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Global Potential of Carbon Sinks under the Kyoto Protocol

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Abstract—Atmospheric CO_2 concentration can be decreased not only by reducing fossil fuel burning but also by increasing the terrestrial ecosystems that serve as sinks for CO_2. The Kyoto Protocol allows countries that are burdened with emission reduction commitments to use carbon sequestration by terrestrial sinks. However, opinions differ widely on how the inclusion of terrestrial carbon sinks in the legally binding framework (Article 3.3) will affect the demand for emission reduction during the commitment period. We approach this issue by combining a simulation model of the carbon stock change with that of land-use change. The result of the simulation shows that the Annex I countries in total may potentially claim for a net carbon offset as high as 0.2 GtC/yr by carrying out ARD (Afforestation, Reforestation and Deforestation) activities. In order to come up with an effective long-term climate regime, political decisions are necessary to realize an appropriate balance between the sink enhancement and the emission reduction. Sink activities should not be too large to eliminate the efforts for emission reduction, nor too small to discourage the efforts in enhancing sinks. Although prediction of sink activities is an extremely difficult venture, several estimates of the potential should be carefully considered before political decisions. Appropriate inclusion of sink activities is also crucial for ratifying the Kyoto Protocol.

INTRODUCTION

Several assessments of the general forestry sink activities, not limited to the scope of the Protocol, show that the potential of these activities could be very large. Dixon *et al*. (1994) estimated the potential magnitude of this sink at 1–2 GtC/yr. The IPCC special report on LULUCF (Watson *et al*., 2000) argued that the carbon sinks counted under the Kyoto protocol Article 3.3 would be negative, except for the case when the FAO definitional scenario is employed and harvesting is not debited as emission. Under the IPCC definitional scenario, when the ARD activities are counted based on the land use changes, they projected (Watson *et al*., 2000; table 3), that the sink (7–46 MtC/yr) formed in Annex I countries by Afforestation/Reforestation will not offset the source (90 MtC/yr) formed by Deforestation. In other words, they suggest that the inclusion of ARD activities in the legally binding emission reduction targets could aggravate rather than alleviate the burden of emission reduction under the IPCC definitional scenario.

In order to assess the global potential of carbon stock changes induced by

ARD activities during the first commitment period, we have ventured a new approach to combine a land-use change prediction model, remotely sensed global tree canopy cover information, and a forest ecosystem carbon stock change model. In this report, after explaining our assessment approach, we discuss the result with a special emphasis on the definitional options for "forest" regarding the ARD activities. Then, by comparing the result with other approaches, we come to the conclusion on the ARD activity potential. Finally, by clarifying the remaining problems of our approach, we show further needs for studies regarding this new research field—integrated assessment of ARD sink potentials—which is only sketched by this study.

ASSESSMENT METHOD

The general scheme of our assessment of carbon stock change due to ARD activities associated with land-use changes is as follows. First, we predict the geographical occurrence of the ARD activities as "forest" and "non-forest" conversions during 1990–2012 using a land-use change model (IMAGE 2.1; Alcamo *et al*., 1998) for each grid node (50×50 km) of global land. Second, the carbon stock changes due to the predicted ARD activities are estimated using a forest ecosystems carbon stock change model (Alexandrov *et al*., 1999) that simulates above- and below-ground carbon stock changes due to ARD activities, based on regional NPP (Net Primary Productivity) and climate data. Third, the carbon stock change values due to ARD activities are adjusted according to the different tree canopy cover threshold used in "forest" definition. The adjustment is conducted by using remotely sensed global tree canopy cover information (Nemani and Running, 1997). And finally, for each global grid node of land, the accounted carbon stock during the commitment period is calculated and aggregated for Annex I and non-Annex I countries.

Changes in land-use

We have predicted the geographical occurrence of ARD activities as conversions between "forest" and "non-forest" land-use using the IMAGE 2.1 model (Alcamo *et al*., 1998). This scenario gives a global field of land-use/land-cover $L(x, y, t)$, for each 50×50 km grid node $\{x, y\}$, where x is latitude and y is longitude, for every 5 years (t = 1990, 1995, 2000, 2005, 2010, 2015). $L(x, y, t)$ takes a value from the set of land-cover codes.

By classifying the land-use/land-cover types into "forest" and "non-forest" as is described in Table 1, we define the global field of "forest" cover, $F(x, y, t)$, which is equal to 1 if $L(x, y, t)$ is "forest", and 0 if $L(x, y, t)$ is "non-forest". The nodes, where $F(x, y, t) = 0$ and $F(x, y, t + 5) = 1$, are considered as reforested during the period $(t, t + 5)$, and similarly, the nodes, where $F(x, y, t) = 1$ and $F(x, y, t + 5) = 0$, are considered as deforested.

Based on this land-use change information, we further define the global field of the forest age (in 2010) of reforested land, $A_s(x, y)$; that is, if a node $\{x, y\}$ was reforested during the period $(t, t + 5)$, then $A_s(x, y) = 2010 - t$. For the nodes that

Table 1. Predicted estimates of carbon fluxes during the first commitment period. These fluxes are counted as carbon stock change due to ARD activities that would be induced by land-use changes since 1990, totals for Annex 1 countries, in GtC/yr. (The estimates for non-Annex 1 countries given in brackets are to show the potentials for cooperation between Annex 1 and non-Annex 1 countries.)

Flux type	The height of tree cover threshold in "forest" definition		
	No threshold	10% threshold	40% threshold
Sequestration	0.228 (0.206)	0.078 (0.041)	0.170 (0.174)
Emission	0.017 (0.591)	0.017 (0.586)	0.012 (0.478)
Net flux	0.211 (–0.385)	0.061 (–0.545)	0.158 (–0.304)

were not reforested between 1990 and 2015, $A_s(x, y) = 0$. Similarly, we define the global field of the years after deforestation, $A_c(x, y)$.

Changes in carbon stocks

The rate of carbon sequestration depends on the reforestation method, the choice of tree species, the productivity of the reforested site, and on a variety of other factors. At local scales it is worth considering as many factors as possible, but assessing carbon sequestration over large areas, we may restrict our attention to the climatic factors.

Proceeding from the climatic factors, we can assess the productivity of a region and the rate of carbon accumulation in biomass, litter and soil organic matter. The methodology of such assessment is explained in detail in our previous paper (Alexandrov *et al.*, 1999) and briefly reviewed in Yamagata and Alexandrov (1999). Applying this methodology, we assess the rate of carbon sequestration over the global grid of half-degree resolution (50 × 50 km), $R(x, y, a_s)$, as a function of the forest age: a_s.

For estimating carbon stock changes resulting from deforestation, we assume that the average age of a cleared forest is 70 years and evaluate the rate of carbon release from deforested land, $E(x, y, a_c)$, as a function of years after the clearing: a_c.

Calculation of carbon fluxes during the commitment period

If a node $\{x, y\}$ was reforested during the period $(t, t + 5)$, the age of forest will vary from $2010 - t$ to $2005 - t$ in 2010, and hence the sequestration rate in 2010 will vary from $R(x, y, 2005 - t)$ to $R(x, y, 2010 - t)$. We use the average of these two figures as the estimate of the sequestration rate during the commitment period of a region.

Adjustment to tree canopy cover

Transition of a node from the "non-forest" to "forest" category, obviously, does not mean that all the territory represented by each node (50 × 50 km) turns from treeless land to land densely covered by tree canopies. In classifying nodes as "non-forest", only the dominant land-use/land-cover type within the node is used. Therefore, a "non-forest" node might represent an area 40% of which is covered by trees, and vice versa, a "forest" node might represent an area 40% of which is covered by "non-forest" land such as pasture. In other words, transition of a node from the "non-forest" to "forest" category may correspond to minor changes in tree cover.

The changes in land-use that do not manifest themselves in pronounced changes of land-cover are very difficult to monitor. Could we recognize the land with only 5% canopy cover as "forest"? FAO (Forest Resource Assessment) suggested that dominant land-use is not a sufficient criterion and included tree canopy cover threshold (10%) in the latest FAO forest definition.

Observing land-use changes remotely, one can judge them only from changes in land-cover. Applying the 10% threshold, a decrease in tree cover from 60% to 15% is considered as forest degradation rather than Deforestation, and an increase from 15% to 60% as forest aggradation rather than Reforestation. Hence, estimates of the ARD activities based on land-use changes are sensitive to tree cover threshold chosen for discriminating "forest" and "non-forest".

Taking into account the tree canopy cover threshold V_c (10%, 40%, etc.), it is judged that Reforestation took place at the node, when not only $F(x, y, t) = 0$ and $F(x, y, t + 5) = 1$, but also $V(x, y, t) < V_c$ and $V(x, y, t + 5) > V_c$, where $V(x, y, t)$ is the remotely sensed global field of tree canopy cover. Similarly, it is judged that Deforestation took place at the node, when not only $F(x, y, t) = 1$ and $F(x, y, t + 5) = 0$, but also $V(x, y, t) > V_c$ and $V(x, y, t + 5) < V_c$.

Since remotely sensed tree canopy cover data is available only for one year (1995), we applied only partial adjustment to the rules for judging ARD activities; that is, a Deforestation activity occurs at a "forest" node $\{x, y\}$, if $F(x, y, t) = 1$ and $F(x, y, t + 5) = 0$ and $V(x, y, 1995) > V_c$, and a Reforestation activity occurs at the "non-forest" node $\{x, y\}$, if $F(x, y, t) = 0$ and $F(x, y, t + 5) = 1$ and $V(x, y, 1995) < V_c$. The effect of applying canopy cover threshold on accounted carbon stock changes is tested against 10% and 40% cases.

Considering the realistic tree canopy cover of each node, instead of assuming 100% canopy cover, we adjusted emission and sequestration rates for all simulation cases (no threshold, 10%, 40%).

RESULTS

Table 1 summarizes the result of our assessment: the estimates of carbon fluxes during the first commitment period (2008–2012) that would be induced by land-use based ARD activities since 1990. The values in this table shows totals for Annex I countries in GtC/yr, while the estimates for non-Annex I countries are given in brackets.

The tendency towards reforestation suggested by the IMAGE scenario predicted a global sequestration rate of 0.44 GtC/yr during the commitment period. Part of this sink, 0.23 GtC/yr is the potential in the Annex I countries. This carbon sequestration could be used for compensating industrial emissions to meet the emission reduction target. The other part, 0.21 GtC/yr, could be considered as the potential for reforestation CDM projects, if sink projects are allowed under the CDM.

The result shows that only a small part of this sink (0.08 GtC/yr) could be accounted and reported as reforestation activities, if 10% canopy cover threshold is employed to discriminate “forest” and “non-forest”. Setting the threshold at 40% also slightly reduces the figure (0.17 GtC/yr).

Global deforestation is predicted to release 0.6 GtC/yr during the commitment period. This emission is caused both by the clearing of forests and by the decomposition of slash (remaining stumps and roots) at the cleared sites. However, only a very small portion of the emission is predicted in Annex I countries (0.02 GtC/yr).

Contrary to reforestation, the result shows that deforestation is well reported at any canopy cover threshold. There is almost no loss in the estimate by applying the 10% threshold. Applying the 40% threshold reduces the estimate by around 20%.

The net global carbon flux due to land-use change is predicted to be an emission (0.17 GtC/yr). The effects of applying different canopy cover thresholds are opposite depending on the threshold. In the case of 10% threshold, the net flux (emission) increased (0.484 GtC/yr) and in the case of 40%, it decreased (0.146 GtC/yr).

The net flux associated with the land-use changes in the Annex I countries is predicted to be positive. The result shows a rather large sequestration rate of 0.211 GtC/yr. However, the magnitude of the flux is dramatically reduced, if low canopy cover threshold is employed. In the case of 10% threshold, it reduces the figure as much as 70% (0.06 GtC/yr).

The reason for this reduction could be attributed to the higher (>10%) tree canopy cover of “non-forest” land. So, even though the “non-land” is converted to “forest” land, the canopy cover change does not cut across the “forest” threshold. However, it should be noted that this effect of the threshold on the accounted carbon stock change is critically dependent on the assessment unit (spatial scale) of the canopy cover and the spatial pattern of the ARD activities.

CONCLUSIONS

Any prediction about the future, especially if it includes socially driven events, is speculative. Although the IPCC special report on LULUCF (Watson *et al.*, 2000) has estimated that the potential of ARD activities (under the IPCC definitional scenario) is negative (emission) for Annex I countries in total, our study shows that the potential is positive and the carbon offset potential is predicted to be as high as 0.2 GtC/yr during the first commitment period.

The demands for further research

Since 1990, the science of climate change faces the need to satisfy a contradictory demand: to provide *credible* recommendations in a *timely* manner.

Strictly speaking, scientific credibility is hardly to be achieved intentionally; it is appearing in the process of science evolution, and this process may take an indefinite amount of time. What can be achieved, in time for the political debates, is the consensus about state-of-the-art methodology in the related field of science.

In this paper, we consider the scenario proposed by Alcamo *et al.* (1998) as reflecting state-of-the-art methodology achieved in the studies of land-use trends. There are many reasons to justify our choice, but the question we raise here is whether a consensus about a plausible scenario of land-use change can be achieved. The demand for plausible land-use change scenarios has become really pressing. The IPCC report on land-use, land-use change and forestry (Watson *et al.*, 2000) left it untouched. Our study here is just a preliminary attempt to fill the gap. However it is obvious that the number of scenarios must be dramatically increased, just as was the case with the IPCC emission scenarios, if we are to come up with reliable policy recommendations.

Another acute problem is plausible scenarios of forest management. The estimates of carbon stock changes resulting from ARD activities are very sensitive to local factors such as tree species used for reforestation, the age of cleared forest and so on. This is a major source of uncertainty, which may increase (or decrease) the rate of sequestration by a factor of two. Hence, what is really critical for improving credibility of these estimates is to build plausible scenarios of forest management.

Another source of uncertainty related to forest management is the "forest" definition. If "forest" would be defined not only in terms of land-use but also in terms of tree cover the area of both forestation and deforestation would be reduced. We have tried to estimate the magnitude of reduction proceeding from global tree cover derived from satellite data and found that in the case of Annex I countries; the 10% threshold may cut the projection of carbon offset in half. The credibility of this estimate would be improved if we could trace the changes in tree cover associated with land-use. For this purpose, the global tree cover time series data since 1990 are needed.

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