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Carbon sequestration in sinks

An overview of potential and costs

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Sammendrag:. Før klimaforhandlingene ble gjenopptatt i Bonn i juli dette året, var det lite realistisk å tro at man skulle enes om de uløste hovedsakene i Kyotoprotokollen. Dette var primært på grunn av at USA trakk seg fra Kyotoprotokollen, og mangelen på enighet i tidligere klimaforhandlinger som hovedsakelig strandet på grunn av uenighet rundt bruken av aktiviteter innenfor areal- og skogbruk (land use, land-use change, and forestry, LULUCF). LULUCF er kontroversielt i klimaforhandlingene, men man har nå kommet til enighet. Denne artikkelen utforsker det mulige bidraget fra LULUCF aktiviteter i å redusere utslipp av klimagasser. En oversikt av litteraturen om potensialet og kostnadene for LULUCF aktiviteter er derfor sentralt. Analyse av nylige klimaforhandlinger er også viktig. Det er klart at potensialet for karbonbinding er stort, men det er store variasjoner i estimatene ettersom faktorer som tilgjengelig areal og raten av karbonbinding kompliserer beregningene. Det er også store variasjoner i kostnadsestimatene, og økonomisk analyse av LULUCF aktiviteter er ikke lett sammenlignbare ettersom det ikke finnes en utbredt metode for analyse. På tross av at det er vanskelig å sammenligne kostnadene ved karbonbinding, er det klart at det er et relativt billig tiltak. Men selv om potensialet for karbonbinding er stort, så vil dens rolle i å redusere klimagassutslipp være begrenset av Kyotoprotokollen. De nylige klimaforhandlingene i Bonn og Marrakesh har spesifisert regler og retningslinjer relatert til LULUCF aktiviteter. En av hovedutfallene innebærer betydelige innrømmelser til Japan, Canada, og Russland, blant annet når det gjelder retten til å trekke fra skogens opptak av karbon i sine klimaregnskap.

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Abstract: Prior to the resumed climate negotiations in Bonn in July this year, it was thought that an agreement on the unresolved crunch issues of the Kyoto Protocol was unrealistic. This was primarily due to the US withdrawal from the Kyoto Protocol, and the failure of the previous climate negotiations that stranded mainly because of disagreement on the inclusion of land use, land-use change, and forestry (LULUCF) activities. The LULUCF issue is controversial in the climate negotiations, but an agreement has now been reached. This paper explores the possible contribution of LULUCF activities in promoting greenhouse gas emissions reductions. A survey on the literature of the potential and cost of LULUCF activities is therefore central. Analysis of the recent climate negotiations is also important. It is clear that the potential for carbon sequestration is large, but there are large variations in the estimates as factors such as land availability and the rate of carbon uptake complicate the calculations. There are also variations in the costs estimates, and economic analysis of LULUCF projects are not easily compared as no standard method of analysis has emerged and come into wide use. Despite the difficulties in comparing the costs of carbon sequestration, it is clear that it is a relatively inexpensive measure. Even though the potential for carbon sequestration is large, its role in reducing emissions of greenhouse gases (GHG) is limited by the Kyoto Protocol. The recent climate negotiations in Bonn and Marrakesh have specified the modalities, rules and guidelines relating to LULUCF activities. One of the main outcomes is that Japan, Canada and Russia are allowed large inclusions of sinks in their GHG emission accounts.

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1 Introduction

The climate negotiations that took place at the Conference of the Parties (COP) in Bonn (COP-6.5) and Marrakesh (COP-7) this year resulted in an agreement that eventually can lead to a sufficient ratification of the Kyoto Protocol.[1] Land use, land-use change, and forestry activities (LULUCF) were one of the crunch issues in the negotiations, as it is a common view that the LULUCF issue was one of the main reasons that the negotiations at COP-6 failed ("it was the sinks that sank the Hague").[2] Although the US withdrawal from the Kyoto Protocol in March was thought to reduce the probability of ratification and implementation of the Kyoto Protocol, the remaining Parties were determined to move on, and the sinks issue was resolved.

The industrialized countries (Annex I) are through the Kyoto Protocol committed to reducing their aggregate emissions in the period 2008–2012 by 5.2% compared to the base year 1990.[3] The focus has primarily been on the emissions from the combustion of oil, coal and gas, as these represent the main source of emissions. However, emissions from LULUCF activities are also important as they account for approximately 30% of the anthropogenic CO_2 emissions (Watson et al., 2000). Forests also play an important role in the carbon cycle as they sequester CO_2 from the atmosphere through photosynthesis.

There has been an increasing interest in sinks as a mitigation strategy, particularly because sequestration is considered a relatively inexpensive strategy. For instance, recent estimates of carbon sequestration costs from Activities Implemented Jointly Pilot Phase and other LULUCF projects range from 0.1 to 28 USD per t C (Brown et al., 2000). Emissions from LULUCF are small relative to fossil fuel carbon emissions, but their inclusion may have a major impact on the cost of achieving the Kyoto commitments. Studies by both MacCracken et al. (1999) and Missfeldt and Haites (2001) show that inclusion of sinks could lower the compliance costs for Annex I countries. Although the Kyoto Protocol allows inclusion of sinks, there have been, until recently, serious difficulties in agreeing how and to what extent sinks should be accounted for.

Given this controversial issue, this paper explores the possible contribution of LULUCF activities in promoting greenhouse gas emissions reductions. This is important because inclusion of LULUCF activities is likely to reduce emissions reduction costs through less abatement within more traditional sectors, and most likely reduce the impacts on the prices of fossil fuels. This will in return reduce the total costs and influence how abatement is distributed among countries implementing the Kyoto Protocol. This paper therefore aims to survey the literature on the potential and cost of sequestering carbon. The survey will also form the basis for including carbon sequestration in an economic model analyzing the effects of implementing the Kyoto Protocol on various countries and sectors. The paper starts with some background information on the role of forest in the carbon cycle and in the Kyoto Protocol. The focus is then turned to the potential of carbon sequestration with regard to land

[1] The entry-into-force provision of the Protocol not only requires ratification by 55 Parties, but also employs a "double trigger," which specifies that as an addition, the ratifying Annex-I Parties must represent at least 55% of the total Annex-I CO_2 emissions in the year 1990.

[2] The Kyoto Protocol refers to the flux of carbon between the terrestrial carbon pool and the atmosphere as "emissions," and the opposite flux as "removals." The latter is often referred to as "uptakes" or "sinks" (Noble and Scholes, 2001).

[3] "Annex I countries" refers to the industrialized countries that have special commitments under the UNFCCC. These countries are with minor exceptions identical to the countries listed in the Annex B to the Kyoto Protocol, where the countries' specific emissions reduction targets are specified. To avoid any confusion, the term "Annex I countries" is hereafter used.

areas and amount of carbon. The paper then continues with a review of the costs of carbon sequestration. Finally, the outcome of recent climate negotiations and some implications are discussed.

2 Background

Carbon is cycled between the atmosphere, oceans, and terrestrial biosphere. The largest natural exchanges occur between the atmosphere and terrestrial biota, and between the atmosphere and ocean surface waters. Significant reservoirs of carbon are found in oceans, vegetation, and soils. Oceans contain about 50 times as much carbon as the atmosphere, while terrestrial vegetation and soils contain about three and a half times as much carbon as the atmosphere. Table 2.1 shows that there are some significant differences in the average global carbon budget between the two time periods 1980–1989 and 1989–1998. The emissions from fossil fuel combustion and cement production have increased by approximately 0.8 Gt C yr^{-1}. The atmospheric stock of carbon increases at a relatively stable rate, while the net ocean uptake has increased slightly. The difference between the emissions from fossil fuel combustion and cement production, and atmospheric and ocean uptake, has increased – resulting in a net terrestrial uptake of carbon of 0.7 $\pm$ 1.0 Gt C yr^{-1} for the period 1989 to 1998 (Bolin and Sukumar, 2000).

Table 2.1 Average annual budget of CO_2 perturbations (Gt C yr^{-1}) for 1980 to 1989 and 1989 to 1998.

	1980 to 1989	1989 to 1998
1) Emissions from fossil fuel combustion and cement production	5.5 $\pm$ 0.5	6.3 $\pm$ 0.6
2) Storage in the atmosphere	3.3 $\pm$ 0.2	3.3 $\pm$ 0.2
3) Ocean uptake	2.0 $\pm$ 0.8	2.3 $\pm$ 0.8
4) Net terrestrial uptake = (1)-[(2)+(3)]	0.2 $\pm$ 1.0	0.7 $\pm$ 1.0
5) Emissions from land-use change	1.7 $\pm$ 0.8	1.6 $\pm$ 0.8
6) Residual terrestrial uptake = (4)+(5)	1.9 $\pm$ 1.3	2.3 $\pm$ 1.3

(Source: Bolin and Sukumar, 2000).

Analysis of the global carbon stocks in vegetation and top 1 m of soils shows that the amount of carbon stored globally in soils is much larger than in vegetation. Soil is a large carbon pool in all biomes, whereas the major carbon stocks in vegetation are found in the forest biomes (Bolin and Sukumar, 2000). Statistics from the FAO (1999) reveal that the area covered by natural forests and forest plantations was estimated to be 2,454 Mha in 1995. This amounts to about 25% of the world's land area, and 55% of the world's forests are found in developing countries (see figure 1.1). The world's forests can be almost equally divided between tropical/subtropical forests and temperate/boreal forests. Forest plantations constitute only about 3% of the world's forests; the remaining 97% are natural or semi-natural forests.

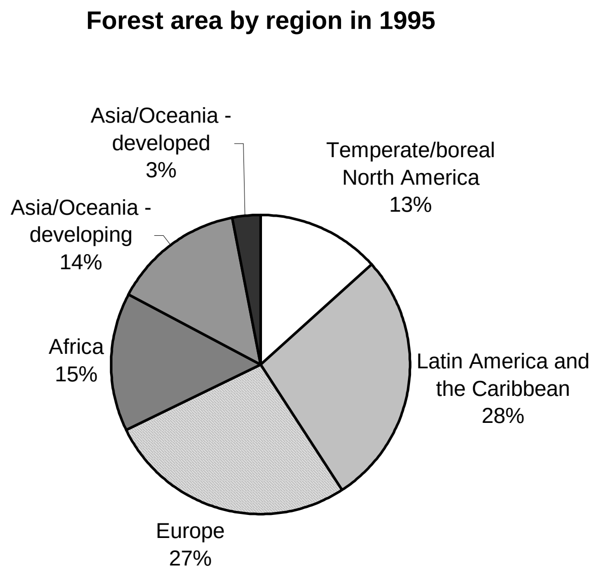

Figure 1.1 Forest area by region in 1995. (Source: FAO, 1999.)

The world's forests decreased in size from 1980 to 1995 by 180 Mha. There was a net increase of 20 Mha in developed countries, but a net loss of 200 Mha in developing countries. The loss of forests is still high, but it seems that the rate of deforestation is slowing. The main factors for deforestation in tropical areas are expansion of subsistence farming in Africa and Asia, and large economic development programs involving resettlement, agriculture and infrastructure in Latin America and Asia (FAO, 1999).

Both the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol recognize the important role of forests. However, whether and how sequestering of carbon should be accepted as meeting emission reduction commitments was highly debated before the Kyoto negotiations took place (Noble and Scholes, 2001). It appeared that sinks were likely to be left out completely, as there were concerns about permanence, saturation, verifiability etc. There was also concern that including sinks would lead to less focus on the primary cause of increasing CO_2 concentration in the atmosphere – the combustion of fossil fuels. The USA, Norway, New Zealand and Australia, all with substantial forest resources, consistently supported including sinks. The main opposition came from the European Union's (EU) position of not including sinks in the initial Protocol, but with a possible addition at a later stage. Consensus on including sinks in the Kyoto Protocol was only reached at the very end of the climate negotiations (Schlamadinger and Marland, 2000).

Some of the most important articles in the Kyoto Protocol concerning sinks are outlined below. Article 3.3 states that the extent to which carbon changes in sinks is limited to "*direct human-induced land use change and forestry activities, limited to afforestation, reforestation, and deforestation since 1990*".[4] Parties may under Article 3.4 add or subtract GHG emissions by sources and removals from sinks from "*additional human-induced activities related to changes in greenhouse gas emissions and removals in the agricultural soil and land use*

[4] Afforestation, reforestation, and deforestation are often referred to as ARD-activities.

change and forestry categories". The term additional refers to activities other than the ARD-activities in Article 3.3. Some countries, especially Australia, had net emissions from LULUCF in the base year 1990. Article 3.7 allows these countries to include their LULUCF emissions in their 1990 emissions base year, opening for some credits for improvements (reductions in emissions).[5, 6]

Including LULUCF activities in the Kyoto Protocol represents several challenges, and it has been one of the unresolved "crunch" issues in climate negotiations. One problem is that the Kyoto Protocol lacks vital definitions of what forests, afforestation, reforestation, and deforestation are. With as many as 130 definitions of forests used around the world (Lund, 1999), some clarification was necessary.[7] Other issues within LULUCF were how carbon sequestration should be measured and verified, permanence, leakage, land conflicts and environmental aspects (Torvanger et al., 2001). A special report was therefore prepared in response to a request from the UNFCCC Subsidiary Body for Scientific and Technological Advice (SUBSTA). The SUBSTA requested a special report examining the scientific and technical state of understanding for carbon sequestration strategies related to land use, land-use change, and forestry activities and relevant articles of the Kyoto Protocol (Watson et al., 2000). The report was completed in the spring of 2000 and addresses several key issues with regards to LULUCF activities. It examines for instance the scientific and technical aspects of carbon sequestration in agricultural and forestry activities, the opportunities and implications of ARD and additional human-induced activities, and identifies questions that Parties may wish to consider regarding definitions and accounting rules. It should therefore be useful in the implementation of various articles of the Kyoto Protocol.

3 Potential for sequestration

There are three major strategies for preventing increased build-up of atmospheric CO_2-concentration through LULUCF activities; 1) preserve existing carbon stocks through for instance reduced deforestation and forest fires, 2) increase existing carbon stocks through planting forests, increase productivity and increase carbon stored in soils, and 3) substituting fossil fuels with biomass fuels through use of bio-energy or replacing energy-intensive products such as steel and concrete (Næss, 1999). Early LULUCF sequestration estimates focused on increasing the uptake of carbon through tree planting (Dyson, 1977) or reforesting degraded pasture and grasslands (Houghton, 1990). These studies focused only on the amount and suitability of the land available, not the practicality of implementing such programs (Bloomfield et al., 2000). Attempts to estimate the global potential for increasing carbon sinks through LULUCF activities are complicated by socio-economic and political factors such as land availability or the rate of uptake of different options (Read et al., 2001). Global studies reveal a wide range of estimates of potential for carbon sequestration. The area available for plantations could range from 345 million (Nilsson and Schopfhauser, 1995), to 465 million ha (Sedjo and Solomon, 1989), and 510 million ha (Nordhaus, 1991).[8, 9] The study by Sedjo and

[5] In addition, Article 6.1 (Joint Implementation) refers to *"...emission reduction units resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gases in any sector"*. Article 12 (the Clean Development Mechanism) has no specific reference to sinks, but it has been decided that afforestation and reforestation will be allowed.

[6] This accounting method is known as the 'net' approach, while the 'gross' approach ignores LULUCF uptake of carbon when calculating the base year emissions (MacCracken et al., 1999).

[7] From Schlamadinger and Marland, 2000.

[8] From Hourcade et al.(1996a) and Brown et al. (1996).

Solomon (1989) estimates that 2.9 Gt of carbon per year can be removed from the atmosphere in forest plantations.[10] At the other extreme, Nordhaus (1991) suggest that on average only 0.28 Gt carbon could be captured annually over a period of 75 years. The large difference between these two studies is almost entirely based on the estimates of carbon yields, as their assumptions of land availability are relatively similar (Hourcade et al., 1996a). The fact that one study estimates a carbon yield only a 1/10 of the other study illustrates some of the difficulties of estimating carbon sequestration.

The Intergovernmental Panel on Climate Change's (IPCC) Second Assessment Report (Brown et al., 1996) states that Nilsson and Schopfhauser (1995) and Trexler and Haugen (1995) are the only studies suitable for global analysis of the mitigation potential of forests. They have been chosen because they are global in nature, include an extensive literature review of the land availability issue, and feasible rates of establishment of management options are included. The former focuses on the potential for afforestation on areas that have been without forests for some time, while the latter focuses on reduced deforestation and natural or assisted regeneration. The two studies are combined and suggest that 700 Mha of forest land could be available for carbon conservation globally. This area is distributed over 138 Mha for slowed tropical deforestation, 217 Mha for regeneration of tropical forests, and 345 Mha for plantations and agroforestry. The cumulative amount of carbon that could potentially be conserved and sequestered from 1995 to 2050 ranges from about 60 to 87 billion tons of carbon.[11] 80% of this is expected in the tropics, while the temperate zone and the boreal zone will account for 17% and 3% of the carbon sequestered. The cost of this sequestration (excluding land and transaction costs) would be about 2 to 8 USD/t carbon (Brown et al., 1996).

IPCC's Third Assessment Report (Kauppi et al., 2001) supports many of the earlier findings, but provides a broader evaluation of potential carbon pool. For instance, Sampson et al. (2000) estimate that the global potential of the alternative forest management regimes to 1,270 Mt carbon annually and the area technically available to 6–30% of the global forest area. Nabuurs et al. (2000) estimate the potential of additional forestry activities in six countries or regions in the temperate and boreal zone (435 million ha of forest). The amount of sequestered carbon amounts to 586 Mt carbon annually, and alternative forest management for carbon sequestration is, on average, technically feasible on 10% of the forest area in each country examined. A study by Sathaye and Ravindranath (1998) suggests that 300 Mha may be available for mitigation purposes in ten tropical and temperate countries in Asia.[12] The study assumes 40 Mha for conservation, protection and management; 79 Mha of degraded forest land for regeneration; and 181 Mha of degraded land for plantation forestry. A further 176 Mha is estimated to be available for agroforestry. The cumulative carbon mitigation potential in the 10 Asian countries is estimated to about 26.5 Gt C. This suggests that the estimates in the IPCC's Second Assessment report were conservative (Kauppi et al., 2001). Sathaye et al. (2001) examine the sequestration potential in seven major developing countries (Brazil, China, India, Indonesia, Mexico, the Philippines and Tanzania) that combined account for about 60% of the forested area in the developing world. The estimated cumulative potential amounts to 1,851 Mt C by 2012 with an average of about 120 Mt carbon annually.

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[9] The study by Nilson and Schopfhauser, (1995) also includes agroforestry.

[10] This is close to half of the current global levels of carbon emissions.

[11] The amount of carbon conserved and sequestered by 2050 is equivalent to about 12 to 15% of the total fossil fuels emissions over the same time period (IPCC 1992 scenario).

[12] The ten countries are China, Indonesia, Mongolia, Philippines, Vietnam, India, South Korea, Pakistan, Thailand, and Myanmar.

Table 3.1 shows some estimates of the potential carbon sequestration resulting from LULUCF activities with emphasis on articles 3.3 and 3.4, as summarized by Nobles and Scholes (2001). It is clear that the potential carbon sequestration is significant in relation to the Annex I countries' emission reduction targets. Over 300 Mt carbon could be available each year from activities in Annex I countries (the quantities for articles 3.3 and 3.4 cannot be summed since they may apply for the same area). However, it is also clear that the potential sequestration is much larger in non-Annex I countries. The largest potential is in forestry related activities, but sequestration activities also exist in improved management of croplands and grazing lands. The potential under article 3.4 is significantly larger than under article 3.3, with the exception of reduced deforestation in developing countries.

Table 3.1 Estimates of carbon sequestration through LULUCF activities by 2010 (Mt C/y)

Activities	Annex I	Non-Annex I
Article 3.3		
- Reduced deforestation	60 (0-90)	1,698
- Afforestation and reforestation	26 (7-46)	373 (190-538)
Article 3.4		
- Croplands (e.g. reduced tillage, erosion control)	75	50
- Forests (e.g. enhanced regeneration, fertililisation)	101	69
- Grazing lands (e.g, herd, fire and wood management)	69	168
- Agroforests (e.g. management of trees in agriculture)	12	14
- Urban land (e.g. tree, waste and wood product man.)	1	1
- Deforested land to agroforest instead of pasture/crop	0	391
- Severely degraded land to crop, grass or forest land	1	3
- Cropland to grassland	24	14
Total for Article 3.4	300	710

(Source: Noble and Scholes, 2001 and Missfeldt and Haites, 2001).

4 Costs of sequestration

The interest for carbon sequestration can partly be explained by suggestions that sufficient lands are available for sequestration and claims that growing trees is relatively inexpensive. In the previous section, we saw that substantial land areas and hence also significant amounts of carbon could be utilized for mitigation purposes. Stavins (1999) finds that the serious attention given by policymakers to carbon sequestration can partly be explained by (implicit) assertions about the respective marginal cost functions. In this section, we therefore examine the costs of carbon sequestration.

Financial analysis of LULUCF projects are not easily compared as no standard method of analyzing direct, indirect, initial, and recurring costs, as well as revenues, has emerged and come into wide use. The cost estimates of for LULUCF projects often include land purchase or rent, land clearing and site preparation, initial planting, maintenance and management, and sometimes data collection and evaluation. The opportunity costs of land are often not included in the cost estimates. Infrastructure costs (e.g. road development), monitoring data collection and interpretation costs, and future maintenance costs are often overlooked (Brown et al, 2000).

Kauppi et al. (2001) distinguishes between three basic ways of estimating the costs of sequestration; point estimates, partial equilibrium estimates and general equilibrium approaches. Many of the *point estimates* studies provided undiscounted private market cost point estimates of carbon sequestered in afforestation projects. These types of estimates usually reveal little about how costs might change if the project was to expand. The estimates tend to be biased downwards, partly because the opportunity costs of land were often not included. *Partial equilibrium* studies provide a more complete estimation of a cost function and includes rising costs associated with increased sequestration activities. Marginal cost functions generated from such studies tend to suggest that costs usually are higher than those of simple point estimates. They will in some cases apply a discount rate to future physical carbon sequestered. The *general equilibrium* approach incorporates sectoral and general equilibrium interrelationships. Such models incorporate changing forest production and prices over time and can also include intertemporal market feedbacks (Missfeldt and Haites, 2001).

IPCC reported in 1992 (IPCC, 1992) regional average annual costs of about USD 8 per t C for tropical forestation and reduction of deforestation, increasing to about USD 28 per t C for forestation in other OECD countries than the USA.[13] Table 4.1 summarizes the estimates of unit costs of carbon sequestration reviewed in IPCC's SAR (Hourcade, 1996a). There are four general categories of studies. One group concentrates on North America's potential to sequester carbon, a second group considers carbon sequestration potential of major ecological regions using the average storage method, a third compromises studies of the global potential and costs of carbon sequestration, while a fourth examines the potential in individual countries. The studies that focus on North America have estimates of carbon costs that fall into a relatively narrow range, and Moulton and Richards (1990) provide the lowest cost range. The studies of broad geographic/climate regions indicate relatively low costs of carbon sequestration for forest plantations, forest management, and agroforestry. Although the average storage method has been used, the costs suggest lower estimates than the studies focusing on North America. Dixon, Schroeder and Winjum (1991) find relatively little difference among the boreal, temperate and tropical regions with respect to the sequestration costs of forest plantations and forest management. However, the sequestration costs of agroforestry in the temperate region are much higher than in the tropics. The two estimates of global costs differ significantly. Nordhaus' (1991) estimate of USD 42–114 per t C is much higher than the two previous groups of studies. Sedjo and Solomon, on the other hand, suggest costs of USD 7 and USD 3 per t C on a cost levelization and flow summation basis respectively. The studies of individual developing countries provide estimates from USD 5–11 per t C for forest plantations in Mexico (Masera et al., 1994) to negative costs for plantations in China (Xu, 1994).

Mulgony et al. (1998) found in a review of LULUCF projects in the tropics that most cost estimates range from USD 2 to USD 25 per t C. Other reviews report costs of sequestration in temperate and tropical biomes ranging from USD 4–26 (Swisher and Masters, 1992) to USD 2–12 per t C (Witthoeft-Muelhmann, 1998).[14] Sathaye and Ravindranath's (1998) study of 10 Asian countries covers a wide range of LULUCF activities, mitigation potential and investment costs. The mitigation options include, among others, plantations, agroforestry, reforestation, and natural regeneration. The mitigation potential of the options will naturally vary. Estimates show that the amount of C/ha could range from 6 tC/ha to 299 tC/ha, and the mitigation potential varies between options and countries. The investment costs in terms of

[13] From Brown et al., 1996.

[14] From Brown et al., 2000.

USD/tC vary significantly (USD 0.1/tC to USD 40.6/tC), but the majority of options require less than USD 10/tC.

Table 4.1 Point estimates and ranges of unit costs of carbon sequestration

Study	Region	Method[a]	Costs of carbon sequestration ($/t)		
			Forest plantation	Forest management	Agro-forestry
Sedjo and Solomon, 1989[b]	Global	L	7	-	-
		FS	3	-	-
Nordhaus, 1991	Global	L	42-114	-	-
Dixon, Schroeder and Winjum, 1991	Boreal	AS	5-8	7	-
	Temperate	AS	2-6	1-13	23
	Tropical	AS	7	1-9	5
Dixon et al., 1994	South America	AS	-	-	4-41
	Africa	AS	-	-	4-69
	South Asia	AS	-	-	2-66
	North America	AS	-	-	1-6
Moulton and Richards, 1990[c]	USA	L	9-41	6-47	-
		FS	2-9	2-9	-
Adams et al., 1993	USA	L	20-61	-	-
Parks and Hardie, 1995	USA	L	5-90	-	-
Richards et al., 1993	USA	L	9-66	-	-
		FS	2-9		-
New York State, 1991	New York State	L	14-54	12	-
Van Kooten et al., 1991	Canada	FS	6-18	8-23	-
		L	66-187	39-108	-
Masera et al., 1995	Mexico	AS	5-11	0.3-3	-
Xu, 1994[e]	China	AS	(12)-2	(2)-1	(13)-(1)
Ravindranath and Somashekhar, 1995[d]	India	FS	0.13-1.06	0.09-1.22	0.95-2.78

(Source: Hourcade, 1996a)

[a] The *flow summation method (FS)* summarizes the total tonnes of carbon sequestered, regardless of when the sequestration takes place. The *average storage method (AS)* divides the present value of the sum of all implementation costs over a specific time period by the mean standing carbon storage averaged over several rotation periods. The *levelization/discounting method* (L) differentiates costs and accomplishments according to when the carbon is sequestered.

[b] Sedjo and Solomon do not provide a unit costs for carbon sequestration. Figures are based on costs and yield estimates treated over 40 years with a 5% discount rate on financial outlays.

[c] The flow summation method is not used in these reports. The figures are supplied for comparison purposes.

[d] The study apparently uses a FS approach, but discusses the application of discounting, which suggests a L method.

[e] Figures in parentheses indicate negative costs

Table 4.2 summarizes some recent estimates of carbon sequestration as discussed in the Special Report on LULUCF (Brown et al., 2000). The table presents undiscounted costs and carbon mitigation over project lifetime for selected Activities Implemented Jointly Pilot Phase and other LULUCF projects. Only summary ranges are reported since different methods have been used, and the table shows that the range for these projects is USD 0.1–28 per t C. Most of the estimated costs range from USD 1-15 per t C, with a higher range for reforestation and afforestation.

Table 4.2 Undiscounted cost and carbon mitigation over project lifetime [a]

Project type (number of projects)	Land area (Mha)	Total carbon mitigation (Mt C)	Costs ($/t C)
Emissions Avoidance via Conservation			
- Forest Protection (7)	2.8	41-48	0.1-15
- Forest Management (3)	0.06	5.3	0.3-8
Carbon Sequestration			
- Reforestation and Afforestation (7)	0.10	10-10.4	1-28
- Agroforestry (2)	0.2	10.5-10.8	0.2-10
Multi-Component and Community Forestry (2)	0.35	9.7	0.2-15

(Source: Brown et al., 2000)

[a] For selected AIJ Pilot Phase and other LULUCF projects in some level of implementation. Figures are taken from project reports and published projects reviews. Cost and carbon mitigation figures have been estimated using different methodologies. May not be comparable, and have not been independently reviewed. Costs values are estimated by dividing undiscounted costs and investments by estimated total carbon mitigation.

It is clear that the costs of carbon sequestration in developing countries are relatively low. This becomes even clearer when comparing these costs with estimates of carbon sequestration for the USA. Stavins (1999) develops and demonstrates a method by which the costs of sequestering carbon can be estimated on the basis of landowners' behavior when considering the opportunity costs of alternative land use. Stavins' estimates are compared with other sequestration studies for the USA, as shown in Table 4.3. Since the other studies are for the United States as a whole, Stavins' results are normalized.

As the previous sections have shown, there are significant variations among studies with respect to both the magnitude and costs of carbon sequestration. The most frequently used method when estimating carbon sequestration is *point estimates*, that is, estimates of the costs of achieving a specified amount of carbon sequestration. A different approach is to develop *cost curves* that illustrate the increasing marginal cost of carbon sequestration as a function of the level of sequestration. Such cost curves could yield information that is not available in point estimates or ranges of cost units such as in Table 4.1. Some studies (Adams et al., 1993; Moulton and Richards, 1990; Dixon, Schroeder, and Winjum, 1991; Parks and Hardie, 1995; Richards et al., 1993) have developed cost curves, but the overall impression is that cost curves are rare.[15] ECON (2000) estimated a cost curve for forestry activities under the CDM in a report commissioned by Greenpeace and WWF. The significant data constraints were

[15] After Hourcade et al., 1996a.

stressed, implying that the sequestration costs and credits generated were highly uncertain. The estimated cost curve was global with no own estimates for different regions.

Table 4.3 Comparison of sequestration cost estimates for the USA

Study	Total quantity		Average cost		Marginal cost	
	Land (M. acres)	Carbon (M. tons/yr)	Land ($/acre/yr)	Carbon ($/ton)	Land ($/acre/yr)	Carbon ($/ton)
Stavins, 1999[a]						
- US normalization	342	518	106	70	≤ 200	≤ 136
- Delta states	5	7	58	38	≤100	≤ 66
Moulton and Richards						
- US[b]	269	690	-	27	≤ 81	≤ 37
- Delta states cropland	25	67	50	22	-	-
Richards et al., 1993						
- US[c]	244	416	-	-	≤ 52	≤ 41
- Delta states cropland[d]	1	29	42	18	-	≤ 22
Adams et al., 1993[e]	274	700	-	-	-	≤ 27
Nordhaus, 1991[f]	248	44	81	64	-	-
Parks and Hardie, 1995[g]	9	22	49	21	-	≤ 24
Rubin et al., 1992[h]	71	73	-	23	-	-
Dudek and LeBlanc, 1992[i]	14	-	-	38	-	-
Plantinga, 1995[j]	0.65	1.5	-	-	-	6-13
Callaway and McCarl, 1996[k]	187	200	-	-	-	≤ 25

(Source: Stavins, 1999)

[a] Pine plantation, periodically harvested, at a 5-percent discount rate

[b] Permanent stands on cropland and pastureland only, i.e., not calculated

[c] Figure for total U.S. carbon sequestration is an annuity calculated at 5 percent over 160 years

[d] These figures were used, but not reported in Richards et al. (1993). Reference is to a permanent pine stand, based on data provided in a personal communication from Richards (1994) with Stavins. Carbon costs and tonnages were annualized over 160 years at a 5-pecent discount rate.

[e] Nationwide results for a scenario with harvesting and sale of timber, recalculated at a 5-percent discount rate.

[f] Permanent forestation of "marginal U.S. land". For this and other studies, acres are converted to hectares at a rate of one hectare = 2.477 acres, and to short tons at a rate of one metric tone = 1.102 short tons.

[g] Figures are for U.S. cropland-only scenario. Marginal costs were computed from marginal costs formula using 22 million tons per year and annualized using a 4-percent discount rate over 10 years.

[h] Nationwide results converted from original study at a rate of 3.67 tons of CO_2 equals one ton of C, and into short tons from metric tons.

[I] An average permanent stand of U.S. tree species, CO_2 converted to C.

[j] Figures are from a 14-country region of Wisconsin for the scenario assuming a least-cost program at a 4-percent discount rate and a constant annual sequestration rate of 2.25 tons of carbon per acre, hectares converted to acres.

[k] Calculations use a 5-percent discount rate, employ carbon yield functions from Birdsey (1993), and do not allow for farm programs.

A regional cost curve for the USA is shown in Figure 4.1 in which Stavins' marginal cost function is compared to those of Adams et al. (1993), Richards et al. (1993 and Callaway and McCarl (1996). All of the marginal cost functions lie within the 95-precent confidence interval, at least up to 300 million tons/year. All studies are less steep than Stavins' central tendency and lie well below it for most of their ranges. The general impression is that Stavins' marginal cost estimates are larger than those earlier reported.

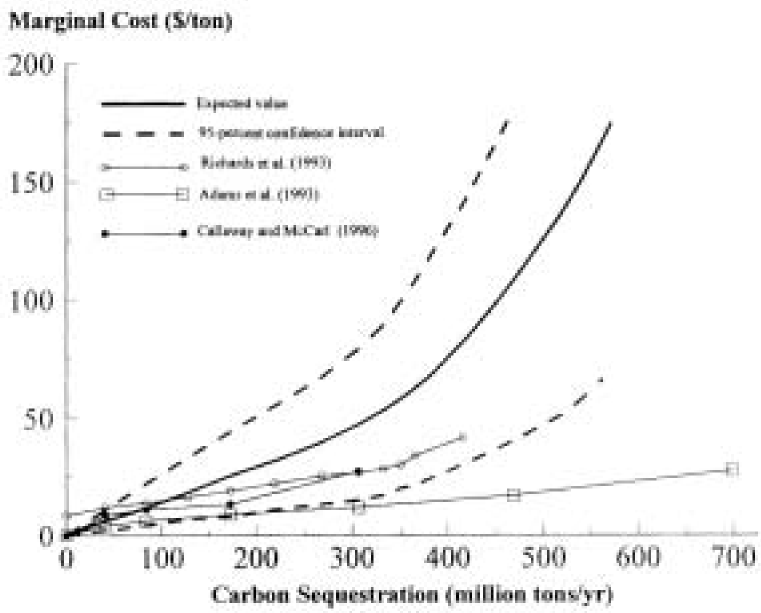

Figure 4.1 Alternative estimates of marginal cost of US carbon sequestration. (Source: Stavins, 1999)

5 Recent climate negotiations

The previous sections have shown that LULUCF activities represent a large and relatively cheap emission reduction alternative with a large variation in cost estimates. However, there are several challenges of including such activities and there are different interests involved under the climate negotiations. A main reason for the failure of COP-6 in The Hague was lack of agreement on an appropriate threshold for additional sinks under Article 3.4. A scheme for forest management carbon credits proposed by Japan, the USA and Canada offered little credits to most European countries, but massive gains could be available for the USA, Russia, Canada and Japan. The NGO community and the EU did not welcome this proposal, so the president of the COP-6, Jan Pronk, released a compromise plan. No agreement was reached at COP-6, but it was decided to resume the negotiations in June 2001, but postponed to July according to American wishes. However, the Kyoto Protocol's future seemed uncertain as the Bush Administration prior to the resumed climate negotiations made it clear that the USA had no intentions of ratifying the Kyoto Protocol, stating it was "fatally flawed". The challenge was therefore for the remaining countries to reach an agreement on the 'crunch' issues. With the USA 'out' of the game, it left the floor open for key countries such as Russia, Japan, Canada and Australia that were needed in order to ratify the Kyoto Protocol. An agreement was thought to be reached in Bonn after exhaustive negotiations, 'saving' the Kyoto

Protocol.[16] It was expected that COP-7 in Marrakesh was to focus on a more detailed level, but it became clear that some countries were determined to make the most of their negotiation position. However, it is now believed that all Parties (except the USA) could ratify the Kyoto Protocol within 2002.

With regards to LULUCF issues, the COP- agreed on several detailed issues. Under Article 3.3, Parties shall determine the area of deforestation using the same spatial assessment unit as is used for determining afforestation and reforestation, but not larger than 1 hectare. Debits from harvesting during the first commitment period (2008–2012) following afforestation and reforestation since 1990 shall not be greater than credits earned on that unit of land. Parties shall also report on how harvesting or forest disturbance that is followed by re-establishment is distinguished from deforestation.

It has been decided that 'forest management', 'cropland management', 'grazing land management' and 'revegetation' are the eligible LULUCF activities under Article 3.4.[17] The Parties themselves decide which of these activities are applied during the first commitment period, and the selection is fixed for the first commitment period. The Parties must also demonstrate that such activities have occurred since 1990 and are human-induced. Emissions by sources and removals by sinks from activities under Article 3.4 shall not be accounted for if these already are accounted for under Article 3.3. Further, net-net accounting should be applied (net emissions or removals over the commitment period less net removals in the base year, times five) for eligible activities under Article 3.4.

'Forest management' can be accounted up to the level of any possible Article 3.3 debits, but not greater than 9.0 megatons of C, times five, if the total anthropogenic GHG emissions by sources and removals by sinks in the managed forests since 1990 is equal to or larger than this Article 3.3 debit. For the first commitment period only, additions to and subtractions from the assigned amount of a party, resulting from 'forest management' under Article 3.4 after the application of the Article 3.3 debit compensation and resulting from forest management undertaken under Article 6, shall not exceed the value shown in Table A.1 in the Appendix, times five. Table A.1 shows that Canada, Japan and Russia, given their negotiation positions, were allowed large inclusions of sinks in their GHG emission accounts. After the negotiations in Bonn, Russia signaled that it was not satisfied with its allocated amount. Since Russia is vital for the ratification of the Kyoto Protocol, it's value in Table A.1 has nearly been doubled.

As for the CDM, the Parties have agreed that afforestation and reforestation are the only eligible LULUCF activities under Article 12. The total additions to and subtractions from the assigned amounts resulting from LULUCF activities under Article 12 shall not exceed 1% of base year emissions of that Party, times five. The treatment of LULUCF activities under the

[16] To see a complete version of the agreed text, see UNFCCC, 2001a.

[17] **'Forest management'** is defined as *"…a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner".*

'Cropland management' is defined as *"…the system of practices on land on which agricultural crops are grown and on land that is set aside or temporarily not being used for crop production."*

'Grazing land management' is defined as *"…the system of practices on land used for livestock production aimed at manipulating the amount and type of vegetation and livestock produced".*

'Revegetation' is defined as *"…a direct human-induced activity to increase the carbon stocks on sites through the establishment of vegetation that covers a minimum area of 0.05 hectares and does not meet the definitions of afforestation and reforestation"* (UNFCCC, 2001b).

CDM in future commitment periods shall be decided as part of the negotiations on the second commitment period (UNFCCC, 2001).

6 Some implications

Emissions from the combustion of fossil fuels constitute a lion's share of the annual anthropogenic CO_2 emissions. However, the LULUCF sector is also important as it represents both a source and sink in the carbon cycle. The interest for sinks as a mitigation option can be explained by the large potential and the relative low costs. The potential for carbon sequestration is large, but there are large variations in the estimates as factors such as land availability and the rate of carbon uptake complicate the calculations. There are also variations in the costs estimates, but financial analysis of LULUCF projects are not easily compared as no standard method of analysis has emerged and come into wide use.

Even before the resumed climate negotiations in Bonn and Marrakesh, it was clear that a Kyoto Protocol without US participation would result in a weakening of the emission reduction target. Analysis by for instance Hagem and Holtsmark (2001) shows that global emissions reductions (in % of Business as Usual emissions) will decrease from 5.5 to 0.9 without US participation.[18] Similarly, Greenpeace (2001) estimates that the allocation of sinks could weaken the Kyoto Protocol's abatement target by several percentage points. A climate agreement without the USA and with the inclusion of sinks is very likely to reduce the demand for emission permits and consequently lower permit prices. This could in turn reduce the incentives for using the CDM. This particular mechanism is characterized by a 2% share of the proceeds from CDM project activities is to cover administrative expenses and to assist developing countries that are particular vulnerable to climate change to meet adaptation costs (Kolshus et al., 2001). However, one could argue that since LULUCF projects are relatively inexpensive, they are still likely to be utilized under the CDM. The limit on the use of LULUCF under the CDM implies that the annual flow of certified emisisons reductions from afforestation and reforestation under Article 12 can't exceed 119.6 Mt CO_2-equivalents.[19]

Some attempts have been made to include carbon sequestration in economic modeling. Manne and Richels (1999) assume costless sink enhancement in Annex I countries in their analysis. A total of 151 Mt carbon each year is assumed, where the regions USA, OECDE, CANZ and EEFSU have respectively 50, 17, 50 and 34 million tons carbon.[20] They emphasize the difficulties in estimating the supply curves for sinks, as the quality of data is uneven. They find that the most reliable information is for Annex I countries, but it is still poor. MacCracken et al. (1999) also include costless sinks in Annex I countries, but to a larger extent than in the study by Manne and Richels (1999). MacCracken et al. include a total of 484 Mt carbon for the first budget period. The former Soviet Union, USA, Canada and Western Europe will have respectively 205, 104, 80 and 60 Mt carbon. Missfeldt and Haites (2001) analyze five scenarios covering different categories of eligible sinks. In all scenarios, at least some of the sinks have costs lower than the market price. The larger the eligible sinks, the lower compliance costs for Annex I countries. It also leads to less non-sink emission reductions in Annex I countries and reduces non-sink activities under the CDM. Future work in this area should focus on the implications of the climate negotiations for

[18] No inclusion of sinks in the analysis.

[19] Based on emission figures from the UNFCCC. An additional 58.5 Mt CO_2-equivalents could be allowed if the USA ratifies the Kyoto Protocol.

[20] OECDE = Western Europe, CANZ = Canada, Australia and New Zealand, EEFSU = Eastern Europe and the Former Soviet Union.

LULUCF activities, incorporating more country-specific data. Additionally, more work needs to be done in formulating regional cost curves for carbon sequestration.

Appendix

Table A.1 Threshold values for forest management under Article 3.4[21]

	Mt C/yr		Mt C/yr
Australia	0.00	Romania	1.10
Austria	0.63	Russian Federation[22]	17.63
Belarus		Slovakia	0.50
Belgium	0.03	Slovenia	0.36
Bulgaria	0.37	Spain	0.67
Canada	12.00	Sweden	0.58
Croatia		Switzerland	0.50
Czech Republic	0.32	Ukraine	1.11
Denmark	0.05	United Kingdom	0.37
Estonia	0.10	**Total**	**54.5**
Finland	0.16		
France	0.88		
Germany	1.24		
Greece	0.09		
Hungary	0.29		
Iceland	0.00		
Ireland	0.05		
Italy	0.18		
Japan	13.00		
Latvia	0.34		
Liechtenstein	0.01		
Lithuania	0.28		
Luxembourg	0.01		
Monaco	0.00		
Netherlands	0.01		
New Zealand	0.20		
Norway	0.40		
Poland	0.82		
Portugal	0.22		

[21] The values shown in Table A.1 in the Appendix was guided by the application of a 85% discount factor to account for the removals due to elevated carbon dioxide concentrations, indirect nitrogen deposition and the dynamic effects of age structure resulting from activities and practices before the reference year, and a 3% cap on forest management. Consideration was also given to national circumstances, including the degree of effort needed to meet Kyoto commitments and the forest management measures implemented (UNFCCC, 2001a,b).

[22] The Russian Federation does not recognise the numerical value in the above table. The COP has decided that the Russian Federation's value is 33 Mt C per year.

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