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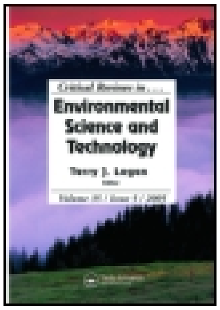

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FOREST BIOMASS AS CARBON SINK — ECONOMIC VALUE AND FOREST MANAGEMENT/POLICY IMPLICATIONS

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ABSTRACT: All countries in Scandinavia have introduced a carbon fee on fossil fuel to reduce the emission of the climate gas CO_2. In Norway the fee is 0.82 NOK (or about 0.12 US$) per liter of gasoline, equivalent to 343 NOK (or 49 US$) per ton CO_2. The fee is an emission cost which gives a corresponding benefit for absorbing atmospheric CO_2 in forest biomass. This article shows that this benefit corresponds to a net economic value of carbon sequestration in forest biomass 2-30 times higher than the net value of timber as raw material for the forest industry in Norway, which has one of the highest timber prices in the world. If a fee high enough to stabilize the CO_2 emission in Norway were to be introduced, the value of carbon sequestration will be at least twice as high as the above estimates. It is argued that this will imply substantial changes in forest management and policy, both in rich and poor countries. Projects to restore and maintain sustainable forest ecosystems will be very profitable, and could simultaneously provide considerable other environmental benefits like increased biodiversity, soil stability, and improved watershed structures.

KEY WORDS: Carbon sequestration, climate change, forestry, economics, policy.

1. INTRODUCTION

Forests play an important role in the global carbon budget both as carbon sinks and through emission of CO_2 (Sedjo 1990, Dixon et al. 1994). One measure, among many others, that has been advocated to lower the concentration of atmospheric CO_2 is to increase the forest biomass. The main arguments for this measure are, first, that tree biomass fixes large quantities of atmospheric CO_2 over a long period — in boreal forests from 40 to 200 years depending upon species and site class. Second, forest biomass can directly (or indirectly as waste) be used for energy purposes and thereby reduce the use of fossil fuels, or can substitute for other materials such as steel or aluminium constructions whose production consume large quantities of fossil fuels. Third, increased stocks of carbon in forests provide flexibility given the uncertainty regarding the impact of global warming. Fourth, increasing the standing stock of forest biomass may in many ecosystems give several environmental benefits other than carbon sequestration, e.g. improved biodiversity, better water quality, less erosion, and improved recreation opportunities. Finally, forest production is based on a well-functioning technology and policy structure, at least in most industrialized countries, which makes increased production easy.

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The third argument, among those listed above, is perhaps the most important one. If human activities are ultimately proved to cause global climate changes, increased stocks of carbon in wood biomass (as trees and/or forest industry products) will have a long-term positive marginal value regarding lowering the quantities of atmospheric CO_2. Thus one can get more time for introducing new energy technologies or other measures to decrease the emission of greenhouse gasses. If global warming is not as detrimental as some have suggested, an increased stock of timber will most likely have a positive value as timber for the production of paper, sawnwood and bioenergy, or for environmental benefits like recreation, water management, soil conservation, or biological diversity.

Several studies have examined the amount of CO_2 which could be sequestered in forest biomass (cf. Dixon et al. 1994). Only a few studies have, however, investigated how preferable the various possible measures in forestry are and how they rank compared to measures in other sectors to reduce the emission of climate gasses (EPA 1990, Lunnan et al. 1991, Hoen and Solberg 1994, Solberg and Hoen 1995). All of these studies are based on cost efficiency — i.e. they use the ratio "tons of carbon sequestered per $", or the inverse, as criterium. These ratios give, under certain assumptions, a consistent internal ranking of the various measures considered, but they give little or no indications of how preferable the investments in these measures are for society as compared to investments in other environmental benefits, goods and services. We may, therefore, avoid a considerable nonoptimal use of resources over time if we could get realistic estimates of the economic value of fixing one unit of atmospheric CO_2 of some sort.

The first objective of this article is to estimate the economic value of a marginal increase in forest biomass as a carbon sink, and compare this value with the value of timber as raw material for forest industry production. The second objective is to discuss some important forest management and policy implications of the findings.

2. METHODOLOGY AND DATA

The main idea here is that the marginal value of fixing one unit of atmospheric CO_2 in forest biomass equals the marginal cost of reducing the emission of CO_2 in the most costly project which is implemented for that purpose. This marginal cost is referred to below as the shadow price P_t. If a carbon tax were introduced with the only purpose to reduce the consumption of fossil fuel, P_t would equal that tax.

The *gross* value (G_t) of the fixation of atmospheric CO_2 per m^3 of stemvolume produced is then calculated as:

$$G_t = P_t * S * F * M * R_t \quad (1)$$

where

G_t is the gross value of the fixation at time t of atmospheric CO_2, measured as NOK (Norwegian kroner) per m^3 stemvolume produced under bark.

P_t is the above defined shadow price at time t in NOK per ton CO_2.

S is the specific weight of the tree species measured as ton dryweight of biomass per m^3 tree volume.

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F is the fraction ton C (carbon) per ton dryweight biomass
M is the molecular weight of CO_2 divided by the atom weight of C.
R_t is the ratio between the total tree biomass (i.e. including roots, branches, bark and stump) and the biomass in the stem at time t.

Here, F is very close to 0.50 for all tree species, and M is the constant 44/12. S and R vary with tree species. In the below calculations for Norway spruce (*Picea abies* L. Karst.) S is 0.503 ton per m^3 (Nagoda 1982) and R is 2.0 (Blingsmo 1990).

The *net* value is calculated by considering that C cannot be stored indefinately in biomass — i.e. from the above defined gross value one has to subtract the cost of the emission of CO_2 from the decaying of the biomass at later points in time:

$$N_{t_0} = G_{t_0} - \left[\sum_{i=0}^{N} \sum_{t=t_0}^{T+a_i+d_i} P_t \cdot q_{t_i} (1+r)^{T-t} \right] (1+r)^{-(T-t_0)} \tag{2}$$

where

N_{t_0} is the net value of the fixation of atmospheric CO_2, measured as NOK per m^3 industrial stemvolume produced under bark in the year t_0.
G_{t_0} is the gross value G in Equation (1), estimated for year t_0.
t_0 is the age of the forest stand t_0 ε [0,T].
q_{t_i} is the emission of CO_2 to the atmosphere at time t from assortment i of the carbon fixed at time per m^3 of industrial stem volume.
T is the rotation length (in years) — i.e. the age of the trees when felled and used.
a_i is the anthropogenic life time (in years) — i.e. the time the wood assortment i is kept in use.
d_i is the decaying time for assortment i — i.e. the time (in years) from the end of the anthropogenic time until 99% of the wood carbon is released to the atmosphere.
P_t is the shadow price defined in Equation (1).
N is the number of end-use assortments (including roots, branches, stump etc. as well as paper,sawnwood, fuelwood) realistic to cover the decay process, altogether 14 as defined in Hoen & Solberg (1994).
i is end-use assortment nos. i.
r is the calculation rate of interest.

To compare the value of forests as carbon sink with the value of forests as raw material for forest industry production, Equation (3) can be used.

$$N_T = \left[\sum_{t=0}^{T} f_t \cdot P_t (1+r)^{T-t} - \sum_{i=t}^{N} \sum_{t=0}^{T+a_i+d_i} P_t \cdot q_{t_i} (1+r)^{-t} \right] \cdot \frac{1}{V_T} \tag{3}$$

where

N_T is the net value at time T of the total fixation of atmospheric CO_2 in a forest stand establishedat time 0 and clearfelled at time T, measured in NOK per m^3 stem volume.

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T is the length of the rotation period — measured in years.

f_t is the fixation of atmospheric CO_2 in the forest stand at time t, measured in tons per ha.

V_T is the volume of the forest stand sold as industrial wood at time T, measured as m^3 under bark per ha.

P_t, T, r, a_i, d_i and q_{ti} are as defined in Equation (2).

In Norway, as well as in many other countries, the Government is committed to stabilise the anthropogenic emissions of CO_2 at the 1989 level. For this reason, a carbon tax with the purpose to reduce the consumption of fossil fuel was introduced in 1991 and it is today 0.82 NOK (about 0.12 US$) per litre gasoline, which corresponds to 343 NOK (or 49 US$) per ton CO_2, assuming 3.15 kg CO_2 per kg of gasoline and a density of 0.76 kg per litre gasoline. A similar tax is introduced in Denmark, Finland and Sweden, and both the USA and the European Union are discussing the introduction of such a tax (Dean 1993). It is also calculated, using general equilibrium growth models, that to stabilise the CO_2 emission on 1989 level in Norway, a national carbon tax corresponding to 900 NOK (or US$ 130) per ton CO_2 would be necessary in the year 2000 (Anon. 1993). The same study estimates that to stabilise the CO_2 emissions from the OECD countries in the year 2000 and the global emissions by the year 2025, a carbon tax of 650 NOK per ton CO_2 would be necessary in the year 2000 increasing to 1450 NOK per ton CO_2 in the year 2025 (all costs at 1990 price level). More recent studies indicate that taxes in the range of US$ 100-400 per ton C (i.e. US$ 27-109 per ton CO_2 or NOK 190-760 per ton CO_2) would be necessary to reduce the emission of carbon to 1990 level *globally* (Dean 1993).

The value of timber as raw material for the forest industry used for comparison in this article, is the net stumpage value — i.e. the gross price paid to the forest owner by the industry minus all the owner's variable costs for cutting and transport. This value was during 1992 in Norway on average 200 NOK per m^3 timber for the economically most important tree species in the Nordic countries, Norway spruce (*Picea abies* L. Karst.).

3. RESULTS

Table 1 gives the gross value G as a function of P_t for Norway spruce. This value should be compared to the above mentioned net stumpage value of timber of 200 NOK per m^3 as raw material for the forest industry. Table 1 shows that at the present CO_2 fee in Norway of 0.82 NOK per litre gasoline (or 343 NOK per ton CO_2), G takes the value of 478 NOK per m^3 timber — i.e. more than twice the value of the resource as production input for the forest industry. The above mentioned fees of 650 and 1450 NOK per ton CO_2 necessary to stabilise the anthropogenic emission of CO_2 in Norway correspond to a value of respectively about 900 and 2000 NOK per m^3 of timber — i.e. from 4 to 10 times the value as raw material for the forest industry.

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TABLE 1
The Gross Value of Timber as CO_2 Sink[1] for *Picea abies* (K.)

Shadow price (P) NOK/ton CO_2[2]	US$/ton CO_2[3]	Gross value of timber G[1] NOK/m[3] stem volume	US$/m[3] stem volume[3]
100 (0.23)	14	139	20
343 (0.82)*	49	478	68
500 (1.17)	71	697	99
700 (1.63)	100	975	139
900 (2.10)	129	1,254	179
1,100 (2.57)	157	1,533	219
1,300 (3.03)	186	1,811	258
1,500 (3.50)	214	2,089	299

* The present (1993) carbon fee on petrol in Norway.
1 As defined in Equation (1).
2 In bracket is the carbon fee in NOK per litre petrol.
3 The exchange rate of 7.00 NOK per US$ is assumed.

Table 2 shows the net economic value of carbon sequestration N in *Picea abies* (K.) as a function of time from fixation of CO_2 to clearfelling, and interest rate, calculated by using Equation (2) and assuming P_t is NOK 100 per ton CO_2. For example it is seen that at 3% p.a. interest rate the value is increasing from NOK 50 to NOK 118 per m^3 stemvolume when going from 5 years to 80 years from clearfelling respectively. The maximum net value is NOK 126 per m^3, because it is 1.26 ton CO_2 per m^3 stemvolume in this species (including branches, roots and top in the CO_2 content), and at high enough interest rates and time to clearfelling the value of the emission of CO_2 is close to zero.

Finally, Table 3 shows the value of N for an average stand of Norway spruce at clearfelling time calculated as defined by Equation (3). It is seen that even at a low interest rate of 2% p.a. the value of sequestering CO_2 when P is 343 NOK per ton CO_2, is 3 times the value of the timber as forest industry production input. It is also seen that the CO_2 value increases strongly with increasing r. At r equalling 7% p.a. (which is the interest rate advocated by the Ministry of Finance in Norway in public project analyses) the CO_2 value is 32 times the industry value. When comparing with the above mentioned proposed stabilising fees of 650 and 1450 NOK per ton CO_2, the CO_2 value at this interest rate is respectively 61 and 135 times higher than the value of wood for industry.

4. DISCUSSION

4.1. Estimation

The above estimated economic values for sequestration of CO_2 in forest biomass might be surprising, but there are four main reasons for the high values:(a) The quantity of CO_2

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TABLE 2
The Net Economic Value[1] of Carbon Sequestration in *Picea Abies* (K.) as a Function of Time to Clearfelling and Interest Rate. (NOK per m³ Stem-Volume Fixed).

Year to clearfelling	Interest rate (% p.a.) 1	3	5	7	10
5	26	50	64	73	84
10	31	61	77	89	100
20	40	77	96	107	116
30	48	90	108	117	123
40	55	99	115	122	125
50	62	106	120	124	126
60	68	111	122	125	126
70	74	115	124	126	126
80	79	118	125	126	126

[1] As defined in Equation (2) assuming P_t is 100 NOK per ton CO_2.

TABLE 3
The Net Value of Timber as Carbon Sink[1] Made Comparable to the Net Value of Industrial Roundwood for one Rotation Period of *Picea abies* (K.) at Medium Site Class[2] (NOK/m³)

Rate of interest (% p.a.)	Shadow price P (NOK/ton CO_2) 100	343	400	700	1,000	1,300	1,500
1	90	316	360	630	900	1,170	1,350
2	175	609	700	1,220	1,740	2,260	2,350
3	290	1,021	1,170	2,040	2,920	3,800	4,400
4	470	1,638	1,870	3,280	4,680	6,080	7,020
5	740	2,592	3,000	5,200	7,400	9,600	11,100
6	1,170	4,101	4,700	8,200	11,700	15,200	17,600
7	1,870	6,528	7,500	13,100	18,700	24,200	28,000
8	2,990	10,480	12,000	21,000	29,900	38,900	44,900
9	4,850	16,984	19,400	34,000	48,500	63,100	72,800
10	7,940	27,784	31,800	55,600	79,400	103,200	119,100

[1] As calculated in Equation (3).
[2] Site class G17 (i.e. dominant height 17 m at 40 years breast height age), planting density 2,500 plants/ha, rotation length 80 years.

sequestered per year is high; (b) the sequestration period is long; (c) a positive r combined with the two previously mentioned reasons gives high accumulated effects over time. It should be emphasised that a positive interest rate reflects the return the society has in the best alternative investment for welfare increase — see Cline (1992) for a thorough discussion on the interest rate. Finally, (d), the estimated CO_2 values rest upon the assumption that P is positive and in the magnitude of order used in the tables, reflecting the costs (or use of resources) which we are willing to use today to lower the emission of CO_2.

The size of P depends upon our CO_2-emission target (the sooner and more we wish to lower the emission of CO_2 to the atmosphere the higher P will be), which again reflects the expected negative consequences of a possible climate change caused by the increase of greenhouse gas concentration in the atmosphere. Nearly all macro-economic analyses done till now conclude that a carbon fee in the range of 500-1000 NOK per ton of CO_2 is necessary only to stabilise the present CO_2 emission; to decrease it will demand even higher fees (Dean 1993). It is also a common result in these analyses that because of future expected growth in population and per capita income, the CO_2 fee has to increase considerably over time to stabilise the emissions (Dean, op.cit.).

The estimates of anthropogenic life and decay time assumed in this analysis, are based upon the present situation in Norway as defined in Hoen and Solberg (1994), and are burdened with many uncertain factors like future type of end-uses, climate, etc. However, sensitivity analysis show that even drastic changes of anthropogenic and decay time do not change much the estimated economic values of N in Tables 2 and 3. For example if we set anthropogenic life time to zero, the estimated economic values in table 3 will decrease only by 5%, 3%, 2%, and 1% for respectively 1, 2, 3 and 4% p.a. calculation rate of interest in Equation (3). The main reason for this is the relatively long rotation period T.

Another factor to consider regarding uncertainty of decay times is, if a carbon fee in the magnitude of 300-1000 NOK per ton of CO_2 is implemented, the value of using paper, fibreboards, second-hand sawnwood and other wood residues for energy production will increase. This will, most likely, imply substitution of fossil fuel for wood residues, which again will decrease the *net* decay rate q in Equation (3), and increase N all other factors equal. One could also imagine that the wood after clearfelling were dumped in mines or at deep sea bottom so that q approaches zero, although at the present that sounds rather farfetched.

The biomass yield estimates over time used in the calculations assume "normal" mortality and today's climate. A possible climate change in the direction of higher temperature and more rain could increase the biomass estimates, whereas the risk for calamities (high wind, fungi, and insect attacks) may increase, lowering the biomass growth. On average, however, these effects may counter balance each other.

The estimates of N in Table 3 are for T being 80 years, which is about the economic optimal rotation age for this site class of Norway spruce when industrial wood is the only production purpose (Solberg and Haight 1989). If a CO_2 fixation benefit is included, the correct T to use when estimating the relative value between N and the value of wood only for industrial purposes, is the T which maximizes the soil expectation value of the joint two benefits. This will for the values of P assumed in Table 3 give an optimal T which is considerably higher than 80 years, and that the estimates of N in Table 3 are low compared to those at optimal rotation age (Hoen and Solberg, this volume). For example, a sensitivity analysis of increasing the rotation age by 10 years to 90 years shows, all other factors equal, that the values of N in table 3 increase by 6, 26, 51, 81, and 117% for r being respectively

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2, 4, 6, 8, and 10% p.a. Only for r equal to 1% p.a. decreases N in Table 3 (because the biomass growth is higher than 1% p.a.).

This question of optimal rotation is decisive for determining how the results in Table 3 depend upon site classes. Lower site class implies less biomass growth and hence less value for CO_2 fixation, whereas on the other hand it implies less timber volume and longer rotation times compared to higher site classes. Only a more detailed study can balance the simultaneous effects of these factors. One main problem is that we have little empirical evidence about how mortality changes when increasing the rotation time.

For the other main industrial tree species in the Nordic countries, Scots pine (*Pinus sylvestris)* and birch (*Betula pendula, Betula pubescens*), one get the same order of magnitudes of the value of CO_2-fixation as shown for Norway spruce in Table 3, but with some changes due to different basic densities, growth patterns, rotation ages, end uses, and industrial value of the timber. Also for tree species in other parts of the world, the same factors will decide the value of carbon sequestration.

4.2. Forest Management Implications

Growing forests for industrial wood production is and has been highly profitable in Norway. The results shown in Table 3 indicate that for P and r in the ranges defined there, the profitability of forest production increases many fold when considering the benefit of sequestration of atmospheric carbon in forest biomass. Benefits in the order of magnitude indicated in Table 3 will have several important forest management implications.

All other factors equal, it will be optimal to increase standing volume, rotation ages, and the investment intensity in silviculture. Because the environmental benefit of CO_2 fixation dominates so strongly the benefit of industrial wood, the question of timber quality will be less important relative to maximising dry weight biomass growth. This will in Scandinavia favour species with high basic density like birch compared to Norway spruce.

To keep high biomass growth it will probably be advantageous to allow more natural forest successions to take place — e.g. in Scandinavia first pioneer trees like birch followed by shadow trees like Norway spruce. To maximise biomass growth, natural regeneration could be supplemented by enrichment planting at different stages.

Silvicultural investments, like planting of abundant agriculture land and grassland, forest fertilisation, aff- and reforestation in general, will be much more profitable than without considering the carbon sequestration benefit.

The increase in rotation time is of high interest for mature or close to mature stands, and will mainly depend upon the growth and mortality of the forest stand with age, r, and its value as industrial wood. This value depends on the end-use; it is not unlikely that a high value of P will imply that one get several successions of wood end-uses: First, today's "normal" use as sawnwood, paper or boards; then recycling of some sorts for paper or construction wood; and finally as bioenergy for substitution of fossil fuels. The balance between these end-uses will depend upon P and the prices of the relevant substitution products (steel, solar energy, etc.).

An important issue here is the relation to other environmental benefits from forestry like recreation and biodiversity conservation. Prolonging the rotation time increases these two benefits in most cases. However, increased fertilisation, ditching of moor land, higher

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planting densities (in particular of monocultures), and afforestation decrease in most cases recreational conditions and biodiversity (Solberg and Hoen 1995). In practise, one will have to find a balance between competing benefits.

Since it is indifferent where on the globe a decrease in the concentration of atmospheric CO_2 occurs, the management implications for Nordic forestry discussed above are in principle relevant for most of the boreal and sub-boreal forests as well as for tropical forest areas. In the latter areas, stopping deforestation is one of the most severe problems. If an international market for tradable emission permits of CO_2 is created (cf. below), values of G in the order of magnitudes indicated in Table 1 could give strong incentives for building up forest biomass in many developing countries. This would involve decreased deforestation, rehabilitation of deforested areas, conservation of natural forest reserves, and tree planting for rural development. In tropical areas there could in many cases, if properly planned, be few conflicts between increased carbon sequestration in forest biomass and other environmental benefits, because increased forest biomass would in the right projects have positive environmental effects like preventing erosion, improving watershed and agriculture conditions, and increased biodiversity.

4.3. Policy Implications

With a carbon fee in the range of magnitude shown in Table 1 the economic value of forests will increase dramatically because of its potential as a carbon sink. This value is a public good, and in addition an international good in the sense that a reduction of the concentration of atmospheric CO_2 in one country benefits other countries. Today, there is no market to stimulate investments for this good. One important challenge will be to introduce policy means (including market mechanisms) that make it possible to arrive at an optimal investment level regarding forests as carbon sinks. This is not a trivial matter, and a lot of literature exists regarding environmental policy mechanisms.

For public forest lands the government can regulate the investment intensity for biomass production quite easily through direct budget allocations. The main problem will be to decide the optimal intensity on the various investments options, but this should not be too difficult, as partly discussed in the above section and by Hoen and Solberg (1994).

For private forest land (which in Scandinavia and some other parts of the world constitutes more than 70% of the total forest area) one can in principle use regulations by law or economic policy means, or combinations of these. It would, however, be very difficult in most countries to make the forest owners willing to increase the forest biomass without economic compensation of some sort — i.e. subsidies or tax incentives. These would have to be based on certain criteria for the different investments options, like quantity of carbon fixation, risk regarding implementation, ease of implementation and control. In Scandinavia it is a long tradition for regulating the investments in forestry for industrial wood production and recreation/conservation, which shows that it is possible to implement efficient forest policy means in practice (Solberg and Tikkanen 1992). One interesting issue here would be the income distribution effects, as subsidies in the order of magnitude indicated by Table 3 would imply severe income transfers to the forest land owners. This issue has to be solved politically.

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Subsidies on CO_2 fixation in forest biomass have to be followed by corresponding taxes on emissions of CO_2 from the end-use of the forest biomass (including decaying in the forest of stump, roots and branches). This is discussed some further in Hoen and Solberg (this volume). In theory this may sound easy, but in practise the implementation problems might be severe.

It is not easy to predict what will happen with the forest industries if the above mentioned taxes and subsidies are implemented. In the short run prices of wood will increase because the timber supply decreases as rotation ages increases. This will press the forest industries for more use of recycled raw materials and residues, and worsen the situation for the industry. At the same time the competing products to wood will also be burdened with a fossil fee corresponding to P, and the price of these competing products will increase. The new equilibrium relative prices between wood and non-wood products will decide the future prospects of forest sector. Also, the increased build up of forest biomass will, after some time, increase the timber supply, lowering the relative price of wood and improve the situation for the forest industry. An important aspect here is that if the above mentioned subsidies and taxes are not introduced internationally, but only in one or a few countries, the forest industry in these countries will be severely hampered, and most likely competed out. In addition, the reduction in net emission of carbon will be negligible, as the production will just shift to other countries.

It is very costly to lower the concentration of greenhouse gases in the atmosphere, and it is important to do this as cost efficiently as possible (Dean 1993). Introduction of tradable emission rights represents a possible strategy. Although beyond the scope of this paper, it should be mentioned that such a system can be introduced on domestic level as well as internationally between two countries or more; needless to say it is more cost efficient the more countries are involved (Torvanger et al. 1994).

Regarding forestry a system of tradable permits for emission of CO_2 could, properly managed, be of considerable value for many developing countries. One could e.g. imagine that some of the emission fees collected from fossil fuel use in industrialised countries, were invested in building up forest biomass in developing countries (e.g. stopping deforestation, rehabilitation of degraded land, establishment of fuelwood or industrial wood plantations, etc.), thus improving agriculture, water catchment, and biodiversity, and providing valuable wood. This would require international agreements, control, and monitoring systems.

Most wealthy countries give technical assistance to poor countries. With a value on carbon sequestration as discussed, many projects on restoring and building up sustainable forest ecosystems in poor countries will be highly profitable investments. Properly planned, both the donor and the receiving countries could gain considerably from such projects.

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