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Avoiding a Lemons Market by Including Uncertainty in the Kyoto Protocol: Same Mechanism — Improved Rules

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Abstract

In its current form the Kyoto Protocol does not consider the issue of uncertainty in the process of mutual recognition of emission reductions between Parties. We argue that a lack of appropriate institutions that police emission reporting will lead to a disintegration of the carbon market due to competition induced quality deterioriation of reporting. The introduction of a verification clause in the Protocol's rules would be a first step towards avoiding disintegrative tendencies and carry the potential of improving the Protocol's effectiveness. Building on a physical approach of verification times we derive an economic model of optimal emission and uncertainty reduction to reach a verifiable emission target. In such a set-up, depending on its competitive advantage, a Party can choose to reduce emissions and/or the associated uncertainties or trade verified certificates. Thus, the proposed model is intended to help prioritize efforts to reach verifiable emission reductions with least costs within a Kyoto type framework.

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Michael Obersteiner, Yuri Ermoliev, Michael Gluck, Matthias Jonas, Sten Nilsson and Anatoly Shvidenko

Introduction

Uncertainty in reporting carbon fluxes is an issue that has been largely ignored by the architects of the Kyoto Protocol. For example, the most recent publication of the Intergovernmental Panel on Climate Change (IPCC), "The Special Report on Land-use, Land-use Change and Forestry (IPCC, 2000), considers a number of aspects dealing with uncertainty but does not define uncertainty as such and falls short of considering any operational rules managing uncertainty.[1]

The Kyoto Protocol (UNFCCC, 1998) to the UN Framework Convention on Climate Change (UNFCCC, 1992) contains the first legally binding commitments to limit or reduce the emissions of six greenhouse gases. Net carbon emissions reported in support of Kyoto commitments require verification, whether emission reduction measures have been applied or not. The carbon accounts must be verifiable in a timely manner, consistent with the commitment periods foreseen under the Protocol. From an economic point of view the main problem associated with non-verifiability is that the carbon market[2] might collapse due to over-reporting races of non-verifiable emission reduction claims. In this paper we provide an economic approach to solve this problem by introducing uncertainty in the Kyoto mechanism without changing the basic structure of the exisiting Protocol. We do so by including a verification clause into the rules of mutual recognition of emission reduction. The approach is based on a physical verification time concept developed by Jonas *et al*. (1999).

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[1] Note: There are no widely accepted concepts of uncertainty. Formal methods describing the full range of uncertainty have yet to be developed, which is the topic of a forthcoming paper (Obersteiner *et al*., 2000b). In this paper uncertainty is used as a concept to describe the level of belief (of both buyers and sellers) of the magnitude of deviation of reported emission reductions from the actual value.

[2] Here, the term market must be based in a wider definition. In our context, a market is already established through mutual recognition of emission reduction and does not preclude the exchange of carbon credits. Thus, the market is defined through the exchange of information.

The Physical Basis

The results of Jonas *et al*. (1999), who studied the verifiability of carbon accounts under the Kyoto Protocol by acknowledging the uncertainty underlying such accounts, provide the basis for this study. The authors evaluated questions related to the methods used for verifying carbon accounts and the effect of different provisions on the feasibility of implementing the Protocol by developing and applying the concept of "verification time". This is the (minimal) time required to verify changes in carbon emissions. It links the dynamics of carbon emissions with the dynamics of the underlying uncertainties. Their findings of importance to this study are:

1. The three quantities determining the projected verification time of carbon emissions are: today's (mean) rate of change in carbon emissions, the associated uncertainty as well as its rate of change.

   This study translates this concept of verification time into economics by preserving its physical basis.

2. Partial Carbon Accounting (PCA), restricted to CO_2 emissions from fossil fuel combustion and cement production, represents the only 'clean' scale-independent carbon accounting approach that is characterized by verification times compatible with the Kyoto Protocol. In the event that the Kyoto Protocol is based on PCA under partial inclusion of biological sources and sinks, caveats are introduced that are related to the mismatch of verification conditions from one country to another and to severe impediments to Full Carbon Accounting (FCA) on large spatial scales.

   This study presupposes that these adverse concomitants are negated and that the Kyoto Protocol will be realized without fundamental changes and continue to include part of the biological sources and sinks.

3. Reaching agreed Kyoto targets will primarily be a question of how much countries will be able to reduce their carbon emissions. Reducing associated uncertainties will play a non-negligible, nevertheless second-order role, particularly in the medium- to long-term.

In this sudy, two of the three physical quantities mentioned above — the rate of change in carbon emissions and the rate of change in the uncertainty — are treated as economic decision variables.

The Importance of Verifiability

The Kyoto Protocol (UNFCCC, 1998) to the UN Framework Convention on Climate Change (UNFCCC, 1992) contains the first legally binding commitments to reduce greenhouse gas (GHG) emissions. The introduction of legally binding commitments for carbon reduction in the Kyoto Protocol lead to methodological questions of verifying compliance with emission targets. Verification requires that binding commitments are not only a function of the rates of net emission changes, but also of the associated uncertainties and their rates of change (Jonas *et al*., 1999).

The economics profession has a long tradition of theory building on how an ideal market should look, but economic theory provides little guidance on how to establish a market. North (1997) has suggested four institutional features that are associated with low-cost transaction and credible commitment, essential for the functioning of any market:

- The cost of measuring;
- The size of the market;
- Enforcement of rules; and
- Attitudes and perceptions.

With respect to the topic of our paper the first and the third features are of special interest. The first feature, the cost of measuring, deals with the fact that when no or poor standards exist with regard to the quality of goods and services, the behavior of agents, etc., every single transaction might be the subject of endless deliberations.

The third feature is the enforcement of rules. When parties dispute or break the rules (e.g., over-report) they should have recourses for cheap ways of solving their differences. This is mainly done by third party solutions. It should, however, be mentioned that the cheapest enforcement occurs when people have internalized certain conducts of behavior as norms.

In the following section we will briefly discuss three arguments that support the idea that at least the efficiency or even the integrity of the market is in danger if there is an institutional vacuum concerning features one and three.

The lemons argument. Verifiability will become a necessary condition for mutual recognition of claimed emission reductions and, thus, become also a necessary precondition for emissions trading and other flexible instruments irrespective of its domestic or international implementation. Based on Ackerlof's lemons market concept, we conclude that for any carbon market arrangement rational actors would want to abstain from a set of commitments, if there is larger latitude of conscious biases in the underlying reporting for the other participants in the market. Unless there is a sufficiently large penalty for at least conscious biases, a successful implementation of the Kyoto Protocol does not seem likely to occur. If other parties prior to trading or recognition cannot observe reporting quality, then the reporting party will be tempted to skimp on it. Other parties will become reluctant to pay relatively higher prices under the instruments contained in the Protocol or will be reluctant to recognize reporting as they learn to expect over-reported emission reductions — or 'lemons' (see Ackerlof, 1970).

The winner-loser gap argument. The lemons argument only applies if in the end buyers care about the quality of the product provided, i.e., in the case of carbon markets the real (verifiable) carbon emission reduction. This does not necessarily need to be applicable to all participants of the Kyoto market. Participants might only care about fulfilling their legal commitments once they are agreed upon and will not worry about their true carbon balance. In this case, some parties would be clearly better off if they over-report. However, as we will show, if the parties are different in their ability to over-report disintegrative tendencies will prevail in most cases. To demonstrate this point let us consider a number of market constellations between buyers and sellers in a game theoretic setting.[3] For simplicity, assume that both buyers and sellers can consist of

[3] For illustrative purposes we take on the analogy of a price forming market of buyers and sellers. However, the intuition gained from the example should be directly transferable to the non-price forming mechanism of mutual recognition of emission reduction.

countries that can over-report (H) and countries that report the true value or even under-report (L). In Figures 1 and 2 the hypothetical pay-offs for the buyer (first number in each cell) and the seller (second number in each cell) relative to a market that requires verification (L-L) are listed.[4] Figures 1 and 2 show the hypothetical pay-offs of a price elastic and a price inelastic market mimicking the market models proposed by the JUSCANNZ[5] alliance and the EU. JUSCANNZ, which is lead by the US, favor a target based on all greenhouse gases, sources and sinks, flexibility, and meaningful participation of key developing countries (Ramos-Martin, 2000). The European Union on the other hand is defending the "common but differentiated responsibility principle" and envisions a less flexible market mechanism with country specific quota of trade of emission rights — a more price inelastic market.

		Seller	
		H	L
Buyer	H	+ +, – –	+ + +, – –
	L	+, + +	0,0

Figure 1: Price elastic markets.

		Seller	
		H	L
Buyer	H	+ +, –	+ + +, – –
	L	+, –	0,0

Figure 2: Price inelastic markets.

<u>Case I (L–L case):</u>

All countries are virtually not able to over-report emission reduction (L–L case). Such a market constellation would correspond to the benchmark market of verifiable carbon accounts. The pay-off from introducing verification would be (0,0).

<u>Case II (H–H case)</u>:

If all countries are able to over-report equally high (H–H) then buyers would gain by decreasing their demand for emission certificates and, in addition, in the price elastic case from lower prices. Sellers, in turn, would lose due to erroding demand and falling prices because of over-supply in the price elastic case.

<u>Case III (L–H case)</u>:

If the group of buyers is mainly dominated by L-types and sellers are mainly H-types, buyers would improve their situation and sellers would either gain or lose depending on the elasticity of demand. If demand is fully elastic (Figure 1) then sellers would be able to sell more carbon credits (some of which will have been produced with zero costs, i.e., over-reported), but at a lower price. Here, we assume that sellers would in total improve their situation because the price effect is over-ruled by the quantity effects. This might, however, not become true depending on the supply/demand quantities. In the case of inelastic demand (Figure 2) sellers would lose, because over-reporting races would lead to falling prices which can not be compensated by quantity responses in a price inelastic market. The pay-off to the buyers would be smaller in the inelastic case compared to the

[4] A more formal analysis on disequilibrium forces in this context will be provided in a forthcoming paper. Such an analysis would go beyond the scope of this paper, which focuses on ways to incorporate a verifiability clause in a Kyoto market.
[5] Japan, USA, Canada, New Zealand.

elastic case due to the fact that countries would not benefit from the 'artificially' lower costs of traded carbon by the substitution of domestic emission reduction.

Case IV (H–L case):

In the case that buyers are able to exploit high uncertainties, buyers will have to perform fewer domestic actions and will also need to purchase less carbon credits from abroad. Under both elastic and inelastic market conditions sellers will lose due to a shrinking market in terms of quantity and falling prices.

The altruist – defector argument. A market failure based on the lemons and the winner-loser-gap argument require direct observation or direct reciprocity. In an anonymous market, as is partially planned to be organized for the trade of emission permits, a more indirect mechanism is in action. As we will elaborate in the following paragraphs, even under conditions of indirect reciprocity the market might become biased towards defectors (countries which over-report), which could lead to market failure. In order to support this argument we take up the concept developed by Nowak and Sigmund (1998). In their model, each player has two interactions per round, one as a donor and one as a recipient. The same individuals are never paired twice and direct reciprocation is thus impossible. Such a game theoretical set up comes somewhat closer to the market conditions of a semi-anonymous market as we envisage the Kyoto market. Depending on the strategies they use, the players can fall into one of three categories (see Figure 3): uncertainty ignorers (indiscriminate altruists), who always accept the official emission reports of other countries; over-reporters (defectors), who always try to over-report; and uncertainty managers (discriminate altruists), who accept the official emission reports if the potential trading partner did not over-report in the last round. Suppose now that the carbon market consists entirely of countries that always accept whatever the other countries report. If the state of altruists is above the lightning bolt some over-reporters will take over. If it is below the sun symbol, defectors (over-reporters) will immediately be selected against and will promptly vanish. But, if a minority of defectors appears while the state is between the lightning bolt and the sun, then defectors will at first exploit the indiscriminate altruists and increase in frequency — thereby, leading to a potential market failure in our terminology used above due to large over-supplies of carbon credits. If there is no immediate restructuring of the institutions governing the market (i.e., a decent uncertainty management) only the discriminate altruists will eventually take over and eliminate the over-reporters. Now, the frequency of discriminate altruists will be below the sun.

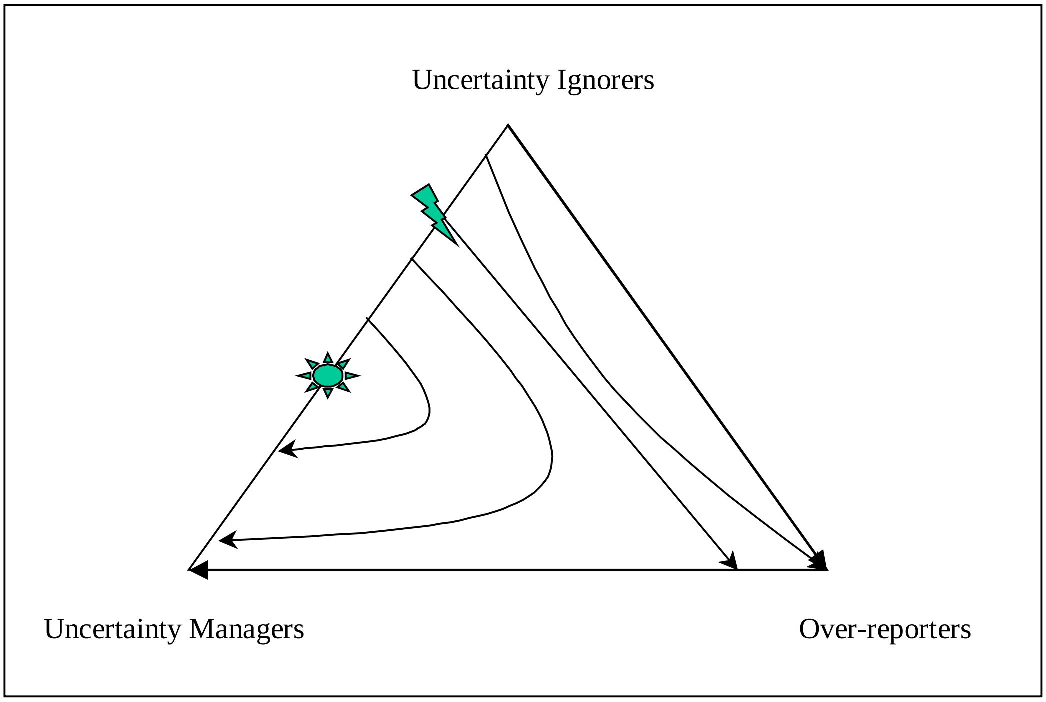

Figure 3: Market Trajectories Under Indirect Reciprocity of Uncertainty Ignorers, Uncertainty Managers and Over-reporters (Source: Adapted from *Options*, Spring 2000).

It follows that an appropriate institutional solution should be developed prior to evolutionary learning which in itself is a very costly process and discrimination will also come at economic cost if the norms are not fully internalized.

From this exercise, we can conclude that the market is most likely to disintegrate if market participants become aware of possible over-reporting, regardless of their aspiration to reduce real carbon emissions. The virulence of the disintegrative forces will depend on the magnitudes of over-reported carbon emissions on both the buyers and sellers side, the distribution of market power between losers and winners, the location(s) where the game is played in the above stated matrices, and the relative difference in the pay-offs. In any case, there will always be winners and losers as soon as parties differ in their ability to over-report on their real emissions and dissatisfaction will rise with the size of the pay-off gap between (and even among) buyers and sellers.

From experimental economics, for example, ultimatum games (Fehr and Gächter, 1997), we know that even in situations where both seller and buyer win (e.g., L-H in the price elastic case) but the difference between the two market participants is too large, the market will disintegrate.

Another side effect of lacking institutions policing emissions reporting is that countries with weak institutions that monitor carbon emissions will push carbon intensive production into the shadow economy or will at least set incentives to protect undiscovered sources. In this sense, it is not clear whether the current Protocol may set incentives or, worse yet, subsidize the creation of black markets.

We argue that for policy makers concerned with the Kyoto Protocol the lemons market phenomenon will become a pressing issue under the realization of the Protocol. In addition, there are also other dimensions to the verifiability concept. The uncertainty concept envisaged by the IPCC (1999) fails to identify adverse compensatory effects that could neutralize or even overrule well-intended Kyoto measures due to negative feedback mechanisms. Negative feedbacks or leakage arise from adverse spatial and temporal spillover effects and should be subtracted from the reported emission reduction or added to the uncertainty.

Bearing in mind that there are budget constraints for Kyoto measures, we must increasingly acknowledge the importance of the effectiveness of Kyoto measures. Effectiveness could be hampered, in a least cost sense of total net emission reduction, if the full range of carbon reduction measures and the range of GHG is restricted. There is a danger for the post-Kyoto process that certain measures are *a priori* disqualified on the grounds of the large uncertainty they carry. However, research by Jonas *et al*. (1999) indicates that technospheric systems should be separated from biospheric systems. This is based on an analysis of verification times, which shows that only technospheric measures will be verifiable within the Kyoto period. In this paper, however, we argue that uncertainty can be priced and in this way be included in a trading scheme. Within such a trade mechanism of verifiable carbon accounts, biospheric measures could turn out to be cost competitive despite large uncertainties in the biosphere. However, the problem of differential systems dynamics remains. This problem can probably be solved by the formation of common carbon markets as illustrated in Obersteiner *et al.* (2000a). Following the above mentioned arguments could lead to a situation where uncertainty and knowledge gaps could mean foregone options of reduction or mitigation strategies.

The three arguments can be summarized in the following question: "*Who is willing to participate in a Clean Development Act or Joint Implementation Program?*" if participating parties:

(1) are unable to verify emission reduction within a short commitment period.

(2) give biased reports leading to a disintegration of the market.

(3) take the risk of implementing actions that are, at best, inefficient or ineffective due to knowledge gaps in finding the minimum cost instruments to combat global warming.

Much remains to be done in order to answer all of these questions. The introduction of a verifiability concept would be a first major step in solving some of these problems. It is, thus, the purpose of this paper to design a model that helps to prioritize efforts to reach verifiable emission reductions with least costs within a Kyoto type framework, and carries the prospect of taking these forward in a post-Kyoto process. The model developed below is equally applicable to project, regional, national, and global levels of emission reduction. The quantification of uncertainties, however, is strictly level specific. The economic solution to the verifiability problem is achieved by attaching an economic cost to uncertainty. In the following description we develop a model that provides a decision maker with an optimal decision rule on emission and uncertainty reductions in a Kyoto market that requires verifiable carbon accounts.

The Model

In the following paragraphs we develop a model 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 4 for the increasing emissions case). In order to meet its commitment the country must choose a certain rate of emission reduction, $\frac{dF}{dt}$, for each time period *t*.[6] 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.[7] 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, if allowed, bank it for use in subsequent periods.

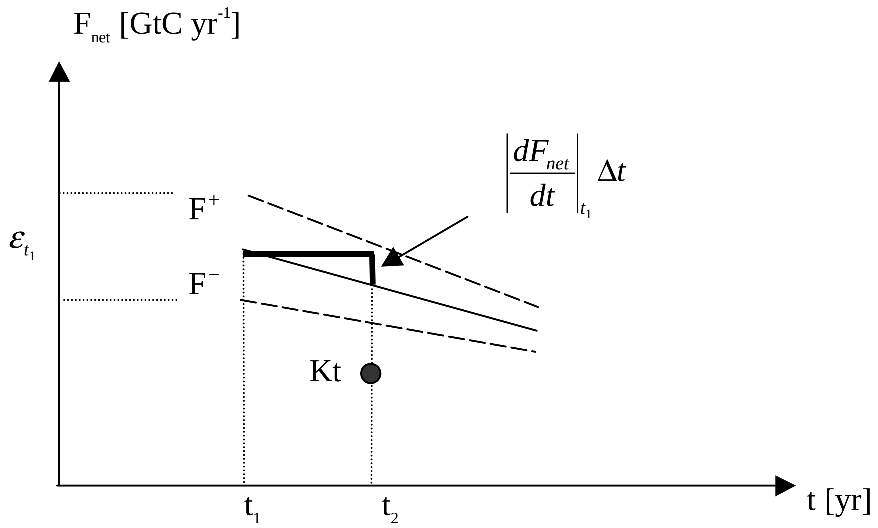

Figure 4: Simplified linear graphical representation of the key variables concerned. Illustration for increasing net carbon emissions ($F_t < F_{t+1}$) and decreasing in their uncertainty ($\varepsilon_t > \varepsilon_{t+1}$) (Source: Adapted from Jonas *et al*., 1999).

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.[8] 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

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[6] For a list of the variables and units, see Appendix 1.

[7] It is, of course, possible that energy cost savings and innovation triggered economic growth create positive externalities that compensate for such costs.

[8] An analogy can be found in, e.g., life insurance markets. A reduced rate is offered after medical examination otherwise a flat rate is given.

$\frac{d\varepsilon}{dt} = \frac{\varepsilon_{t_2} - \varepsilon_{t_1}}{t_2 - t_1}$ through measures reaching from improved statistical reporting of apparent consumption data of fossil fuels, detailed measurements of fugitive emissions, and more frequent and detailed assessments of conversion factors to improved inventories of LUF measures.[9] 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. To solve this problem we formulate a profit maximization (loss minimization) for the commitment period. Profits are maximized by optimally choosing carbon emission changes *(*$\Delta F = -\text{sgn}\left(\frac{\partial F}{\partial t}\Delta t\right)\left|\frac{\partial F}{\partial t}\Delta t\right|$*)* and change of uncertainties ($\Delta\varepsilon = -\text{sgn}\left(\frac{\partial \varepsilon}{\partial t}\Delta t\right)\left|\frac{\partial \varepsilon}{\partial t}\Delta t\right|$) over this one period $\Delta t = 20 yrs$.[10] In the aggregate in order to achieve market clearing revenues must balance costs. Revenues, within a Kyoto framework, are calculated by the (discounted[11]) 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[12,13]). 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 given that emissions are verifiable. 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 F and ΔF and this cost function 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) The total cost of uncertainty reduction is equal to the total amount of uncertainty reduced over the commitment period multiplied by the specific average cost c_ε.

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[9] Applicable concepts to quantify uncertainties have yet to be scientifically worked out.

[10] 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.

[11] For simplicity we ignore a discount rate for this period. In addition, there are methodological issues to be solved by 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.

[12] Other verification concepts and various notions of uncertainty (see Obersteiner *et al*., 2000a,b) are possible by changing the nature of $\Delta\varepsilon$.

[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: $\left(\left|\frac{dF}{dt}\right|\Delta t - \varepsilon - \frac{d\varepsilon}{dt}\Delta t\right) = 0 \Leftrightarrow \frac{\varepsilon}{\left|\frac{dF}{dt}\right| - \frac{d\varepsilon}{dt}} = \Delta t$.

c_ε is a function of ε and $\Delta\varepsilon$ and is assumed to exhibit the required properties in microeconomic analyses.

The task is to maximize the following goal function with respect to the two choice variables ΔF and $\Delta\varepsilon$:

$$\max_{\Delta F,\Delta\varepsilon,\lambda} \pi = \left(\Delta F - (\varepsilon - \Delta\varepsilon)\right)p - c_F\left(\Delta F\right) - c_\varepsilon\left(\Delta\varepsilon\right)$$

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.

Setting up the Lagrangian,

$$\max_{\Delta F,\Delta\varepsilon,\lambda} \pi = \left(\Delta F - \varepsilon + \Delta\varepsilon\right)p - c_F\left(\Delta F\right) - c_\varepsilon\left(\Delta\varepsilon\right) - \lambda\left\{Kt - \left(\Delta F - \varepsilon + \Delta\varepsilon\right)\right\} \quad (1)$$

In order to find the maximum we need to calculate the first order conditions (FOC):[14]

$$\frac{\partial\pi}{\partial(\Delta F)} = p - \left\{(\Delta F)c_F' + c_F\right\} + \lambda = 0 \quad (2)$$

$$\frac{\partial\pi}{\partial(\Delta\varepsilon)} = p - \left\{(\Delta\varepsilon)c_\varepsilon' + c_\varepsilon\right\} + \lambda = 0 \quad (3)$$

$$\frac{\partial\pi}{\partial(\lambda)} = -Kt + \left\{\Delta F - \varepsilon + \Delta\varepsilon\right\} = 0 \quad (4)$$

From equations (2) $\frac{\partial\pi}{\partial(\Delta F)} = 0$ and (3) $\frac{\partial\pi}{\partial(\Delta\varepsilon)} = 0$ we find

$$\Delta F = \frac{(\Delta\varepsilon)c_\varepsilon' + c_\varepsilon - c_F}{c_F'} \quad (5)$$

and

$$\Delta\varepsilon = \frac{(\Delta F)c_F' + c_F - c_\varepsilon}{c_\varepsilon'} \quad (6)$$

[14] Notational simplification: We define $\frac{\partial c_F}{\partial\Delta F} = c_F'$ and $\frac{\partial c_\varepsilon}{\partial\Delta\varepsilon} = c_\varepsilon'$.

respectively. Inserting equation (6) into equation (4) yields the expression for the optimal ΔF;

$$\Delta F^* = \frac{c'_\varepsilon}{c'_\varepsilon + c'_F}\{Kt + \varepsilon\} + \frac{c_\varepsilon - c_F}{c'_\varepsilon + c'_F} \qquad (7)$$

or when inserting equation (5) into equation (4) get the corresponding expression for the optimal $\Delta\varepsilon$;

$$\Delta\varepsilon^* = \frac{c'_F}{c'_\varepsilon + c'_F}\{Kt + \varepsilon\} + \frac{c_F - c_\varepsilon}{c'_\varepsilon + c'_F}\,. \qquad (8)$$

Equation (7) shows the optimal decision rule for $\Delta F^* = \Delta F^*(\varepsilon, c_F, c'_F, c_\varepsilon, c'_\varepsilon; Kt)$. ΔF^* is a function of the initial uncertainty, the average cost and the marginal average cost of emission and uncertainty reductions, and the emission reduction target. Likewise, equation (8) shows the optimal decision rules of uncertainty reduction $\Delta\varepsilon^* = \Delta\varepsilon^*(\varepsilon, c_\varepsilon, c'_\varepsilon, c_F, c'_F; Kt)$. $\Delta\varepsilon^*$ is a function of the initial uncertainty, the average cost and the marginal average cost of uncertainty and emission reductions, and the emission reduction target. Equations (7) and (8) give the expression for the optimal emission/uncertainty reduction. Given the optimal decision rules and necessary parameters like the Kyoto target, the cost schedule for abatement strategies and sink enhancement measures, 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. All of the variables entering the decision rules are *ex ante* quantifiable.

Discussion

So far, the uncertainty discussion of economists has centered on the uncertainty of the effects of climatic change *per se*. On these lines, Bretteville (1999) and van Kooten *et al*. (1997) have shown that the uncertainty of climate change (cooling — neutral-warming) delays actions, since there is nobody willing to carry the cost of the risk premium of a climate action policy if there is a sufficiently large probability that carbon emissions do not change the world’s climate. However, these types of uncertainties are eliminated by the precautionary principle, which is already clearly embedded in the UN Framework Convention on Climate Change agreed on at the Earth Summit in 1992.

In this paper we are, however, more interested in the role of uncertainties related to carbon accounting within the Kyoto framework, which demands a different type of analysis. This type of uncertainty is related to issues of verifying emission reductions. We argue that a transparent system of legally binding emission reduction commitments is a necessary precondition for the functioning of any such mechanism design. In the absence of full transparency and built-in verification mechanisms carbon markets can be expected to turn into a lemons market, where over-reporting races of unverifiable emission reductions will lead, at least, to a very inefficient carbon market killing the momentum for an improved post-Kyoto process. Verification has proved to be an indispensable tool for many other international agreements like issues of disarmament. Transparency and verification can only be achieved if uncertainties of the reported emission reductions are quantified and if these uncertainties are taken into account in the process of the mutual recognition of emission reductions and in the system of emission trading. If we are unable to include uncertainties in this mechanism, Kyoto might only prove to be an interesting socioeconomic experiment. However, in its core business of contributing to solving the climate problem, it will have limited success and the parties will necessarily lose their commitment for continuation in a post-Kyoto process. It is, thus, indispensable to include uncertainties in the Kyoto Protocol and that appropriate institutions are created that are able to police the reported carbon accounts.

The purpose of this paper was to develop a simple model that could serve as a theoretical basis for an improved Kyoto mechanism by allowing for uncertainties without changing the basic structure of the Protocol. Introducing uncertainties reveals two advantages: (1) avoidance of sub-optimal solutions with regard to a minimum cost criterium to reduce atmospheric carbon, and (2) verifiability of emission reductions. It was also a requirement that the model should continue the analytical rigor of the analysis of the physical system and its interpretation of uncertainties (Jonas *et al*., 1999). In addition, this paper endeavors to build on much of the political achievements of the Kyoto process and in its basic structure it is general enough to be applied for post-Kyoto cases.

In this paper we deducted a simple optimal decision rule for agents in the Kyoto market of mutually recognized legally binding emission reductions and tradable emission certificates by including uncertainties. Assessment and recognition of uncertainties become an integral part of the rules governing the market. Uncertainties need to be included in such a mechanism in order to eliminate adverse effects of a lemons market. Under such modified rules the optimal strategy of emission reductions to meet a (post-) Kyoto target is a function of initial uncertainties, the emission reduction target itself *(Kt)*, the cost and marginal cost of emission reduction, and the cost and marginal cost of uncertainty reduction. If a country decides to take only its own (domestic and joint implementation) actions to reach the Kyoto target, it is the relative cost advantage of uncertainty reduction versus the cost of emission reduction that mainly rule the decisions. If the specific cost for emission reduction is larger than the specific cost for reducing uncertainty, then it is better to start with uncertainty reduction until the cost for uncertainty reduction becomes larger than that for emission reduction. It should be noted, however, that at least in the long-run, emission reduction will be the prime decision variable. If a country decides to also participate in a carbon market, it is the cost competitiveness of emission and uncertainty reductions versus the revenue from carbon trading of verified certificates that drives the decision processes. Carbon trading can generate additional income if the country's own actions are cheaper than that of the average market or can help to avoid cost explosion from domestic actions due to large uncertainties and high abatement costs.

There is also a need to look beyond the simplified assumptions in the model. One interesting example is the assumption of independence of the uncertainty reduction and the costs of emission reduction. It is most likely to assume that uncertainty reduction increases the knowledge of the carbon system, which improves the chances to find the least cost strategies for emission reduction.

The second important issue is that the decrease of uncertainties is an adaptive process, which can for instance be implemented at the project level with permanent monitoring and the use of complementary methods.

The third issue relates to the fact that uncertainty is usually defined in probabilistic terms. Such questions as the appropriate confidence limits still need to be considered in greater detail.

The fourth issue is that we face a dynamic system where the state variables used in the optimization problem are time dependent. In Appendix 2 we provide an analysis of the dynamic description of the problem.

All variables governing the optimal decision rule are in principle quantifiable at the beginning of the commitment period. Estimates of cost schedules for fossil fuel reduction measures have already been worked out. However, estimates on specific costs of uncertainty reduction have still not been examined. In the model presented above, we did not distinguish between random and systematic errors and, for simplicity, we attached a uniform cost to the lump-sum uncertainty. The cost of those two errors are by nature inherently different. Let us illustrate this point with a simple example referring to the sink strength of Russian forests, which under FCA could become a significant carbon player. Over the past 35 years the mean yearly sink is approximately 240 TgC (yr^{-1}) (fossil fuel emissions: 650 TgC (yr^{-1})). If we assume that a unit of carbon is worth 10$ (Sohngen and Mendelsohn, 1999) a 2.4 billion $ carbon credit can be attributed to the sink strength of Russian forests.[15] Increasing the precision estimates of the sink strength would mainly be achieved through a denser inventory net, which will require funds in the one digit million $ dimension.

With respect to a more comprehensive analysis of NPP, NEP and NBP involving remote sensing similar to the Canadian BEPS, which also involves the elimination of a number of biases, would cost around 5 million CDN $ (Chen, 2000). From these numbers we can conclude that for at least Russia the relative costs of reducing uncertainties of biospheric actions on large scales are probably very small compared to the abatement costs of fossil fuel actions and the cost of biospheric actions such as reforestation and afforestation, where we face the problem of spatial spillovers. With respect to the reduction of uncertainties of fossil fuel emissions similar relations can be expected, however, with a different parameterization of the cost function bearing in mind that c_ε is a function of ε and $\Delta\varepsilon$.

Finally, it should be mentioned that not only the carbon community draws benefits from instruments that reduce uncertainties but forest fire detection systems, precision farming, improved industry and macroeconomic statistics for investors would also largely benefit from improved understanding and monitoring of the carbon system. Thus, co-financing schemes for monitoring systems of carbon fluxes within an integrated country information system could be a viable way to further reduce the costs of uncertainty reduction.

Uncertainty reduction involves significant increasing returns to scale, large sunk costs and probably long amortization periods. Due to the increasing return property, but also for credibility reasons, the grand part of the uncertainty issue should be tackled by international networking efforts rather than on an individual project or country level. Although we face the problem that the international community has closer access to sovereign information it can be expected that the positive externalities outweigh this

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[15] Note that the abatement costs in the energy and industry sectors are much higher than those for maintaining sink strength.

disadvantage. More collaboration across national boundaries, improved knowledge and certainty of the global carbon cycle will help to maintain the momentum of the Kyoto process.

Concluding Remarks

The main thesis that prompted us to write this paper was that verifiability of carbon accounts will eventually become a necessary condition for the mutual recognition of legally binding commitments and for carbon trading. Verifiability has proved to be an indispensable part of many other international agreements mainly related to disarmament. Without proper procedures and institutional embedding of verification and sufficient penalization for uncertainty, over-reporting of claimed emission reduction will lead to the disintegration of the carbon market. We provide a first step towards verifiability by developing a carbon trade model under which uncertainty is included. In this model a country can choose to reduce emissions and/or reduce uncertainties to reach the verifiable emission reduction target at least cost. In the model, over-reporting comes at the cost of creating incentives to trim the uncertainty band of reporting. A shrinking uncertainty band reduces the range of possible emission reporting.

The policy recommendation is now rather conclusive. It is a must that emission reductions have to be mutually recognized and accepted as "true" emission reductions by all participating parties. This can only be guaranteed if emission reductions and uncertainty ranges are certified by an independent neutral third party. Only emission reductions that can be verified should be acknowledged to be "true". However, Jonas *et al*. (1999) show that some emission reductions can not favorably be verified within the 20 year time frame of the Kyoto mechanism. Thus, a trading scheme that penalizes uncertainties will make unfavorably verifiable emission reductions manageable from an economic point of view in the process of mutual recognition. Such uncertainty management will provide an incentive to reduce the uncertainty band, which will help to make carbon accounts physically verifiable in a shorter time span.

From a methodological point of view it is interesting to observe that the physical verification time concept can be independently derived from an economic formulation of the problem.

Verification is strongly linked to the properties of the types of errors a system exhibits. There is large latitude for conscious and unconscious biases in reporting depending on how uncertainty itself and the system boundaries of the carbon system are defined. Thus, depending on the type of carbon accounting and uncertainty definition, we are currently developing concepts of weak and strong verification. Strong verification comes under a full carbon accounting system. FCA has the advantage that the probability for biases is reduced, which under PCA may have been ignored. FCA, however, carries the disadvantage that the estimates of FCA fluxes show higher random errors (lower precision) than those under PCA. This is due to the fact that PCA is a sub-system of the largest possible carbon system — FCA (for a further discussion on this issue see Obersteiner *et al*., 2000b).

Another problem that can be solved by including uncertainty in a (post-) Kyoto Protocol is that components of the carbon system can *a priori* not be disqualified on the grounds of the high uncertainty they are bearing. This especially applies to land-use change and other biospheric measures, which are to some extent still poorly understood and are still associated with large uncertainties. This is, among others, one reason why a post-Kyoto process may be restrictive to include biological sources and sinks as well as a wide range of different GHGs. Nonetheless, it should be acknowledged that emissions from the destruction of vegetation make up about one third of the total anthropogenic carbon emissions and that CO_2-C is only half of the GHG story. Thus, if the uncertainty question can be solved we might be able to include more effective measures in carbon reduction mechanisms. This would not only lead to a more comprehensive approach to the climate change problem, but would also help to prioritize efforts to reach verifiable emission reduction involving smaller costs with respect to the ultimate goal of slowing global warming. We should mention, however, that the problem of drastically different systems dynamics between biospheric and technospheric systems remains. Obersteiner *et al*. (2000a) propose a solution to this problem by suggesting the formation of common carbon markets.

Finally, we would like to note that the model presented in this paper is general enough to be applicable to many other mechanism designs outside the Kyoto world involving verification and active uncertainty reduction.

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Appendix 1: List of Variables and Units

$\Delta F \ldots TgC(20yr)^{-1}$.

$\varepsilon \ldots TgC(yr)^{-1}$.

$\Delta\varepsilon \ldots TgC(yr)^{-1}$.

$p \ldots$ monetary unit (mU) to be paid per TgC.

$c_F \ldots mU(TgC)^{-1}$.

$c_\varepsilon \ldots mU(TgC)^{-1}$.

$Kt \ldots TgC(yr)^{-1}$.

Appendix 2: Dynamic Description of the Problem

Reaching the target means that a country must choose a certain schedule (path) of emission reduction ΔF_t and uncertainty reduction $\Delta\varepsilon_t$ for each time period t = 1,2,…,N. The reduction means that a country incurs a cost $c(t, \Delta F_t)$, $d(t, \Delta\varepsilon_t)$. The problem to be solved is now to minimize

$$\sum_{t=1}^{N} c(t, \Delta F_t) + \sum_{t=1}^{N} d(t, \Delta\varepsilon_t)$$

s.t.

$$\sum_{t=1}^{N} \Delta F_t - \varepsilon + \sum_{t=1}^{N} \Delta\varepsilon_t \geq Kt_N$$

$$\Delta F_t \geq 0, \Delta\varepsilon_t \geq 0$$

where Kt_N is the Kyoto target. Setting up the Lagrangian with $\lambda \geq 0$,

$$\sum_{t=1}^{N} c(t, \Delta F_t) + \sum_{t=1}^{N} d(t, \Delta\varepsilon_t) + \lambda(Kt_N - \sum_{t=1}^{N} \Delta F_t - \varepsilon + \sum_{t=1}^{N} \Delta\varepsilon_t).$$

We find that the optimal values ΔF_t^{opt}, $\Delta\varepsilon_t^{opt}$ satisfy equations

$$c'_{\Delta F_t}(t, \Delta F_t) = \lambda, \quad t = 1,2,..., N$$

$$c'_{\Delta\varepsilon_t}(t, \Delta\varepsilon_t) = \lambda, \quad t = 1,2,..., N$$

$$Kt_N = \sum_{t=1}^{N} \Delta F_t - \varepsilon + \sum_{t=1}^{N} \Delta\varepsilon_t.$$

Assume that cost functions $c(t, \Delta F_t) = c(\Delta F_t)$, $d(t, \Delta\varepsilon_t) = d(\Delta\varepsilon_t)$. Then from the FOCs it follows that

$$\Delta F_1^{opt} = \Delta F_2^{opt} = ... = \Delta F_N^{opt}$$

$$\Delta\varepsilon_1^{opt} = \Delta\varepsilon_2^{opt} = ... = \Delta\varepsilon_N^{opt}.$$

Therefore, the optimal path requires the same rates at each t = 1,2,…,N.

The problem in this case is formulated as follows, we minimize

$$Nc(\Delta F) + Nd(\Delta\varepsilon)$$

s.t.

$$N\Delta F - \varepsilon + N\Delta\varepsilon \geq Kt_N$$

$$\Delta F \geq 0, \Delta\varepsilon \geq 0.$$

The optimal levels ΔF^{opt}, $\Delta\varepsilon^{opt}$ satisfy

$$c'_{\Delta F}(\Delta F) = \lambda$$
$$c'_{\Delta\varepsilon}(\Delta\varepsilon) = \lambda$$
$$N\Delta F - \varepsilon + N\Delta\varepsilon = Kt_N.$$

Instead of the cost functions $c(t, \Delta F_t) = c(\Delta F_t)$, $d(t, \Delta\varepsilon_t) = d(\Delta\varepsilon_t)$ it is possible to consider the costs in the form $c(\Delta F) = a(\Delta F)\Delta F$, $d(\Delta\varepsilon) = b(\Delta\varepsilon)\Delta\varepsilon$:

$$a'(\Delta F)\Delta F + a(\Delta F) = \lambda$$
$$b'(\Delta\varepsilon)\Delta\varepsilon + b(\Delta\varepsilon) = \lambda.$$