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ABSTRACT

The Kyoto Protocol was adopted in order to reduce the net emission of greenhouse gases to the atmosphere. That included management of the biosphere. However, the wording that has been adopted may be difficult and costly to implement, and may ultimately make it impossible to cost-effectively include biosphere management to reduce net greenhouse gas emissions.

An alternative scheme is proposed here to more effectively deal with the anthropogenic component of carbon emissions from the biosphere. It would categorise the terrestrial biosphere into different land-use types, with each one having a characteristic average carbon density determined by environmental factors and management. Each transition from one land-use type to another, or a change in average carbon density within a specified type, due, for example, to changing management, would be defined as anthropogenic. Under this scheme, this change would be credited or debited to the responsible nation. To calculate annual credits and/ or debits, a characteristic further time course for each possible land-use transition needs to be defined, and the annual debit/ credit would then be calculated as the change in carbon density multiplied by the land area involved and divided by the relevant time constants.

We believe that this scheme would be simpler and less costly to implement than one based on the measurement of annual carbon fluxes from all identified areas of land. It would also avoid undue credits or debits, because credits and debits could only accrue due to identified anthropogenic components of biospheric carbon changes. Carbon fluxes that are due to natural variation, on the other hand, would not result in credits or debits. It would thereby only reward and encourage those land-use changes that would lead to ultimate net increases in carbon storage.

1. INTRODUCTION

In the Kyoto Protocol, the management of vegetation sinks is included through Articles 3.4, 3.7 and, most specifically, Article 3.3 (UNFCCC 1997). The negotiators for the Kyoto Protocol were faced with an enormous challenge to derive a wording that was fair to all nations with their greatly differing national circumstances and yet resulted in an overall outcome that encouraged individual nations to take action towards increasing the carbon storage in the part of the biosphere over which they could exercise some control.

In the end, the Kyoto Protocol has left us with a wording that will lead to many unintended outcomes and accounting anomalies (Watson et al. 2000). For example, actual net changes in overall carbon storage for individual nations are unlikely to match reported changes according to Article 3.3 rules. Discrepancies are likely to be greater with certain definitional choices, but are unlikely to be completely avoidable with any of the possible definitions (Noble et al. 2000; Schlamadinger et al. 2000).

Compliance with the reporting requirements may also be very costly. Strict adherence to the wording of Article 3.3 may require nations to trace the specific site history of all their land area and then measure changes in carbon stocks on just those parcels of land that fall under specified categories of land-use histories. This is likely to result in significant costs with little or no direct benefit for the atmospheric CO_2 concentration. Benefits for the atmosphere result from the establishment and growth of new forests, not from the exercise of measuring their actual carbon increments.

Some nations might even have increasing biomass stocks, yet might have to go to great expense to report a decrease in biomass stocks under particular definitions of reforestation and deforestation. Other possible definitions might enable nations to claim large credits from sustained-yield forestry where there is no actual net increase in total carbon stored in a forest estate (Schlamadinger et al. 2000). It is proving to be very difficult to devise a set of definitions under which there are no accounting anomalies such as undeserved credits or debits (Noble et al 2000).

If these unintended outcomes or accounting anomalies are deemed to be too serious, and/ or if costs are too great, the rules to be adopted by COP 6 might only allow for very limited inclusion of biosphere management. Some might consider that a satisfactory outcome as it would keep the focus firmly on fossil fuels (Greenpeace 1998; Lashof and Hare 1999). However, significant greenhouse-gas exchanges with the biosphere have been documented in national inventories (e.g. Cannell 1999), and under certain circumstances, management of the biosphere probably can make a useful and cost-effective contribution to the management of the atmospheric CO_2 concentration (Kirschbaum 1996; Marland and Schlamadinger 1997, 1999; Chomitz 2000). It would be unfortunate if those opportunities were lost.

Hence, it might be easier to operationalise Article 3.3 if we take a broader view of the Protocol and interpret the Article in line with the ultimate objective of the UN Framework Convention on Climate Change (UNFCCC) which "..is to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." (UNFCCC 1994).

The biosphere can only make an on-going contribution towards reducing net emissions of CO_2 to the atmosphere to the extent that carbon storage in the biosphere is increasing or if a current rate of loss is reduced. Since the terrestrial land area is essentially fixed, carbon storage can only be increased if the average carbon storage per unit land (carbon density) is increased. Maximum carbon density on any unit of land is constrained by climatic and soil conditions, and short-term fluctuations are frequently determined by weather (rainfall, temperature) and disturbance (especially fire). Many of these factors are beyond human control, but management plays an important role in determining the average carbon density that is attained within the constraints imposed by given climatic and soils conditions: a wheat field, for example, can attain a different average carbon density than a neighbouring, undisturbed forest.

Hence, the objective of the UNFCCC would be best served through encouragement of management options that increase the average carbon density of all land areas. What matters in terms of the UNFCCC is to have a scheme that influences the land management choices of individual nations so that they take steps to increase their biospheric carbon stocks. It is also important to have a scheme that is cost-effective to implement and that avoids unintended outcomes With unintended outcomes, we mean outcomes that would ultimately reduce terrestrial carbon stocks. Hence, we propose a scheme here that is relatively cost-effective to implement, avoids unintended outcomes and is consistent with the objectives of the UNFCCC.

The key aim is to devise a set of rules that reward such actions by individual land managers or national governments that ultimately lead to reduced atmospheric CO_2 concentrations. These rules must avoid loop holes and any perverse incentives that could lead to the opposite outcome. In this context, it is not critically important to be able to quantify actual carbon fluxes with great precision as that in itself would not reduce atmospheric CO_2 concentrations. It is of key importance instead to provide incentive and disincentive that can affect the decision making of land managers where this can lead to beneficial outcomes for the atmosphere.

2. THE PROPOSED SCHEME

The following outlines the rules of the proposed scheme and then illustrates its working through a set of examples.

1) A nation's biosphere would be sub-divided into a number of biosphere domains each with its own land use (such as native forests, softwood plantations, agroforestry, cropped agricultural land, grazing land, urban infrastructure, etc). These domains could be further sub-divided by bio-climatic zone where the productive, and carbon storage, potential varies significantly across a nation. Each nation would then be responsible for reporting the areal coverage of each land-use type. Each nation would be free to choose a set of sub-divisions that most closely match the information available in inventories, land-use data bases, etc.

2) For each biosphere domain, a potential average carbon density [C_{pot}] would need to be established. It is defined here as the potential carbon density that each biosphere units could attain over its typical land-use pattern. For a production forest, for example, it would be the average over typical rotation lengths. This would be a function of natural factors, such as the prevailing climate in a region, and anthropogenic factors, principally related to land use, that may modify the average carbon storage potential.

3) Potential carbon stocks for each nation would then be calculated as:

$$\Sigma\ A\ C_{pot} \tag{1}$$

as the sum over all identified biosphere domains, with A being the area of each biosphere domain and C_{pot} its potential average carbon density. This calculation must be done at the beginning and end of a commitment period, and the difference added to or subtracted from a party's assigned amount. This becomes somewhat more complex through a system of delayed crediting/ debiting. Possible schemes for implementing this are discussed in Section 3.

4) The potential average carbon density of each biosphere domain can be expressed as the product of an inherent site capacity for carbon storage and a term that describes its modification through the prevailing land use:

$$C_{pot} = C_{eq}\ f_{lu} \tag{2}$$

The land-use term [f_{lu}] must account for modification of the average carbon density across all of an identified domain. It must therefore also account for that part of the total carbon storage not attributable to the primary land use within that domain. For example, the access roads to a forest must be taken into account in determining the average carbon storage within a domain classified as forest.

Large values for this term imply that the particular land use leads to high carbon storage (e.g. undisturbed forest), and low values imply that the land use leads to low carbon storage (e.g. annual cropping). The land-use term would normally be in the range of 0 to 1, but there is no in-principle reason why it could not be greater than 1 where, for example, the productivity and carbon storage capacity of land has been increased by irrigation or fertilisation.

The potential average carbon density, C_{pot}, is the carbon density that each land-use type can attain under continuation of current land use, and must thereby conform to observable attributes of each land-use type. The purpose of calculating C_{eq} and f_{lu} as separate terms is to allow a distinction to be made between changes in carbon density that are the responsibility of responsible land managers and changes that are beyond their control.

5) Where potential carbon stocks change for reasons beyond land managers' control, such as due to climate change, it should not lead to debits or credits for the affected nation. Such changes can be accommodated through adjustments in the equilibrium carbon storage term. Further details of applicable accounting are given in Example 3.

It is important to recognise that the calculated carbon density would be the potential rather than actual carbon density. It is the potential average carbon density that could be attained over a period of decades under respective land-use categories. Hence, it would not change due to short-term irregular fluctuations, nor depend on a forest estate being young or mature. However, that average carbon storage potential is precisely what is relevant in the Kyoto context which is focussed on the anthropogenic component of net emissions.

Hence, under this scheme, there would be no penalty for nations when their forests are approaching maturity, such as Canada (Kurz and Apps 1999), provided that after harvesting the forests are replaced with the same forest type and the same management regime. Similarly, there would be no windfall gains for regions that happen to have young growing stands, such as Europe (Kuusela 1994) or New Zealand (Maclaren 1996).

Benefits can principally accrue if the area of high carbon-density land-use types is increased at the expense of the area of low carbon-density types. Losses similarly would accrue if low carbon-density types (annual cropping, roads) replaced higher density types (most forest classes). The change in area would be the principal reason for short-term changes in carbon stocks.

Changes could also arise from assessed changes in potential average carbon storage, resulting, for instance, from changes in potential vegetation and soil organic matter in response to climate change. For example, it seems likely that soils will lose carbon in response to soil warming, although they may gain carbon due to increasing CO_2 concentration or nitrogen deposition (Thornley et al. 1991; Kirschbaum 2000a). In these situations, it would be inappropriate to give credits or debits to affected nations because these changes occurred for reasons beyond the control of land managers.

Equilibrium amounts of carbon storage may also be reassessed as scientific understanding improves over time. There is only imperfect knowledge and understanding of the amounts of carbon stored in different parts of the biosphere, but that knowledge is likely to improve with further measurements and better understanding of the relevant controlling processes. Hence, estimated values of C_{eq} and f_{lu} are likely to change over time. Changes in calculated amounts that result purely from better understanding of relevant processes need to be omitted from the calculations of credits or debits. Similarly, carbon storage changes due to global climate change are beyond the control of individual nations and should also be excluded. These changes can be accounted through adjusting the term C_{eq} in eqn. 2.

Changes in carbon storage at maturity could also result from gradual changes in composition within defined categories. For example, carbon storage in a possible category, ‘nature reserve of native ecosystems’ might change over time as new areas with higher or lower than average carbon density are included in a reserve system and thereby shift the overall average carbon density of the reserve system. Such changes would be anthropogenic in origin and thereby should be included in changes in calculated overall carbon storage amounts, reflected in changes in the land-use term f_{lu}.

Actual changes in equilibrium carbon storage, in contrast to those due to improved understanding, would presumably be small over time. However, even quite small adjustments could potentially translate into large stock changes because these adjustments would be applied to a large land area. Since any adjustment would be made explicitly, and the reasons clearly specified, it should be possible to avoid these adjustments leading to unwarranted carbon debits or credits.

The other factor that could change carbon stocks would be a change in the land-use term, due, for example, to a change in average rotation lengths of commercial plantations. Average rotation lengths in many commercially managed forest estates are shortening at present as increasing use of adhesives allows smaller stems to be utilised. A greater proportion of wood is also being used for making paper (FAO 1997). A shift to shorter rotation lengths would clearly be an anthropogenic change in carbon storage and should thus be considered under a nation’s sphere of influence. There may also be more subtle effects, such as changes in the frequency of fires which may change as a result of improved efforts and success at fire suppression, or due to cessation of the use of fire as a management tool.

Some systems directionally gain or lose carbon. Cultivated croplands, for example, are likely to lose soil carbon for years to decades before a new equilibrium is reached (e.g. Mann 1986; Davidson and Ackerman 1993). Drained peat lands similarly are likely to lose substantial amounts of carbon once the anaerobic conditions that prevented earlier decomposition have been relieved (Cannell et al. 1993). Other systems, such as improved pastures, are likely to gain soil carbon (e.g Barrow 1969; McIntosh et al. 1997). In all these cases, the appropriate carbon density for accounting purposes should be taken to be the final carbon density after the system has reached a new equilibrium under the defined management system for each land-use type.

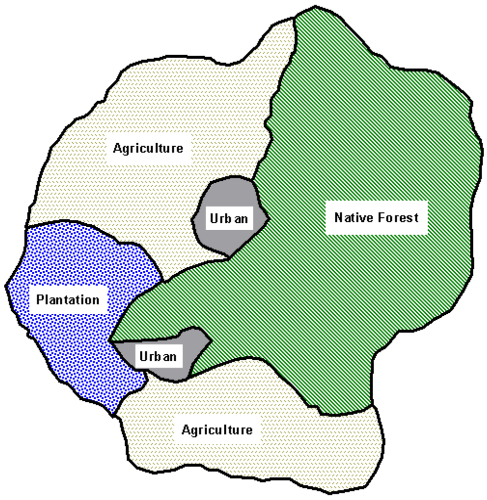
The scheme proposed here would differ significantly from the IPCC default methodology currently used for reporting under the UNFCCC (IPCC 1997; Lim et al. 2000) under which only specified fluxes that are deemed to be anthropogenic, such as wood harvesting, are included and specifically accounted for. The present approach instead assumes that essentially all of the terrestrial biosphere is affected by land management decisions, and that a separation of fluxes between anthropogenic and non-anthropogenic origins is both problematic and likely to lead to accounting anomalies (Lim et al. 1997; Kirschbaum 2000b). By explicitly making the potential carbon storage of different land-use types the basis of calculations, the present approach also goes one step further than the IPCC default methodology in focussing on the anthropogenic component of carbon emissions.

In the following, we try to illustrate how the system might operate in practice. We illustrate this through three examples affecting three different aspects of the accounting.

2.1 Example I

A region of 1,000,000 ha might consist of 50% native forest, 10% under plantations, 35% under agriculture and 5% under urban infrastructure (Fig. 1; Table 1).

Figure 1: A hypothetical region with native forests, forest plantations, agriculture and urban land.



In this example, the whole area is assumed to have the same equilibrium carbon density because the region is assumed to be small enough to be climatically uniform. A more sophisticated assessment might have included different equilibrium carbon densities across the region in line with different soils and/ or climatic factors or other more specific local reasons, but for simplicity in the calculations here, the same equilibrium carbon density is assumed throughout.

The principal difference between land-use types is in the land-use term. The native forest is given a value of '1' as that forest is essentially unmanaged and its equilibrium carbon density therefore corresponds to the region's natural equilibrium carbon density. Plantations are assigned a value of f_{lu} = 0.75 to reflect the fact that they are managed on a regular rotation, and this particular type of plantation is assumed to have half the equilibrium in above-ground biomass but unchanged soil carbon. It is assumed that there are equal amounts of carbon above and below ground. Hence, the land-use term is calculated as:

f_{lu} = 0.5*0.5 (above ground) + 0.5*1.0 (below ground) = 0.75.

Agricultural land is assumed to have only very small amounts of above-ground carbon and also to lose 20% of soil carbon before reaching a new equilibrium. Hence, the land-use term is 0.4 (0.5*0 + 0.5*0.8). Urban land is assumed to have virtually no above-ground biomass and lose most of its soil carbon over time, with only small amounts of very resistant material ultimately remaining.

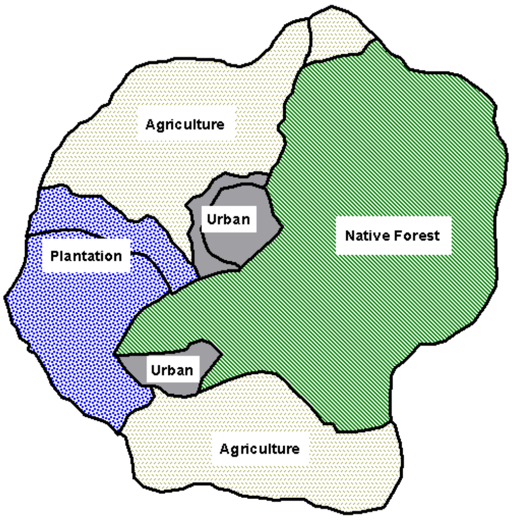
Figure 2 and Table 2 give hypothetical carbon changes for the region. In this example, it is assumed that 5,000 ha of native forest are converted to agriculture. Of existing agricultural land, it is assumed that

Table 1: Example of the land-use types included in a hypothetical region shown in Figure 1 at the start of a commitment period.

Type	Area [A]	Equilibrium carbon [C_{eq}]	Land-use term [f_{lu}]	Total carbon
Forest	500,000	500 tC ha^{-1}	1	250 MtC
Plantation	100,000	500 tC ha^{-1}	0.75	37.5 MtC
Agriculture	350,000	500 tC ha^{-1}	0.4	70 MtC
Urban	50,000	500 tC ha^{-1}	0.1	2.5 MtC
Total	1,000,000			360.0 MtC

5,000 ha are converted to urban infrastructure and 10,000 ha to commercial plantations, giving a net loss of agricultural land of 10,000 ha. Types of change are also important as changes between land-use types do not necessarily lead to symmetrical and reversible changes in carbon storage. These issues are discussed below.

Figure 2: A hypothetical region with changes in the area of native forests, forest plantations, agriculture and urban land.



The conversion of 5,000 ha of native forest to agriculture leads to a net loss of -1.5 MtC because agricultural land is assumed to store only 200 tC ha^{-1}. This results in a potential loss of 300 tC for each hectare that is converted from forest to agriculture.

Similar changes occur for plantations and urban area. After the carbon in all new areas is summed up, it results in an overall loss of -0.5 MtC in this particular example. This is the amount lost from this region from land-use change. It is important to emphasise that these changes are changes in potential carbon storage. Actual changes may take decades or even longer to eventuate.

There may also be temporal short-term changes in the opposite direction from long-term changes. For example, a change from plantations to native forest is likely to result in a short-term loss of carbon as plantation trees are harvested. In the long term, the undisturbed native forest will attain a greater carbon density because of the lack of repeated harvest cycles, but this long term trend will not be reflected in the short-term changes when the change is initiated.

However, in the context of controlling the anthropogenic impact on the biosphere, it is not the actual short-term changes and trends that matter, but the amount of land under uses with higher or lower average carbon-storage potentials. In the short term, carbon storage in the biosphere is only partly under human control. That control is principally exercised through land-use decisions, but it interacts with natural factors that are only partly controllable, such as climatic variability or wildfire.

Table 2: Example of hypothetical changes in carbon storage over a commitment period resulting from changes in area in different land-use types.

Type	New Area	Area change	C_{eq}	f_{lu}	New carbon	Carbon change
Forest	495,000	-5,000	500 tC ha^{-1}	1	247.5 MtC	
Plantation	110,000	+10,000	500 tC ha^{-1}	0.75	41.25 MtC	
Agriculture	340,000	-10,000	500 tC ha^{-1}	0.4	68.0 MtC	
Urban	55,000	+5,000	500 tC ha^{-1}	0.1	2.75 MtC	
Total	**1,000,000**				**359.5 MtC**	**-0.5 MtC**

2.2 Example II

This second example uses the same base information as the first, but in this case, changes are assumed to occur within each land-use type. In this example, we assume that an extensive road system is built within the native forest estate in order to gain greater access to the forest. This is calculated to lead to a loss of -0.5% of equilibrium carbon storage across all forests within that category. In plantations, the average rotation length is shortened in such a way that average carbon storage is reduced from 75% to 74% of that in native forests. Agriculture is increasingly converted to minimum tillage with attendant slight positive effects on soil carbon (only 18% rather than 20% soil carbon loss), and urban areas have an aggressive program of planting urban trees, which increases the overall carbon density by 0.1%.

These different measures lead to the carbon storage changes as shown in the final column in Table 3. In this particular example, the positive and negative changes largely cancel out so that there is almost no overall change.

Table 3: Example of hypothetical changes in carbon storage resulting from changes in the land-use term.

Type	Area	C_{eq}	updated f_{lu}	Change in f_{lu}	Newly calc-ulated carbon	Carbon change
Forest	500,000	500 tC ha^{-1}	0.995	-0.005	248.75 MtC	
Plantation	100,000	500 tC ha^{-1}	0.74	-0.01	37.0 MtC	
Agriculture	350,000	500 tC ha^{-1}	0.41	0.01	71.75 MtC	
Urban	50,000	500 tC ha^{-1}	0.101	0.001	2.525 MtC	
Total	**1,000,000**				**360.025 MtC**	**0.025 MtC**

2.3 Example III

If the carbon amount at equilibrium, C_{eq}, needs to be adjusted, then the new value must be used only from the beginning of a new commitment period, whereas the old value of C_{eq} must be used for calculations at both the beginning and end of the previous commitment period. Any changes in the equilibrium amount, which are assumed to be non-anthropogenic in their origin, then do not lead to credits or debits for individual nations because the same values for C_{eq} are used for calculation at the beginning and end of a commitment period.

The procedure is illustrated in Table 4. Here, it is assumed that the equilibrium amount of carbon decreases by 1% over each five-year period. The land-use term is assumed to remain unchanged at 0.5.

Hence, the total amount of carbon stored in this particular land-use type decreases by 1% over each commitment period. However, because this decrease occurs for reasons that are beyond the control of land managers, no debits accrue. The anthropogenic credit/ debit can be calculated by using the same equilibrium carbon amounts at the beginning and end of a commitment period. Hence, for calculations in 2012, the old C_{eq} can be used for calculating carbon amounts for both the beginning and end of the commitment period. The anthropogenic credit/ debit over the 2008-2012 period would then be calculated as:

$$\text{Credit}_{2008/2012} = [A_{2012} * C_{eq(2008)} * f_{lu(2012)}] - [A_{2008} * C_{eq(2008)} * f_{lu(2008)}]$$
$$= [10{,}000 * 500 * 0.5] - [10{,}000 * 500 * 0.5] = 0.$$

For calculations for the 2013-2017 period, credit/ debit would be calculated as:

$$\text{Credit}_{2013/2017} = [A_{2017} * C_{eq(2013)} * f_{lu(2017)}] - [A_{2013} * C_{eq(2013)} * f_{lu(2013)}].$$
$$= [10{,}000 * 495 * 0.5] - [10{,}000 * 495 * 0.5] = 0.$$

Table 4: Example of hypothetical changes in equilibrium carbon storage by the end of a commitment period.

Year	2008	2013	2018	2023
Area	10,000	10,000	10,000	10,000
C_{eq}	500	495.0	490.1	485.3
f_{lu}	0.5	0.5	0.5	0.5
Credit/ debit		0	0	0

This calculation procedure ensures that nations neither gain nor lose as a result of changes in average carbon density that are beyond their control. Only changes in A or f_{lu} which are the terms under anthropogenic control should lead to carbon gains or debits.

3. TIME DELAY IN CREDITING/DEBITING

Biospheric carbon stocks change only slowly. A forest can have an average carbon storage potential that exceeds that of an agricultural field by several hundred tons of carbon, but it is likely to take decades to reach that carbon potential. While it would seem to be appropriate to base calculations on the changes in carbon storage that are attained at equilibrium, it is necessary to take the slowness of these changes into consideration. Hence, if the full ultimate carbon change were credited at the time it is initiated, it would give large rewards for taking early action and gain the credit long before atmospheric changes would occur. If delayed crediting were not employed, it would greatly, and probably unduly, enhance the attractiveness of using vegetation management to meet nations' commitments under the Kyoto Protocol. To provide an appropriate balance, some form of delayed crediting/debiting is needed to more adequately reflect the actual slow changes in biospheric carbon stocks.

There are at least three options. In this discussion, a time constant is used as being the time over which a change is taken to have occurred in a linear fashion. Alternatively, and somewhat more realistically, the change could be assumed to occur in an exponential fashion, but in the interest of simplicity, the linear scheme is discussed here.

Option 1 would define a characteristic time course for the transition between any two land-uses and record carbon changes based on the time courses for different transitions. For example, transitions between forest and pasture tend to lead to rapid carbon losses as soon as the previous forest is cut and maybe burnt. If a single time constant is used, a constant of one year might be appropriate. Carbon build-up in the biomass of new forests, on the other hand, can take decades or even centuries depending on species and region. A time constant of 50 years might be appropriate to describe that slow growth. The problem with using this option is that characteristic time constants for every

Table 5: Transition matrix with time constants for transition between different land-use types. These are typical estimated values without being linked specifically to any particular global region. They are likely to differ greatly between regions and the definition of each of these land-use types.

Type	Forest	Plantation	Agriculture	Urban	C_{pot}
Forest		1	10	15	500 tC ha^{-1}
Plantation	50		10	15	375 tC ha^{-1}
Agriculture	75	25		50	200 tC ha^{-1}
Urban	100	50	50		50 tC ha^{-1}

possible transition would need to be established, and the type of transition would need to be recorded for each parcel of land. This would require a large spatially explicit data base to be maintained which records the land-use type for each unit and the time when specified transitions have taken place.

Option 2 would be much simpler by giving an overall time weighting to biospheric carbon changes of, say, 50 years. Hence, if a 1 MtC change were calculated, for example, it would be credited/ debited as a 20 ktC yr^{-1} change each year over a 50-year period. A problem with that approach is that the typically different time constants of different land-use conversions, and the typically more rapid losses than gains of carbon, would not be reflected in the reported changes. It is not obvious, however, whether it would be important to reflect these differential time constants to avoid unintended outcomes in biospheric carbon management.

Option 3 would give a shorter time constant, say 10 years, for transitions that result in an overall loss of biospheric carbon for a nation as a whole and a longer time constant, say 50 years, for transitions that result in an overall increase in biospheric carbon. This option would thus be intermediate between the other two options, still recognising that transitions that lower biospheric carbon storage tend to be completed more rapidly than those which increase biospheric carbon, yet retaining the overall simplicity. There would be no need to maintain a large data base that records the date when particular transitions take place. Only a data base for the on-going status of land-use types would be needed.

If option 1 were to be employed, it would require a large transition matrix to be constructed, with typical time constants listed for each transition. A typical example is given in Table 5. These are just examples that do not try to be representative of any particular global region.

It is readily apparent that transitions from land-use types with higher to lower carbon densities (those above the blackened diagonal in Table 5) typically have shorter time constants than the equivalent changes from lower to higher carbon densities. Representation of these transitions by single time constants still represents a great simplification of the true situation. Transition from natural forest to plantations, for example, would usually start with clearfelling the original forest and thus result in an immediate and large loss of carbon. Carbon storage would then increase slowly over time as the new vegetation grows to its potential average carbon storage. Similarly, loss of living biomass tends to be relatively fast processes (in transition from forest to agriculture, for example), but subsequent losses or gains of soil carbon tend to be slow. If averaged over larger tracts of lands (e.g. landscape or national level), such effects would become less important, however.

If time courses are to be presented through a single time constant, then these more complex temporal patterns cannot be captured. However, if the aim is the encouragement of management of the biosphere to maximise overall carbon storage, then these simplifications may be of less concern. The critical question is whether they could encourage action by parties with the ultimate result of reducing net greenhouse gas emissions, including maximising biospheric carbon storage, or whether the scheme could lead to counter-productive ultimate outcomes.

4. ADVANTAGES

The proposed system has several advantages over a system based on a strict and literal reading of the provisions in Articles 3.3, 3.4 and 3.7 of the Kyoto Protocol. Some of these advantages are:

4.1 Ease of implementation

It would be relatively easy to implement this proposed scheme as the key data requirement is the categorisation of a whole nation's land area into different land-use types which could be done using satellite imagery and planning information. Average carbon density could be based on a number of discrete scientific studies. It would not be necessary to measure the carbon stocks of each one of many individually identified hectares across a nation.

The system could therefore probably be implemented at lower cost than requirements envisaged under current understanding of the Kyoto rules. The monitoring for reporting as currently envisaged would likely be costly, involving costs of remote sensing and forest inventory systems and especially the requirement for detailed monitoring of numerous individual parcels of land that may or may not qualify under the Kyoto rules depending on their specific land-use histories (Noble et al. 2000; Schlamadinger et al. 2000).

The system could also allow nations great flexibility to use whatever information is available to them. In principle, it would not matter in what way a nation's biosphere is sub-divided. It would even be possible to treat all of a nation's biosphere as a single domain. In that case, the area of land would remain the same, but changes could occur through changes in average carbon density. If they result from changes in the land-use term f_{lu}, they would create debits or credits for an affected nation.

Such changes could come about simply by changing the relative proportions of land-use types within the recognised accounting unit. For example, if the proportion of agricultural land were to increase and the proportion of forest to decrease, then the land-use term would have to be reduced for that land-use type.

However, in practice it is likely to be easier to implement the scheme if area changes were to account for the bulk of changes, and if average carbon totals within each unit were to remain the same, or change only marginally and gradually over each commitment period.

There could be a temptation for nations to try to manipulate the definitions of land-use types or carbon density to maximise their advantage. However, as stated above, such manipulations would be difficult. If nations put more of, say, marginal forests into a higher class, it might increase the area in that class, but the average carbon density would have to be correspondingly reduced. There will always be some remaining loopholes and ways to manipulate the scheme to gain an unfair advantage, but with this scheme they would be minimised. The extent to which the system would be open to manipulation is discussed below.

4.2 Avoidance of unintended consequences

It would be difficult to conceive of situations where a nation would be rewarded for actions that would not also result in ultimate net improvements in biospheric carbon storage, provided an appropriate scheme for delayed crediting/ debiting is employed. Scheduling of harvesting or thinning just before the commencement of a commitment period, for example, could not result in spurious gains, and conversion of land from one land use to another could not result in gains if they result in only short-term growth increments during the commitment period without long-term increases in average carbon density.

If carbon storage changes due to short-term factors beyond human control, either because of unexpectedly high growth rates in a series of good growth seasons, or if trees die due to natural factors, such as fire or insect attack, no debits or credits would be given, either. Such short-term (annual to decadal) changes in carbon storage would not be relevant because credits and debits should be assessed on the basis of change towards the long-term carbon storage potential for each land-use type. Credits or debits would accrue only if climatic or other environmental factors were to lead to long-term changes in potential carbon density for that land-use type. In that case, it would need to be assessed whether those changes were due to natural factors, to be reflected in changes in C_{eq}, or due to anthropogenic factors, to be reflected in changes in f_{lu}.

An additional benefit to the proposed system is that it would tend to eliminate the accounting irregularities which result from short-term (commitment period) assessments of activities that influence C stocks with different long-term behaviours. The proposed system would essentially favour long-term improvements in carbon storage, such as land-use changes and increases in carbon density that would not require detailed numerous short-term measurements which might simply reflect short-term anomalies. As the greenhouse effect is a longer-term problem that will only fully manifest itself over a period of decades to centuries, it would be appropriate to adopt this longer-term outlook in devising a scheme for biospheric carbon management.

4.3 Differentiation between human and natural changes

In the longer term, this scheme should provide a reasonably close match between actual and reported carbon stock changes. A difference would occur where a forest estate is either being rejuvenated or is maturing. If this occurs without a change in average rotation length, actual changes in stocks would differ from reported changes.

However, where that difference is encountered, it would, in fact, be appropriate to concentrate on the potential changes as outlined here rather than the actual changes that might be observable in stands over time. The purpose of the Kyoto Protocol is not to give credits or debits to nations that happen to have forest estates in particular parts of their regrowth cycle, but to encourage nations to change their land-use management in order to achieve long-term increases in carbon storage in the biosphere under their control. Nations that can demonstrate that they are increasing the area under land-use types with high carbon storage potential could receive credits under this scheme. Conversely, nations where the area under land-use types with high carbon storage potential decreases, would be debited for the resultant long-term loss of carbon.

Carbon stocks of nations may also change due to largely uncontrollable natural factors, such as fire or drought. Again, the proposed scheme would ensure that nations would not receive debits or credits for these natural fluctuations. Only changes of anthropogenic origin could lead to credits or debits.

Concerns have been expressed about the permanence of carbon stored in vegetation sinks or the soil (Bolin et al. 2000). This scheme partly addresses this problem by explicitly allowing adjustments to the term C_{eq} in response to factors beyond the control of individual nations, such as climate change. If nations establish biospheric sinks, they will not subsequently have to take debits if carbon from those sinks should subsequently be lost through factors beyond the immediate control of those nations. It would be very important to establish strict requirements of proof, however, so that this mechanism cannot be exploited in cases where it would not be justified.

4.4 Ease of verification

The proposed system would also be relatively easy to verify. The occurrence of land-use changes can be relatively easily recorded and observed by remote methods, provided high-resolution imagery is used (Mantovani and Setzer 1997). The carbon density factors are more difficult to verify, but that could be done across large relevant regions, with using some appropriate means of stratification. These measurements would not need to be repeated frequently.

The greatest difficulty may lie in documenting changes in average carbon density due to the inclusion of higher or lower than average-density units within a defined domain. For example, the average carbon density of forestry plantations may decrease because new plantations are increasingly established on more marginal land. This could then only be documented, and average carbon densities adjusted, if the specific location of new plantations is recorded and if enough is known about the respective carbon storage potential at the new and the average of all old locations. If that information is available, it might be simpler to treat the unit ‘plantation forests’ as two sub-units ‘plantation forests on highly productive land’ and ‘plantation forests on marginal land’. There are likely to be optimal compromises between further sub-division of groups that will require potential carbon densities to be established for more units, but make it easier to find those carbon densities because of the units greater internal uniformity. Modelling may also play a role in that the different bioclimatic suitability of different regions could be explicitly included, and that would provide an objective means of adjusting the average carbon storage of respective domains.

5. CAN TRENDS BE VERIFIED?

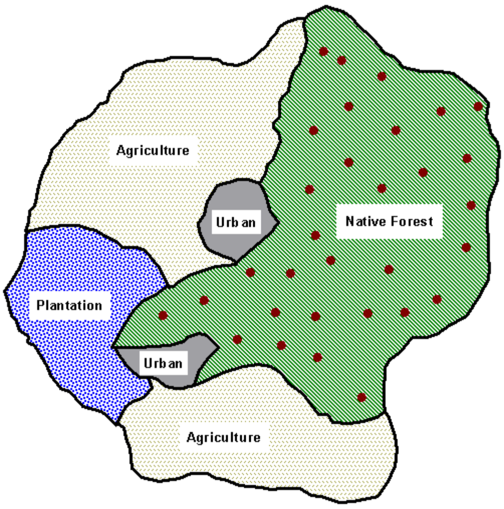
One of the key requirements of any scheme to implement the Kyoto Protocol must be an assurance that it cannot readily be manipulated to show spurious carbon savings even if there are none in reality, or hide carbon emissions that may actually be taking place. It needs to be assured that this proposed new scheme cannot be manipulated more easily than alternative options.

We would envisage that nations may be required to submit maps like those shown in Figs. 1-3 to clearly indicate the location of their recognised land-use types, and a full definition of each land-use type. ‘Native forest’, for example, could be defined more fully as ‘forest occupied mainly by species native to the area, used as water shed, wildlife habitat and recreation without grazing, mining or commercial timber extraction’.

Maps would need to be spatially explicit to an internationally agreed resolution (say, 1ha). Any international verification authority could then conduct a number of spot-checks at a number of randomly chosen locations within each land-use type. Thirty spot checks were chosen in this example for the native-forest land-use type (Fig. 3). The required number of samples is largely dependent on the heterogeneity of observations within the domain. The more internally uniform a domain is, the smaller number of samples would be required to establish an average carbon density to an agreed level of confidence (Garten and Wullschleger 1999; Post et al. 1999; Nobel et al. 2000).

This could be complemented by remotely sensed data to ascertain whether disturbance events, such as timber harvesting, might have taken place that are inconsistent with the defined land-use characteristics. Hence, it should be possible to ascertain with high confidence that land-use types correspond to those reported by individual nations.

Figure 3: A hypothetical region with native forests, forest plantations, agriculture and urban land. For the forest area, a number of plots randomly chosen for verification are shown.



The more difficult assessment is that of an average carbon density for each biosphere domain. It requires essentially a scientific assessment across each domain, taking into account factors such as generally known relationships between climate and average carbon density and allometric relationships between the various tree components. General relationships need to be refined for local conditions, taking account of differences between species, response to soil types and conditions, characteristic disturbance frequencies and specific histories. Greatest accuracy is required for those biosphere domains that are undergoing land-use changes.

It then needs to be ascertained that these general relationships are indeed consistent with specific on-the-ground observations, as might be obtained as part of the spot-check investigation. For example, a lower than average carbon density across several sites might be explained by an unusually severe fire season that affected many stands a few years earlier. However, if apparently mature stands predominate that have a much lower than expected carbon density, then the previously claimed carbon density would have to be revised.

It might be even more difficult to assess the anthropogenic component of the observed carbon density. In some cases, it is not too difficult. For example, generally available statistics on forest operations could be examined to assess any change in average rotation lengths of plantations, and effects on average carbon storage could be deduced from that. However, changes in soil carbon storage following changes in management practices are much harder to assess and verify. Many of these difficulties are the same as those currently envisaged in the implementation of any additional activities under Article 3.4 of the Kyoto Protocol (Sampson et al. 2000).

The greatest problems may be encountered to verify changes in carbon density, through either C_{eq} or f_{lu}, that are to the detriment of the nation where they occur. Each nation would have a vested interest to record any changes that are to its advantage, and one would expect that close international scrutiny will be applied before such changes are accepted. Changes that would be of detriment to a nation's carbon budget, however, might remain undetected because affected nations would have no interest to invest resources in proving changes to carbon density if those changes would only have the effect of negatively affecting the nation's carbon bottom line.

These verification requirements are not trivial, but management of the biosphere with its enormous diversity does not lend itself to simple approaches. Importantly, the scheme proposed here would be simpler than one that would require measurements of the actual carbon exchange rates as they might occur in different patches in the landscape.

6. WOULD THIS SCHEME BE CONSISTENT WITH THE WORDING OF ARTICLE 3.3?

Given that the wording of the Kyoto Protocol was adopted at COP3, would the scheme proposed here be consistent with this wording? The specific phrases in Article 3.3 of the Kyoto Protocol (UNFCCC 1997) are:

"Net changes in GHG emissions .. from direct human-induced land-use change". There is no problem with that part of Article 3.3 as any change between categories would involve a human planning decision, followed by altered on-the-ground land-use activity. The fact that "net changes .. from direct human-induced" should be used would in fact be particularly consistent with the fact that potential changes are calculated that are the result of direct human intervention rather than the actual changes that may have multiple causes.

"limited to afforestation, reforestation and deforestation". One can take a fairly broad view here and define deforestation as the replacement of high carbon-density land-use types with lower carbon-density types, and afforestation and reforestation as the replacement of a land-use types with low carbon density with those with higher carbon density. One might reasonably infer that this interpretation would be consistent with the ultimate objective of the UNFCCC as it treats all land-use changes equally and focuses directly on the resultant effect on carbon storage.

Including a carbon density change within one class as fitting under that definition might be more difficult, however. In other words, if the total area of a forest type has remained exactly the same, but carbon density has decreased because the average rotation length has decreased from 50 years to 49 years, it might be difficult to classify that as 'deforestation'. However, these changes might be very similar to the types of activities that change C content within a land-use or land-cover class that negotiators had in mind in the drafting of Article 3.4 (Sampson et al. 2000).

"limited to ARD since 1990". Under the scheme, it could be interpreted as the changes resulting from management actions between 1990 and 2012.

"measured as verifiable changes in carbon stocks". Under the proposed scheme, one would calculate changes in carbon stocks, thus being consistent with the Protocol, and each part of the overall equation is independently measurable and verifiable in an open and transparent manner.

Under the proposed scheme, one would not measure actual carbon stocks, but potential stocks that represent an equilibrium amount for each land-use type. That should be acceptable since the first part of Article 3.3 only asks for those net changes that result from direct human-induced land-use change and forestry activities. Hence, the change in potential stocks is the one that results from direct human activity whereas actual stocks would change as a result of a combination of direct-human induced and natural factors.

Hence, by and large, the scheme would be consistent with the wording of the Protocol apart from the difficulty of defining carbon changes within a land-use type which would be difficult to classify as an ARD activity.

7. OTHER ARTICLES IN THE KYOTO PROTOCOL

If one defines transitions between land-use types as ARD activities under Article 3.3, then changes of potential carbon density within land-use types could be defined as additional activities under Article 3.4.

Article 3.7 provides for adjustments to the baseline. Net greenhouse gas emissions from land-use change should be calculated for the baseline year as outlined here, and resultant net emissions could be added to parties' assigned amount through Article 3.7.

Article 6 deals with projects agreed to between Annex I countries, and Article 12 (The Clean Development Mechanism) deals with projects carried out in non-Annex I countries, but paid for, and carbon credits accruing to Annex I countries. Neither of these Articles gives much detail as to the kinds of projects that would be eligible, or how carbon credits are to be calculated.

The scheme described here could, therefore, be applied readily to emission trading projects between nations. A host country would thus have to provide the applicable potential carbon densities for a range of land-use classes, and an emission buyer would have to pay for the transition between land-use classes. These transitions could be large and obvious ones, such as between cropland and forest plantations, or more subtle, such as between conventional and low-impact logging. A baseline could be taken to be the continuation of the previous land use. Verification of emission units would require verification that a claimed land use both before and after any conversion did indeed correspond to the defined characteristics of that particular land use in the particular geographic region. Specific carbon storage or flux measurements would not be required for each individual project. Use of this scheme would thus keep to fairly simple requirements for the use of biosphere projects in emissions trading.

8. CONCLUSIONS

The United Framework Convention on Climate Change and particularly the Kyoto Protocol have been the first attempts to limit the emissions of greenhouse gases to the atmosphere (Oberthür and Ott 1999). Management of the biosphere has been included as part of the measures included in the Protocol, but the wording adopted in the Protocol is ambiguous and will require additional clarification and further decisions at COP 6 before it can be operationalised. A special IPCC report has been prepared to clarify the main options and issues (Watson et al. 2000).

Yet, the approach taken in Kyoto has been handicapped from the beginning by not recognising an essential difference between anthropogenic emissions from the use of fossil fuels and those resulting from management of the biosphere: fossil fuel emissions are under direct and immediate human control, but biospheric net emissions are not.

An engine can be switched on or off, and that action has an immediate and direct result on emissions. Biospheric net emissions, on the other hand, are not so easily controlled, and the biosphere can take up or release carbon for many years following a natural or anthropogenic disturbance. The biosphere may also take up or release carbon for reasons that are beyond the control of land managers. Over short time scales (up to a year), the fluxes that are beyond the control of land managers (e.g. wildfire) can be many times larger than the fluxes that would be deemed to be a direct result of land managers' actions (planting trees, fertilisation or wood harvesting). It is, therefore, necessary to design and implement a scheme for biospheric carbon management differently from one for fossil fuel management.

Such a scheme is outlined here. It is designed to be relatively easy and cheap to implement, to avoid credits and debits that result from natural rather than anthropogenic factors and to prevent the creation of incentives that would have counter-productive effects on the emission of net greenhouse gases to the atmosphere. We believe that this advocated scheme would lead to more beneficial outcomes for the atmosphere than the way the implementation of the Kyoto Protocol is currently envisaged.

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