}\Delta t\right)\left|\frac{d\varepsilon}{dt}\Delta t\right|$) over this one period $\Delta t = 20\,yrs$.[11] In the aggregate in order to achieve market clearing revenues must balance costs. Revenues, within a Kyoto framework, are calculated by the (discounted[12]) value of total reported emission reductions corrected for uncertainties in 2010 (which is the uncertainty in 1990 (ε) minus its change over the 20 year period).[13] Total revenue is positive if emission reduction is verifiable and the emission target was reached, and negative if emission reduction is not verifiable and/or the emission target was not reached. The price *p* is assumed to be the aggregate solution of the respective competitive carbon market. Two types of costs arise if the country decides to take its own steps to actively reduce carbon emissions:

(1) Total cost of emission reduction, which is equal to the total amount of carbon reduced over the commitment period multiplied by the specific average cost c_F. The specific average cost is a function of ΔF and should exhibit the usual properties needed for microeconomic analyses (e.g., Varian, 1992). On a country level this cost function not only includes technological variables but also factors such as population and economic growth; and

(2) Total cost of uncertainty reduction, which is equal to the total amount of carbon reduced over the commitment period multiplied by the specific average cost c_ε. Similar to c_F, c_ε is a function of $\Delta\varepsilon$ and is assumed to exhibit the required properties in microeconomic analyses.

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[11] The model set up is general enough so that ΔF can take on the definition of the necessary rate of emission reduction to reach the Kyoto target in 2010 or any other emission reduction target under a different convention also taking into account the polluter pays principle and the principle of equity.

[12] For simplicity we ignore a discount rate for this period problem. In addition, there are methodological issues to be solved of applying a discount rate if the quality of rewards is not fully understood. A multiperiod model involving a discount rate will be developed in a follow-up paper to analyze optimal behavior under Kyoto and post-Kyoto scenarios.

[13] Note: From a methodological point of view, it is interesting to observe that we can derive the verification time formula of Jonas *et al*. (1999) from the revenue function: $\left(\frac{\partial F}{\partial t}\Delta t - \varepsilon - \frac{\partial \varepsilon}{\partial t}\Delta t\right) = 0 \Leftrightarrow \frac{\varepsilon}{\frac{\partial F}{\partial t} - \frac{\partial \varepsilon}{\partial t}} = \Delta t$. If we are interested in a more statistical interpretation of the verification time concept and ignoring for reasons of simplicity the change in uncertainty, we can apply the Student t-Test from which follows that $\frac{\varepsilon t_w}{\frac{\partial F}{\partial t}} = \Delta t$, with t_w being the tabular value of the t-Test given the appropiate degrees of freedom using the one-sided t-Test (Note: t_w is always a larger one for confidence intervals larger that 90%, which are considered by the IPCC from which it follows that verifications times will be larger using the statistical interpretation compared to the verification times used by Jonas *et al*., 1999).

Within one system the task is to maximize the following goal function with respect to the two choice variables $\Delta F, \Delta\varepsilon$:

$$\max_{\Delta F, \Delta\varepsilon, \lambda} \pi = \left(\Delta F - (\varepsilon - \Delta\varepsilon)\right) p - c_{F\,(\Delta F)}\left(\Delta F\right) - c_{\varepsilon\,(\Delta\varepsilon)}\left(\Delta\varepsilon\right)$$
$$s.t$$
$$Kt \leq \left(\Delta F - (\varepsilon - \Delta\varepsilon)\right)$$

This maximization problem can be used to analyze the optimal solution for an individual country or even an individual project as well as for an ensemble of countries participating in the carbon market. The optimization problem needs to be constrained by the emission reduction target (*Kt*). It is demanded that the collection of countries (over-) fulfill their joint commitment target.

However, in this paper we are interested in the 'optimal' comprehensiveness of the carbon system to be used as the reference system for carbon accounting. We, thus, must ask the question: "Which reference carbon system will maximize total profits given the rules governing the market, i.e., under no verification clause, verification under PCA or verification under FCA?" For this purpose, we need to distinguish at least two carbon systems. One that builds the core carbon system, which in the current situation is established by the Kyoto Protocol consisting mainly of the fossil fuel carbon system, and the other that is added to the FF system, which if we move toward FCA would be the complementary rest of the carbon system. Let us now call $\Delta F^{B}, \varepsilon^{B}$ the change in emission and its uncertainty of the core carbon system, and $\Delta F^{A}, \varepsilon^{A}$ the change in emission and its uncertainty of the added carbon system, and $\Delta F, \varepsilon$ the change in emission and its uncertainty of the total FCA carbon system. The decision rule of whether or not to enlarge the core carbon system will depend on whether total profits can be expected to be increased. Consequently we are interested in maximizing the positive difference between the profits gained from taking the core and the added system as the reference system and profits from the core system, i.e., $\max(\pi^{BA} - \pi^{B})$.

Setting up the problem to compute π^{BA} looks as follows:

$$\max_{\Delta F^{B}, \Delta F^{A}, \Delta\varepsilon_{v}, \lambda} \pi^{BA} = \left(\Delta F^{B} + \Delta F^{A} + \left(\Delta F^{B} \Delta F^{A}\right)\mu - \left(\varepsilon_{v} + \Delta\varepsilon_{v}\right)\right) p - c^{B}_{F\,(\Delta F^{B})}\left(\Delta F^{B}\right) - c^{B}_{F\,(\Delta F^{B})}\left(\Delta F^{B}\right) - c_{\varepsilon\,(\Delta\varepsilon)}\left(\Delta\varepsilon_{v}\right)$$
$$s.t.$$
$$Kt \leq \left(\Delta F^{B} + \Delta F^{A} + \left(\Delta F^{B} \Delta F^{A}\right)\mu - \left(\varepsilon_{v} + \Delta\varepsilon_{v}\right)\right)$$

There are a few additional details that need to be considered in this set-up. First we introduce a factor μ, which symbolizes a linear interaction factor for emission reduction measures taken in both systems. μ can either take on positive or negative values depending on the type of interaction. Furthermore, the subscript in ε_{v} stands for the different types of interpretation of the uncertainty, i.e., $\varepsilon_{PCA}, \varepsilon_{PCA|s_i s_j = 0}, \varepsilon_{FCA}$.

From this set-up we can, analogously to Obersteiner *et al*. (2000a), compute the optimal decision rule for $\Delta F^{*AB} = \Delta F^{*}(\varepsilon_v, c_{F^{B,A}}, c'_{F^{B,A}}, c_{\varepsilon^{B,A}}, c'_{\varepsilon^{B,A}}, \mu; Kt)$. ΔF^{*BA} is then a function of the initial uncertainty, the average cost and the marginal average cost of emission reduction and uncertainty reduction, the interaction term, and the emission reduction target. Likewise, we can compute the optimal decision rules of uncertainty reduction $\Delta\varepsilon^{*BA} = \Delta\varepsilon^{*}(\varepsilon_v, c_{\varepsilon^{B,A}}, c'_{\varepsilon^{B,A}}, c_{F^{B,A}}, c'_{F^{B,A}}, \mu; Kt)$. $\Delta\varepsilon^{*BA}$ is a function of the initial uncertainty, the average cost and the marginal average cost of uncertainty reduction and emission reduction, the interaction term, and the emission reduction target. Given the optimal decision rules and necessary parameters like the Kyoto target, the cost schedule for abatement strategies and sink enhancement measures, the interaction parameter, the initial level of uncertainty of the relevant carbon system as well as the cost schedule for uncertainty reduction a country can specify its optimal Kyoto policy with respect to opt for the optimal comprehensiveness of the reference carbon system under a given institutional setting demanding no, weak or strong verification. All of the variables entering the decision rules are *ex ante* quantifiable and the computation of the maximum difference of the profits is then straightforward.

Summary and Conclusion

Our analysis shows that there is a strong indication that it is paramount to always operate in a FCA framework even if actual measures are taken in a PCA manner. If carbon subsystems are sufficiently interlinked then the relative error of interaction with the rest of the system becomes larger the smaller the subsystem gets. Thus, meaningful baselines can only be established if they are computed in a FCA framework.

In our analysis we defined uncertainties by means of two error categories — random errors and biases. Within the category of biases we distinguish between conscious and unconscious biases. We have shown that the summarized random error (we also called internal error) increases with the number of subsystems added. Thus, a FCA system will by definition always exhibit larger internal errors than its subcomponents. Contrarily the probability of undetected biases is larger in PCA systems. With respect to the potential range of carbon reduction measures FCA systems, compared to PCA systems, are superior due to their maximum comprehensiveness. However, in a situation where the uncertainties of the FCA system are too large it proves to be better to exclude a highly uncertain subsystem from the reference carbon system eligible for a Kyoto-type market. Under the condition of strong verification, an exclusion is allowable as long as the interactions of this system with the total system are known and taken into account (e.g., import-export statistics are reliable versus fraudulent production figures for the calculation of apparent domestic consumption).

From the above it follows that accounting should be separately treated from accountable activities for trading and mutual recognition of emission reductions. With respect to the nature of uncertainties biased reporting can be used for intentional cheating and should thus be eliminated from accountable emission reduction claims. As shown in this paper it is reasonable to assume that the probability of biases decreases with the comprehensiveness of the system analyzed, because we can make consistency checks. It is, thus, indispensable to always monitor the entire GHG system (Full GHG Accounting

[FGA]) irrespective of what kind of actions are credited for in the Kyoto mechanism. A FGA should always be the compulsory monitoring system, whereas actions that are the means to get to the target and are subject to the Kyoto market rules have to be accounted for as (a) consistent subsystem(s) (Partial GHG Account [PGA]) within a FGA. Verification should make sure that the acknowledged credit influences the atmospheric GHG balance in the intended (claimed) fashion. FGA provides the necessary accounting framework and carries the possibility of top-down verification under certain conditions. These conclusions are also in line with the most recent findings in the field of economic and thermodynamic analysis (Baumgärtner, 2000).

Under the condition that we are allowed to exclude subsystems from FCA, we must give answers to the question of the optimal comprehensiveness of the reference carbon system that should be eligible for the mutual recognition of emission reduction. In this paper, we developed a decision rule that gives an answer to this problem under various types of verification modi. Based on analysis using the law of error propagation we are confronted with the computation of, in principle, four types of error definition to be used for verification: (1) the error is zero; (2) error excluding interactions with other systems (internal error); (3) error including interaction with another PCA system; and (4) error including interactions with the global rest of the FCA system. For the computation of the optimal comprehensiveness, interactions are not only of interest with respect to the computation of errors but combining measures (PCA systems) can lead to positive and negative spillover effects (feedback loops) in reducing emissions/carbon sequestration.

Future research will be on the empirical computation of the optimal comprehensiveness for a set of countries. Another task will be to establish a criteria and indicator catalogue for the concepts of weak and strong verifiability and we will also need to look into issues of the institutional set-up and implementability of these concepts.

References

Baumgärtner, S. (2000). *Ambivalent Joint Production and the Natural Environment — An Economic and Thermodynamic Analysis*. Physical Verlag, Heidelberg, Germany.

Gödel, K. (1931). Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme. “Monatshefte für Mathematik und Physik”, Vol. 38, pp. 173–198. English translation: http://www.ddc.net/ygg/etext/godel/index.htm.

Houghton, J. (1999). As Things Hot Up. In: The World in 2000. *The Economist,* Special Publication.

IPCC (1996). Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.), Cambridge University Press, Cambridge, UK.

IPCC (1999). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Updated information made available by the National Greenhouse Gas Inventories Program of the Intergovernmental Panel on Climate Change (IPCC) on the Internet: http://www.iea.org/ipcc.htm.

Jonas, M., B. Mayr, S. Schidler, M. Sotoudeh and H.M. Knoflacher (1998). Land-use Change and Forestry in Austria: A Scientific Assessment of Austria’s Carbon Balance in Light of Article 3 of the Kyoto Protocol. Interim Report IR-98-028. International Institute for Applied Systems Analysis, Laxenburg, Austria. Available on the Internet: http://www.iiasa.ac.at.

Jonas, M., S. Nilsson, A. Shvidenko, V. Stolbovoi, M. Gluck, M. Obersteiner and A. Öskog (1999). Full Carbon Accounting and the Kyoto Protocol: A Systems-Analytical View. Interim Report IR-99-025. International Institute for Applied Systems Analysis, Laxenburg, Austria. Available on the Internet: http://www.iiasa.ac.at.

Nabuurs, G.J., A.J. Dolman, E. Verkaik, A.P. Whitmore, W.P. Daamen. O. Oenema, P. Kabat and G.M.J. Mohren (1999). *Resolving Issues on Terrestrial Biospheric Sinks in the Kyoto Protocol.* Report No. 410 200 030, Dutch National Research Programme on Global Air Pollution and Climate Change, Bilthoven, Netherlands.

Nilsson, S., A. Shvidenko, V. Stolbovoi, M. Gluck, M. Jonas and M. Obersteiner (2000). Full Carbon Account for Russia. Interim Report IR-00-021. International Institute for Applied Systems Analysis, Laxenburg, Austria. Available on the Internet: http://www.iiasa.ac.at.

Obersteiner, M., Y.M. Ermoliev, M. Gluck, M. Jonas, S. Nilsson and A. Shvidenko (2000a). Avoiding a Lemons Market by Including Uncertainty in the Kyoto Protocol: Same Mechanism — Improved Rules. Interim Report IR-00-043. International Institute for Applied Systems Analysis, Laxenburg, Austria. Available on the Internet: http://www.iiasa.ac.at.

Obersteiner, M., M. Jonas, S. Nilsson, A. Shvidenko and M. Gluck (2000b). Trading Flexibility for Predictability — Differential Emission Dynamics and the Formation of Common Carbon Markets. Interim Report IR-00-063. International Institute for Applied Systems Analysis, Laxenburg, Austria. Available on the Internet: http://www.iiasa.ac.at.

Rypdal, K. and L. Zhang (2000). Uncertainties in the Norwegian Greenhouse Gas Emission Inventory. Rapporter 2000/13 (May). Statistics Norway, Oslo. ISBN 82-537-4808-6.

SBSTA (1998). *Methodological Issues: Issues Related to Land-Use Change and Forestry. Note by the Secretariat.* Document FCCC/SBSTA/1998/INF.1. Available on the Internet: http://www.unfccc.de/.

Schimel, D., J. Melillo, H. Tian, D. McGuire, D. Kicklighter, T. Kittel, N. Rosenbloom, S. Running, P. Thornton, D. Ojima, W. Parton, R. Kelly, M. Sykes, R. Neilson and B. Rizzo (2000). Contribution of Increasing CO_2 and Climate to Carbon Storage by Ecosystems in the United States. *Science*, Vol. 287, 17 March.

Shvidenko, A.Z., S. Nilsson, V.A. Rojkov and V. Strakhov (1996). Carbon budget of the Russian boreal forests: A systems analysis approach to uncertainty. In: *Forest Ecosystems, Forest Management and the Global Carbon Cycle.* M.J. Apps and D.T. Price (eds.). NATO ASI Series, Series I, Vol. 40, Springer-Verlag, Heidelberg, Germany, 145–162.

Varian, H.R. (1992). *Microeconomic Analysis*. W.W. Norton. New York.

Vine, E. and J. Sathaye (1997). The Monitoring, Evaluation, Reporting, and Verification of Climate Change Mitigation Projects: Discussion of Issues and Methodologies and Review of Existing Protocols and Guidelines. LBNL-40316, Lawrence Berkeley National Laboratory, Berkeley, USA.

Vine, E., J. Sathaye and W. Makundi (1999). Guidelines for the Monitoring, Evaluation, Reporting, Verification and Certification of Forestry Projects for Climate Change Mitigation. LBNL-41877, Lawrence Berkeley National Laboratory, Berkeley, USA.