Economic Impacts of Carbon Sequestration in Reforestation: Examples from Boreal and Moist Tropical Conditions

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The impact of carbon sequestration on the financial profitability of four tree plantation cases in Finland and the Philippines were examined. On the basis of stem wood growth; the accumulation of carbon in forest biomass, the formation and decomposition of litter, and the carbon flows in wood-based products were assessed for each reforestation case representing boreal (Finland) and moist tropical conditions (the Philippines). Using different unit values for carbon sequestration the profitability of reforestation was estimated for a fixed 100 year period on a per hectare basis. The financial profitability of reforestation increased notably when the sequestered carbon had high positive values. For example, when the value of carbon sequestration was set to be Twenty-five United States Dollars per megagram of carbon (25 USD/Mg C), the internal rate of return (IRR) of a reforestation investment with spruce (*Picea abies*) in Finland increased from 3.2 % to 4.1 %. Equally, the IRR of reforestation with mahogany (*Swietenia macrophylla,* King) in the Philippines increased from 12.8 % to 15.5 %. The present value of carbon sequestration ranged from 39–48 % and from 77–101 % of the present value of the reforestation costs in Finland and the Philippines, respectively, when a 25 USD/Mg C shadow price and a 5 % discount rate were applied. Sequestration of one Mg of carbon in reforestation in Finland and the Philippines was estimated to cost from 10.5–20.0 and from 4.0–13.6 USD, respectively.

Keywords plantation forestry, carbon, profitability, environment, boreal, tropical, Finland, Philippines

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1 Introduction

The potential of forest plantations in the global stabilisation of the carbon dioxide balance of the atmosphere has been discussed and outlined in many contexts (e.g. Sedjo 1989, Vitousek 1991, Woodwell 1992). If forest plantations were used purposefully to sequester carbon the impact on the CO_2 balance could be substantial. In theory, it is even possible to compensate for all of the carbon released in fossil fuel combustion and deforestation by plantations. According to Vitousek (1991) that would require afforestation of approximately 800 million hectares, assuming that forest plantations can sequester carbon at a rate of 7.5 Mg C/ha/yr.

The role of forest plantations in carbon sequestration have been examined in some country specific studies. In New Zealand, the annual storage of carbon for 1988–89 in forest plantations of 1.24 million hectares was estimated to be 3.6 million tonnes after harvest, equivalent to 70 % of New Zealand's total fossil fuel emissions, but less than 0.1 % of the total global fossil fuel emissions (MacLaren et al. 1993). Similarly in Britain, the rate of carbon removal by 1.3 million hectares of plantation forests in 1990 was estimated to be 2.5 million tonnes, representing only 1.5 % of Britain's annual carbon emissions (Cannell and Dewar 1995). The carbon storage capacity of short rotation tropical plantation species has also been examined (e.g. Schroeder 1992).

Technically, the flows of carbon associated with reforestation are dependent on similar factors to those in natural forest management: carbon stored in the woody biomass of living, growing trees, accumulation of carbon on soil and timber products, and the cumulative emissions of carbon lost as a result of energy consumed in forest management and wood processing (Matthews 1993). In Fig. 1 major carbon fluxes and carbon storage sites in forest plantations are presented, excluding the energy processes in forest management and wood processing.

The role that forest plantations could play as a global sink for carbon will depend less on the technical factors of carbon sequestration than on economic expediency. The area under forest plantations could be technically expanded rather easily if it was considered socially and environmentally feasible and economically profitable. Although the role of forest plantations in carbon sequestration has been investigated from the economic point of view (see Nabuurs 1994), there seem to be few studies as of yet which have examined the problem from the perspective of plantation profitability, especially in boreal and tropical zones. One such study done in British Columbia (van Kooten et al. 1993) estimated that the profitability of reforestation of inadequately stocked lands was improved when the economic impacts of carbon sequestration were included in the profitability analysis.

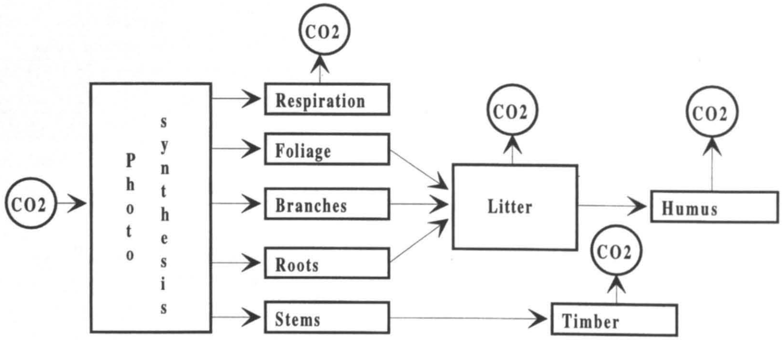

Fig. 1. A simplified diagram of fluxes and stocks of carbon in a forest ecosystem. CO_2 refers to a release of carbon to the atmosphere either through respiration or decomposition (Nabuurs and Mohren 1993).

Finland and the Philippines were selected to represent distinctly different but typical examples from boreal and moist tropical conditions respectively. The Philippines represents a case of a developing tropical country, where after a long period of large scale deforestation and forest degradation recent extensive goals and programs of reforestation have been established to slow environmental damage and secure a future timber supply. In many respect Finland represents an opposite case: an industrialized country where forests and the forest industry provide a backbone for the economy and where a long-term commitment to forest management and silviculture has resulted in expanding its forest resources. The growth and yield possibilities for planted trees, and the economic environments for plantation forestry do differ in these countries at least as much as they generally do for boreal and tropical conditions. However, both countries share the concern for the stabilisation of the atmospheric carbon dioxide balance and the new challenges and opportunities that forest plantations may offer in this global issue.

The purpose of this study was to examine the impacts of carbon sequestration on the profitability of reforestation in Finland and the Philippines. More specifically, the aim was to examine the impacts of varying growth and yield conditions, rotation cycles and end-use patterns on the quantity and timing of carbon flows, in addition to assessing their impacts on the economic value of carbon sequestration and the profitability of reforestation.

2 Methodology of the Study

2.1 Profitability Analysis

Net present value (NPV) and internal rate of return (IRR) were the two criteria used to indicate the profitability of reforestation investments. The NPV is the current value of the sum of the annual costs and revenues with a given discount rate. The IRR is the discount rate at which the NPV is equal to zero. Profitability analyses were first calculated solely for reforestation investments (a formal financial profitability analysis), and then for reforestation investments where the carbon flows were valued and included in the profitability analysis. The latter approach represents an environmental economic profitability at the firm level, in a case when shadow prices are given by the society. Various unit values for carbon flows in United States Dollars per megagram of carbon (USD/Mg C) and two discount rates were applied.

2.2 Reforestation Options

Both in Finland and in the Philippines one reforestation option studied represented fast-growing (short rotation), and the other slow-growing (long rotation) tree plantation. It was assumed that reforestation is done on bare land. In other words, the previous vegetation was assumed to have no influence on the growth and yield of a forest plantation, or on the carbon flows in the future. Therefore, the opportunity cost of land in terms of carbon sequestration was assumed to be zero.

In Finland, reforestation of former agricultural land with birch (*Betula pendula*) was considered as an example of a tree plantation with fast growth. Plantation establishment costs were the average costs in field afforestation (Aarnio and Rantala 1994), and growth and yield data, including two thinnings (30 %) at the ages of 20 and 30 years were applied from Oikarinen (1983, 45). Reforestation with spruce (*Picea abies*) after a clear felling on a moderately fertile soil (blueberry type), was considered as a slow-growing tree plantation. For spruce, the average planting costs in reforestation (Yearbook of forest statistics 1993–1994), and the average growth and yield data, including two thinnings (30 %) at the ages of 45 and 70 years, were applied (Vuokila and Väliaho 1980, 147) (Table 1).

In the Philippines, reforestation with *Acacia auriculiformis* using a 15 year rotation period and with mahogany (*Swietenia macrophylla*, King) using a 25 year rotation period were considered as a fast- and slow-growing tree plantations, respectively. The basic cost data for reforestation was the same as used in the national forestry sector planning (DENR 1990). Since only scattered data

Table 1. Studied reforestation options.

Species	Rotation (yr)	MAI (m^3/ha/yr)	End-use of stem wood
Betula pendula	50	8	66 % plywood, 34 % chemical pulp & paper
Picea abies	100	5	77 % saw timber, 23 % mechanical pulp & paper
Acacia auriculiformis	15	12	100 % chemical pulp & paper
Swietenia macrophylla, King	25	10	70 % saw timber, 30 % fuelwood

on forest plantation growth and yield on different soils were available, the growth and yield estimates had to be based on different sources (Firewood crops... 1980, Pandey 1983, Ten-year development... 1988, Master plan... 1990, Forestry sector... 1994). The average mean annual increments in the Philippines (MAI) were estimated without thinnings (Table 1).

2.3 Carbon Sequestration

2.3.1 *Accumulation of Carbon on Growing Biomass*

In this study, photosynthesis and respiration were not explicitly considered. Instead, the carbon increment rates were estimated indirectly from the stem volume increments (Nabuurs and Mohren 1993). The assessment of carbon fluxes and carbon storage structures via stem volume increment was based on an assumption that the total weight of foliage, branches, and roots have a high correlation with the stem diameter and the volume of stem wood (e.g. Evans 1992).

Specific values for the carbon content, the assimilate allocation, decomposition, and the residence time of carbon in the litter for *Acacia auriculiformis* and mahogany were the same as used for *Albizia* spp. plantations in the tropics. The specific values for spruce and birch plantations were the same as those used for spruce forests in the Boreonemoral zone of Russia and for poplar plantations on former agricultural land in Europe, respectively (Nabuurs and Mohren 1993).

The stem volume increment was converted into a stem biomass increment using specific conversion factors for basic density (oven dry weight per fresh volume). The oven-dry stem biomass was further converted into the mass of carbon using the values for the carbon content in oven-dry structural biomass (Appendix 1, Table A).

The allocation of forest biomass on various structures (foliage, branches and roots) during the stand development was, as mentioned earlier, based on stem wood increment. The specific factors used for conversion are presented in Appendix 1, Table B. Turnover rates of biomass structures (Appendix 1, Table C) were used to assess the formation of litter. Finally, the residence time of various biomass compartments in litter was assessed using the values presented in Appendix 1, Table D.

Since the formation of humus as well as its decomposition are relatively slow processes, and the study was limited to studying the carbon flows during the first 100 years after reforestation, they were both excluded from the analysis.

2.3.2 *Carbon Flows in Wood-Based Products*

In addition to the biological carbon processes, the carbon flows in wood-based products were also estimated. On the whole, the residence time of carbon in the wood-based products was assumed to be higher for sawn wood and plywood than for paper products or fuelwood. The residence time of carbon in the wood-based products was estimated using life span equation (Karjalainen et al. 1994). The life span indicates the average time over which products in a given category are in use. Similarly, a certain amount of carbon is removed from use in subsequent years as

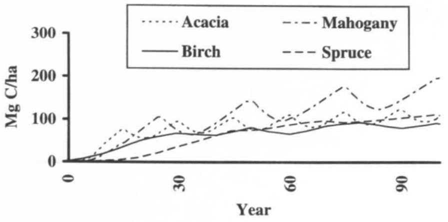

Fig. 2. Carbon sequestration (Mg C/ha) on studied tree plantations over a 100 year period.

$$pu = [d - (a / 1 + b \times e^{-c \times t})] \times 100$$

where pu is the proportion of products still in use of the original cohort at a given time. Values for the parameters for different wood-based products are presented in Appendix 1, Table E.

In general, the carbon flows were followed, first, up to the decomposition of litter; and second, up to the assumed decomposition of the end products (see Fig. 1). To illustrate the estimated carbon flows, the accumulation of carbon in different tree plantations is presented in Fig. 2, where the trends and cycles in the accumulated carbon are due to the rotation and thinning cycles.

2.4 Valuation of Carbon Sequestration

Crucial to the economic analysis is whether carbon sequestration can be treated as an economic benefit or not. If it can be treated as a benefit, what will be the proper unit price level (shadow price) for the carbon sink that forests will provide?

The shadow price of a unit of CO_2 is the value of the external damage caused by an emission. Determinations of the shadow price level for emission control, however, vary strikingly according to the method of pricing the external damages or the costs of preventing them (Table 2). Since the unit values of carbon emissions are usually presented as present-valued lump sums the shadow prices of CO_2 depends also on the discount rate used. In conclusion, the shadow price of carbon dioxide emission can be assumed to be positive, although it seems impossible to objectively determine any exact or core estimates.

Theoretically, it has been shown that when market distortions are rejected, marketable emission permits will minimise the total costs used for pollution control if limitations for a maximum pollution level are given (Randall 1987). This theory was assumed here to be relevant also in the valuation of carbon sequestration: Since forests clearly offer an opportunity for emission control investments (e.g. in industry and energy production) emission control costs can be assumed to describe the value of carbon sequestration in plantation forests. Consequently, the recommendation made by Andersson and Williams (1994) that the Global Environmental Facility (GEF) should apply 25 USD/Mg shadow price for carbon in GEF funded projects (e.g. afforestation projects) for 1993, increasing by 10 % per

Table 2. Unit value for carbon emission control.

Method of pricing CO_2	Unit value (USD/Mg C)	Reference
Cost of damages in global warming	20	Frankhauser (1992), cf. Pearce and Brown (1994)
Marginal cost of abatement	1–6	Falk and Mendelson (1993)
Eight various methods	1–380	Price and Willis (1993), Price (1994)
Marginal cost of limiting C emissions in energy production	25–120	Andersson and Williams (1994)
Direct subjective estimation of nine experts (interview)	113 (s.d. 150)	Schauer (1995)
Reforestation costs	1–60	Sedjo et al. (1995)

s.d. standard deviation

annum until the year 2010, was considered most relevant for this study. The shadow price for carbon flows – 25 USD/Mg – was assumed constant as were wood prices. Sensitivity analyses were made with shadow prices between 1 and 50 USD/Mg C.

Table 3. Internal rate of return (%) of reforestation investments with and without carbon sequestration (25 USD/Mg C) calculated for a 100 year period.

	Birch	Spruce	Acacia	Mahogany
Financial profitability	5.2	3.2	15.3	12.8
Profitability with carbon sequestration	6.6	4.1	20.3	15.5

3 Results

3.1 Profitability of Reforestation and Costs of Carbon Sequestration

Reforestation with fast-growing tree species was estimated to be financially more profitable than reforestation with slow-growing species both under boreal and moist tropical conditions. The profitability of reforestation increased more in the Philippines than in Finland when the environmental benefits of carbon sequestration were included in the profitability analysis (Table 3).

In general, the greatest impacts on the profitability were by; the growth and yield data, the plantation establishment costs, the rotation period, the end-use of wood products, and the discount rate. For example, when a 10 percent discount rate was applied, reforestation in Finland was unprofitable even if the environmental value of carbon sequestration was included in the profitability analysis. The environmental value of carbon sequestration also decreased when the discount rate was increased (Table 4). Sequestration of one Mg of carbon in boreal and moist tropical forest plantations was estimated to cost 10.5–20.0 and 4.0–13.6 USD, respectively (Table 5).

3.2 Sensitivity Analysis

An increase in the shadow price of carbon sequestration by one USD/Mg C increased the NPV of the reforestation investment by 35, 20, 46 and 47 USD/ha in birch, spruce, acacia and mahogany plantations, respectively, when a five percent discount rate was applied (Table 6). When the shadow price of carbon sequestration was set to be higher than 47 and 66 USD/Mg C, reforestation with spruce (5 % discount rate) and birch (10 % discount rate), respectively, generated a positive NPV for the reforestation investment.

The present value of carbon sequestration was estimated to be equal to 48, 39, 77 and 101 percentages of the present value of the plantation establishment costs for birch, spruce, acacia, and mahogany plantations, respectively, when a five percent discount rate and a 25 USD/Mg C shadow price were applied. More generally, an increase in the shadow price of carbon sequestration by one USD/Mg C covered approximately 1–2 and 3–4 percentages of the present values of the plantation establishment costs in Finland and the Philippines, respectively (Table 7).

Table 4. Net present value of reforestation investments (USD/ha) with and without carbon sequestration (25 USD/Mg C) calculated for a 100 year period.

Discount rate (%)	Birch	Spruce	Acacia	Mahogany
Financial profitability				
5	171	–927	4041	5039
10	–1282	–1150	888	648
Value of carbon sequestration				
5	870	501	1159	1191
10	491	160	684	560
Profitability with carbon sequestration				
5	1041	–426	5200	6230
10	–791	–990	1571	1209

Table 5. Costs (USD/Mg C) of carbon sequestration using reforestation.

Discount rate (%)	Birch	Spruce	Acacia	Mahogany
5	20.0	11.4	13.6	5.9
10	17.2	10.5	8.4	4.0

4 Discussion and Conclusions

For a forest plantation in general, the better the growth and yield is, the more carbon that can be sequestered on trees. Similarly, in general, the longer the rotation period is, the more carbon that is sequestered on forest biomass. Further-

Table 6. Net present value of reforestation investment (USD/ha) with different shadow prices for carbon sequestration calculated for a 100 year period.

Species	Discount rate (%)	Shadow price of carbon sequestration (USD/Mg C)				
		0	1	10	25	50
Birch	5	171	206	519	1041	1912
	10	–1282	–1262	–1086	–791	–299
Spruce	5	–927	–907	–727	–426	75
	10	–1150	–1143	–1086	–990	–829
Acacia	5	4041	4087	4504	5200	6359
	10	888	915	1161	1571	2255
Mahogany	5	5039	5086	5515	6230	7421
	10	648	671	873	1209	1769

Table 7. Value of carbon sequestration relative to the plantation establishment costs (%).

Species	Discount rate (%)	Shadow price of carbon sequestration (USD/Mg C)				
		0	1	10	25	50
Birch	5	0	2	19	48	96
	10	0	1	13	31	63
Spruce	5	0	2	16	39	79
	10	0	1	5	14	27
Acacia	5	0	3	31	77	155
	10	0	3	29	73	147
Mahogany	5	0	4	40	101	202
	10	0	3	28	70	139

more, the end-use pattern of wood products and the factors that affect decomposition in general, also influence the amount of sequestered carbon.

Basically, the same factors that influence the amount of sequestered carbon, also influence the value of carbon sequestration. However, there are smaller than expected differences in the value of carbon sequestration between the Philippines and Finland due to the discounting and assumed patterns of end use. It seems that discounting greatly reduces differences in end-use, for example, making them almost insignificant in the case of a spruce plantation in Finland.

It seems (Table 3) that the profitability increase (measured in percentage increases of IRR) due to carbon sequestration is higher in the Philippines, where the financial profitability of plantations is already much higher than in Finland. However, the relative improvements in IRR (measured in relative increase of IRR) vary in the same range (21–35%) in both countries.

When the profitability was measured by NPV (Table 4) the lower discount rate (5 %) resulted in higher relative profitability changes in Finland than in the Philippines. However, with the higher discount rate (10 %) the opposite was true. In general, the assumed shadow price of carbon sequestration (25 USD/Mg C) increased the profitability of reforestation significantly, similar to the IRR results.

As demonstrated by the sensitivity analysis, the impact of carbon sequestration on the profitability of reforestation largely depends on the assumed level of the shadow price for carbon fixation. The uncertainties related to the determination of the proper unit price for carbon fixation may help to describe the wide range of the results in the sensitivity analysis.

It can be assumed that reforestation is one of the most cost-effective ways to control the concentration of carbon dioxide in the atmosphere, since the more traditional benefits of reforestation (financial, economic, and other environmental) in many cases fully or partially cover the costs of the investment. For example, even if the financial revenues from harvested timber were not included, the sequestration of one Mg of carbon was estimated to cost only 4.0–20.0 USD.

The present value of carbon sequestration was estimated as higher with fast-growing tree plantations than with slow-growing tree plantations, although the total growth within the 100 year period did not vary much between these types of plantations. This leads to a discussion on the role of discounting when the value for carbon sequestration is assessed.

Discounting makes the future harvest values commensurate to the present plantation establishment costs. The choice of a proper discount rate is a known sustainable headache for forest economists. In assessing the economic importance of carbon sequestration, the time factor and discounting play similar crucial, and perhaps an even more complicated role than in traditional economic calculations. The discount rate holds the crucial balance between the immediate benefits of burning fossil fuels, and the uncertain consequences of releasing CO_2 over centuries (Price and Willis 1993). Price and Willis (1993) suggest, among other things, that the uncertainty of climatic change should be a reason for an increased weight on the future. In response to that, we think that a selective reduction of the discount rate for the carbon values could be appropriate. This consequently, would contribute significantly to the benefits of forestry.

When considering the other implications of the improved profitability of forest plantations, one should keep in mind that in practice forest owners who plant the trees rarely will have any financial compensation (transfer payments) for the carbon sequestration. Therefore, carbon sequestration does not improve the financial profitability unless there is an appropriate incentive provided. In addition, the assumption that forest plantations decelerate deforestation in the tropics, therefore also decreasing carbon emissions from the destruction of the natural forests, provides that the grounds for incentives seem to be especially relevant (Andrasko et al. 1991).

Appropriately planned tree plantations (from farm level agroforestry to watershed and industrial plantations) will produce wood products, employment, and income, while at the same time counteracting land degradation and soil erosion, reducing pressure on natural forests and sequestering carbon from the atmosphere. Of course, some negative environmental impacts are related to tree plantations in the developing world and the profile of the impacts of forest plantations may be in some respects quite different from what it is in industrialised countries. For all these reasons, among which the carbon sequestration potential may play a major role, the economics of the multiple role of forest plantations in developing and developed countries certainly deserves more intensified research efforts.

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Appendix 1

Table A. Conversion factors from fresh volume to oven dry matter (kg/m^3) and carbon content in oven-dry structural biomass (%) for the studied tree species.

Species	Conversion factor to oven dry matter (kg/m^3)	Carbon content (%)
Acacia	460[1]	50.0[4]
Mahogany	550[2]	50.0[4]
Birch	490[3]	50.5[5]
Spruce	385[3]	51.9[5]

1) Saquino (1991), 2) Gimoto (1992), 3) Kellomäki et al. (1992), 4) Nabuurs and Mohren (1993), 5) Karjalainen et al. (1994)

Table B. Assimilate allocation during stand development, relative to stem oven dry weight (Nabuurs and Mohren 1993).

Age (yr)	0	5	10	20	30	40	50	60	70	80	100
Acacia & mahogany											
– foliage	0.7	0.7	0.4	0.4	0.4	-	-	-	-	-	-
– branches	0.6	0.4	0.4	0.4	0.4	-	-	-	-	-	-
– roots	0.7	0.7	0.4	0.4	0.4	-	-	-	-	-	-
Birch											
– foliage	2.5	1.0	0.3	0.5	0.8	0.9	1.2	-	-	-	-
– branches	1.5	0.8	0.2	0.35	0.4	0.5	0.5	-	-	-	-
– roots	2.0	0.8	0.1	0.3	0.35	0.4	0.5	-	-	-	-
Spruce											
– foliage	1.0	1.0	1.0	0.75	0.65	0.65	0.65	0.65	0.65	0.7	0.7
– branches	1.0	1.0	0.4	0.25	0.23	0.22	0.22	0.21	0.21	0.2	0.2
– roots	1.0	1.0	0.9	0.8	0.6	0.6	0.6	0.5	0.5	0.5	0.5

Table C. Turnover rates of biomass structures (yr^{-1}) (Nabuurs and Mohren 1993).

Plantation species	Foliage	Branches	Roots
Acacia & mahogany	0.5	0.05	0.06
Birch	0.3	0.03	0.07
Spruce	1.0	0.06	0.1

Table D. Average residence time of dead branches, roots and foliage in various plantations (yr) (Nabuurs and Mohren 1993).

Plantation species	Residence time, branches and roots	Residence time, foliage
Acacia & mahogany	10	1
Birch	10	1
Spruce	30	6

Table E. Basic values for parameters in the product lifespan equation and assumed distribution of products into lifespan categories (Karjalainen et al. 1994).

Product lifespan category	Parameters for product lifespan equation				Sawn goods	Plywood	Mechanical pulp & paper	Chemical pulp & paper	Fuelwood
	a	b	c	d					
Short	120	5	0.5	120	-	-	34	14	100
Medium–short	120	5	0.15	120	-	-	66	86	-
Medium–long	120	5	0.065	120	50	50	-	-	-
Long	120	5	0.03	120	50	50	-	-	-