The role of forests in the global carbon cycle and in climate change policy

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Abstract
It is now widely accepted that increasing levels of greenhouse gases in the atmosphere are altering the Earth's climate system. Forests store and sequester vast amounts of carbon and are therefore a key component of the global carbon cycle. Understanding the nature of that contribution is vital to understanding current and future climate trends. The ability of forests to sequester atmospheric carbon led to their inclusion in the Kyoto Protocol as a means to mitigate greenhouse gas emissions. This paper discusses the role of forest in both the global carbon cycle and climate change policy. The various means by which forests can contribute to reduction of greenhouse gas emissions are also discussed.

Key words: Carbon sequestration, forest ecosystems, Kyoto Protocol

Introduction
The global carbon (C) cycle is a vital component of the Earth's system and consists of various reservoirs (stocks), and the dynamic transfer of carbon between them (fluxes). Both internal, i.e. photosynthesis and respiration, and external forces, i.e. environmental and human disturbance, can cause each of these reservoirs to act as sources and sinks of carbon at various temporal scales. The largest reservoirs of carbon include the oceans, fossil fuel reserves, the terrestrial environment and the atmosphere. Since the onset of the industrial revolution, the burning of fossil fuels has resulted in a large anthropogenic flux of C to the atmosphere. It is widely accepted that this shift in the C balance has largely contributed to the onset of global climate change.

Identification of options for mitigating atmospheric C concentrations and development of global climate policy measures has lead to the requirement to report forest related activities under the United Nations Framework Convention on Climate Change (UNFCCC) and subsequently to the Kyoto Protocol, should it enter into force.

Such reporting focuses on changes in carbon stocks following afforestation, reforestation and deforestation activities as well as forest management practices. Analysis of current climate change policy indicates a focus towards relatively cheap carbon storage through land use practices. However, available land for increasing carbon stocks through human induced, i.e. afforestation/reforestation activities, is a limited resource and subsequently so too is the potential of vegetation management as a mitigation measure. Alternatives which can provide long-term solutions are the

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utilisation of biomass through the direct substitution of fossil fuel intensive products and energy generation.

Global carbon cycle and climate change

From approximately 420,000 years ago until the onset of the industrial revolution (circa 1750) the Earth's climate system acted within a limited temperature range which was influenced by the relatively stable concentration of carbon dioxide (CO_2) and methane (CH_4) in the atmosphere (Petit et al. 1999). GHGs occur naturally in the atmosphere and absorb infrared radiation that the Earth re-radiates to space. This phenomenon maintains the Earth's temperature within the delicate range required to sustain life. However, atmospheric CO_2 levels are now nearly 100 ppm higher than at any time during the previous 420,000 years; concentrations of CO_2, CH_4 and N_2O in the atmosphere have increased by 31, 150 and 16% respectively since 1750[1] (IPCC 2001). Increases in these gases are primarily driven by human activities such as burning fossil fuel, agriculture and land use change. It is generally accepted that these increases are causing a shift in the Earth's radiative balance with consequent effects on the global climate system. The Intergovernmental Panel on Climate Change (IPCC) estimated that during the 20th century the global average surface temperature increased by about 0.6 °C, snow cover and ice extent decreased, sea level rose 0.1–0.2 m and rainfall increased in mid- and high latitudes These changes are likely to continue with the global average surface temperature expected to increase by 1.4–5.8 °C during 1990-2100. Further changes in sea level and weather patterns are expected (IPCC 2001).

Forests and the global carbon cycle

About half of the CO_2 emitted by fossil fuel combustion and tropical deforestation accumulates in the atmosphere. The rest is taken up by the oceans and terrestrial biosphere (Bousquet et al. 2000, Prentice et al. 2001). It is likely that forests account for a large portion of this biospheric uptake, since they are estimated to contain 77% of the carbon contained in vegetation and 39% of that stored in soils (Bolin et al. 2000). According to Prentice et al. (2001) (Table 1), during the 1980s the Earth's terrestrial ecosystems were a small net C sink (0.2 Pg C year^{-1}), the size of which increased during the 1990s to 1.4 Pg C year^{-1}.

Despite this overall increase in C uptake changes in land use (e.g. afforestation, reforestation, deforestation, forest management, fire and agriculture) resulted in the average annual C release of 2.0 (±0.8) Pg during the 1980s and 2.2 (±0.8) Pg during the 1990s (Table 1). Included in these estimates is the accumulation of C as a result of afforestation and reforestation. However, the combination of the average net terrestrial sink for the 1980s (0.2 Pg year^{-1}), with the average annual net source due to land-use change for the same period (2.0 Pg year^{-1}), suggests the existence of an additional sink, accounting for on average 2.2 Pg year^{-1} during the 1980s. During the 1990s this additional or residual sink increased to 3.6 Pg year^{-1}. This sink is calculated as

[1] Although the principal GHGs are CO_2, CH_4 and N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), play a significant but smaller role.

Table 1. *The global carbon budget (modified from Prentice et al. 2001) units are Pg year^{-1}).*

	1980s	*1990s*
Fossil fuel emissions	5.4 ± 0.3	6.4 ± 0.6
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.2
Oceanic uptake	-1.9 ± 0.5	-1.7 ± 0.5
Net terrestrial flux	-0.2 ± 0.7	-1.4 ± 0.7
Land-use change	2.0 ± 0.8 (1.2-1.8)	2.2 ± 0.6
Residual terrestrial flux	-2.2 ± 1.1	-3.6 (highly uncertain)

Source: Houghton (2003).

differences between other components in the global C budget and therefore if emissions due to land-use change were lower the residual sink would also be lower. Increased understanding and estimates of the known C sinks within the global budget may enable the magnitude of this residual sink to be reduced.

The forest carbon cycle

The C cycle in forests is characterised by a number of 'pools' and 'fluxes'. Pools are sites of C accumulation such as above- and below-ground biomass, litter on the forest floor and organic matter in the soil. Each pool contains a quantity of C that is referred to as the 'stock'. C is transferred between pools by many different processes including photosynthesis, respiration and decomposition. The amount of C transferred into or out of a stock is known as a 'flux'. The net flux of C between a forest and the atmosphere is determined by the balance between C uptake as a result of photosynthesis and C loss as a result of respiration by trees, both above- and below-ground, and decomposition of soil organic matter. Therefore if C uptake exceeds loss the forest is a 'sink' for atmospheric C. Conversely, if loss exceeds uptake the forest is a 'source' for atmospheric C. The forest C cycle extends beyond the forest boundaries when timber is removed from the forest during harvesting to be used in forest products, or biomass is removed to generate energy.

Forests as sinks and sources of carbon

In common with all green plants, trees capture CO_2 from the atmosphere through the process of photosynthesis. Initially sugar molecules are formed which then combine to produce cellulose, in addition to lignin in the case of woody plants. This growth and maintenance of living material has an energy cost as a result of which much of the CO_2 captured through photosynthesis is lost through respiration. The remaining C is added to the various components of the biomass C pool such as foliage, roots, stem and branch biomass creating a sink. Processes such as litterfall, litter decomposition and root turnover can add C to the soil pool.

The magnitude of a forest C sink can be affected by many factors such as changes in land use, soil type, forest management activities such as harvesting and fertilisation, changes in climate, nitrogen deposition, disease outbreaks and fire. In the initial establishment stages of the forest growth cycle a net carbon loss (particularly from soil) could be experienced as a result of site preparation. Following this initial growth phase a rapid uptake of carbon is experienced, which subsequently levels off as the stand reaches maturity. Finally the forest reaches the mature growth stage and the carbon is in steady state (neither a source or a sink) with accumulation associated with new growth balanced by mortality and disturbances (Matthews and Robertson 2002). Forest stands managed for commercial production experience periodic harvesting prior to maturity and generally have lower carbon stocks than old growth stands that are not harvested. The longer-term C stock and its status as a source or a sink depends on a balance between the impacts of harvesting and the rate of forest regeneration.

Afforestation generally results in the creation of a sink in that it increases C stocks on previously non-forested land. This is particularly the case if such land was previously under intensive management (e.g. arable crop production) and had depleted soil C stocks. However, drainage and afforestation of C rich soils such as peatlands may accelerate decomposition of soil C. Such losses may exceed C uptake by biomass (Hargreaves et al. 2003) at least in the initial stages of crop growth resulting in the land area being a C source.

International negotiations and the Kyoto Protocol

The first global attempt to deal with climate change was formalised with the United Nations Framework Convention on Climate Change (UNFCCC), agreed at the Earth Summit held in Rio de Janeiro in 1992. Its goal is *the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*. Ireland ratified the UNFCCC in 1994. As a Party it is required to develop, periodically update, publish and make available to the Conference of the Parties (COP) national inventories of emissions by sources and removals by sinks of GHGs and to promote the conservation and enhancement of sources and sinks of all GHGs. Forests represent one sector for which a national inventory is required.

In recognising concerns about climate change the UNFCCC provided an essential first step in the move towards tackling the problem. However, its objective could only be achieved with the establishment of legally binding targets to reduce GHG emissions. This was accomplished at the Third Conference of the Parties (COP3) in December 1997, when the Kyoto Protocol to the UNFCCC was negotiated. Its salient features are:

- 1990 is the base year against which all emission reduction commitments are calculated.
- Developed countries (so-called Annex I) committed to reduce annual GHG emissions to 5.2% below 1990 levels by the first commitment period of 2008-2012.

- The European Union committed to a reduction of 8%. The Protocol could only enter into force when ratified by at least 55% of Annex I countries, which cumulatively represent at least 55% of global GHG emissions.
- The Protocol made provision for the use of C sequestration by land use, land use change and forestry (LULUCF) as a means to offset GHG emissions.

In recognition of the differences in economic development between Member States, the European Union negotiated an agreement to share its reduction commitment. Under this agreement Ireland is committed to limiting its GHG emissions to 13% above 1990 levels by the first commitment period. The fact that emissions in 2002 were 29% above 1990 level (EPA 2004) underlines the magnitude of this challenge.

The use of sinks was a controversial aspect of the negotiations leading up to the Kyoto Protocol. On the one hand, sinks play a significant role in the global C cycle and are a relatively inexpensive means of potentially achieving emissions reductions. However an over dependence on sinks may undermine attempts to reduce fossil fuel emissions. This could reduce the incentive to develop the kinds of technologies that are needed to achieve further reductions and therefore increase the cost of reductions in the medium to long term. On the other hand, it could be argued that lower compliance costs in the first commitment period could make countries more willing to accept further reductions in subsequent commitment periods.

Although LULUCF activities were included in the Kyoto Protocol, the use of sinks is limited to specific activities. Article 3.3 refers to *...net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period ...* Article 3.4 refers to *...additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories ... A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided these activities have taken place since 1990.* Other articles that include provision for the use of forest sinks are Article 6 which deals the trading of emission reduction units and Article 12 – the clean development mechanism (CDM) which deals with emission-offset trading projects between developed (Annex I) and developing countries (non-Annex I).

While the Protocol established targets for the reduction of GHG emissions and identified mechanisms by which this could be done, it did not define rules and modalities for achieving such reductions. For instance the Protocol did not define reforestation so the term was open to interpretation. Reforestation has been variously defined as the restocking of forest sites after clearfelling or as the establishment of forest on land that had been forest at some time in the past but has been since converted to another land use. The choice of definition has important implications for the manner in which Parties may account for C stocks and stock changes in their forests. Final agreement on the way forward was achieved at COP7 in Marrakesh in November 2001 with the completion of the 'Marrakesh Accords' (MA).

The MA include a number of definitions. 'Forest' is a minimum area of land of 0.05-

1.0 ha with tree crown cover (or equivalent stocking level) of more than 10-30 per cent with trees having the potential to reach a minimum height of 2-5 metres at maturity *in situ*. 'Afforestation' is the direct human induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources. 'Reforestation' is the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human induced promotion of natural seed sources, on land that was forested but had been converted to non-forested land. For the first commitment period, reforestation activities will be limited to those lands that did not contain forest on 31 December 1989. 'Deforestation' is the direct human-induced conversion of land to non-forested land.

One of the most contentious aspects of the negotiations was the means by which Parties may apply Article 3.4 to forest management. In the absence of a clear methodology a limit was set to the amount of credits a Party may claim.

The MA place no cap on the amount of credit a Party (e.g. Ireland) may claim under Article 3.3. As stated above, forest management is one of the eligible activities under Article 3.4 and the amount of credit Ireland can claim has been capped at 50,000 t C year^{-1} during the first commitment period. Parties should account for changes in the following C pools: above-ground biomass, below-ground biomass, litter, dead wood, and soil organic matter. A Party may only choose not to account for a given pool providing it can show that the pool is not a C source.

As stated, the UNFCCC required that Parties develop GHG inventories. Guidance in the preparation of inventories is provided by the *Revised 1996 IPCC Guidelines for National Greenhouse Inventories* (Houghton 1997). However, the Kyoto Protocol has additional reporting requirements not covered in these Guidelines. For instance, the human induced activities under Articles 3.3 and 3.4 have particular requirements on issues such as, identification of areas, temporal and spatial boundaries, avoidance of double counting, inclusion of C pools and definitional differences in LULUCF activities to the UNFCCC. In order to assist this the IPCC has prepared a report on *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC 2004). This provides guidance to Parties as to best report sources and sinks in the LULUCF sector whilst making the most use of available resources and limiting uncertainty. While the report provides default data and methods, Parties are encouraged to apply nationally specific data where possible.

Alternatives to sequestration in the mitigation or reduction of GHG emissions

The Kyoto Protocol focuses on the use of forests as a C sink, mitigating increases in atmospheric CO_2 concentrations. It has been suggested that such a focus on cheap carbon storage may impede the development of bioenergy and poses no long-term solution for mitigation of GHG emissions (Schlamadinger et al. 2001) As previously established, forests have a finite capacity to remove CO_2 from the atmosphere. Under current conditions there may be potential to promote carbon sinks globally in the relative short term (next 100 years or more) but this will be limited by C stocks in vegetation and soils reaching equilibrium and the limited availability of land to create new C sinks. Various estimates have been suggested regarding the potential global C sink capacity generated through vegetation management. Green and Byrne (2004) report a range between 60 and 87 Gt C by 2050, or 14-20% of the projected fossil fuel emissions. If reducing GHG emissions is the objective, additional mitigation measures will need to be adopted.

Other than afforestation, carbon stocks in forest and forest products can be managed to influence C stocks and fluxes and therefore GHG emissions.

Forest management practices undertaken in existing forest in order to conserve and enhance existing C stocks can include forest regeneration, forest fertilisation, pest management, fire management, harvest quantity and timing, low impact harvesting (in terms of quantity and timing of removal in addition to site disturbance) and reducing forest degradation (Sampson et al. 2000). While these practices can lead to increased C storage it should be remembered that forest management techniques which aim to increase C stock needs to be compatible with the wider management objectives. For example, reduced thinning intensity may lead to greater C stock at stand level. However, this would not only have an impact upon the timber quality and range of assortments produced at the time of final felling, but would also, if applied on a large scale, affect the processing sector which utilises such thinnings.

If, however, the objective goes beyond that of providing sinks for emissions resulting from fossil fuels and becomes one of permanently offsetting emissions by replacing fossil fuel intensive products and technology then forest can possibly provide a much longer-term solution.

Global C cycle (Kirschbaum 2003) and climate policy modelling (Gielen et al. 2002) of use options for forest biomass indicate that longer term planning, i.e. 50 to 100 years, favours the use of biomass for energy. Global estimates of the potential for GHG emissions avoidance through bioenergy initiatives range from 2.0 to 6.2 Gt C year^{-1}, or 17% to 54% of projected emissions from fossil fuels.

Forest management residues including branches, tops and small diameter stems from thinning and harvest of commercial plantations are an under-utilised source of biomass, with a potential commercial value. Full utilization of thinnings, which may represent approximately 25% of the biomass produced, permits energy recovery from a resource that may otherwise decay on the forest floor. In both cases the carbon in the biomass is returned to atmosphere, but where bioenergy is produced, greenhouse mitigation benefit is obtained from displacement of fossil fuel emissions (IEA Bioenergy Task 25 1998, Matthews and Robertson 2002, Green and Byrne 2004).

Indirectly, biomass could also displace fossil fuels by providing substitute products for energy intensive materials such as steel, aluminium and plastics. Current estimates of the global C stock in the wood products range between 2 – 8 Gt C (Broadmeadow and Matthews 2003, Kirschbaum 2003, Green and Byrne 2004). Although increasing this pool through product substitution will be dependent on practical and technically feasible applications at a local to regional level, there is a large potential to replace a range of materials in domestic and industrial applications.

The potential carbon sink in wood products is estimated to be relatively small compared to the carbon sink in living vegetation and biomass, or compared to the potential of wood products to displace fossil fuel consumption. However, utilising the full range of options may enable such products to play a significant role.

Conclusions

Forests play a significant role in combating climate change. Release of the carbon contained in the world's forests would be sufficient to raise atmospheric CO_2 levels to more than 1000 ppm and lead to a rise in temperature of 5-8 °C (Broadmeadow and Matthews 2003). Conserving and protecting global forests, and therefore their C stocks, is an integral component of efforts to combat climate change. Current global climate change policy has an emphasis on increasing carbon stocks through land use change and forestry activities. It is important to recognise that forests are not capable of mitigating all greenhouse gas emissions. Although policy has identified a relatively cheap C sink potential with a short term implementation period, increasing C storage in existing forests is limited by land availability and the fact that such sinks reach equilibrium in the short term. With this focus on cheap carbon storage, current policy has the potential to impede the development of bioenergy and poses no long-term solution for GHG emissions (Schlamadinger et al. 2001). However, efforts taken now to enhance and expand forest areas will assist efforts to mitigate climate change in the short term to medium term, increasing the biomass resource and perhaps mitigation options available to future generations and when practiced in the context of sustainable forest management, bring multiple benefits to society.

References

Bolin, B., Sukumar, R., Ciais, P., Cramer, W., Jarvis, P., Kheshgi, H., Nobre, C., Semenov, S. and Steffen, S. 2000. *Global perspective*. In: Land Use, Land-Use Change, and Forestry, Eds. R. T. Watson, Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J. pp 23-52. Cambridge University Press, Cambridge, United Kingdom.

Bousquet, P., Peylin, P., Ciais P, Le Quéré, C., Freiedlingstein, P. and Tans, P. P. 2000. Regional changes in carbon dioxide fluxes of land and oceans since 1980. *Science* 290, 1342-1346.

EPA. 2004. *Ireland's Environment 2004*. Environmental Protection Agency, Wexford, Ireland.

Gielen, D.J., Fujino, J., Hashimoto, S. and Moriguchi, Y. 2002. Biomass strategies for climate policies? *Climate Policy* 2, 319-333.

Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J. and Callander, B.A. 1997. *Revised 1996 IPCC Guidelines for National Greenhouse Inventories*. IPCC/OECD/IEA, Paris, France.

Houghton, R.A. 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. *Tellus* B55(2): 378-390.

IEA Bioenergy Task 25. 1998. *The Role of Bioenergy in Greenhouse Gas Mitigation*. pp 4. Joanneum Research, Graz, Austria.

IPCC. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 881 pp.

IPCC. 2004. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Eds. J. Penman, Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miya, K., Ngara, T., Tanabe, K. and Wagner, F. IPCC National Greenhouse Gases Inventory Programme.

Kirschbaum, M. U. F. 2003. To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels. *Biomass and Bioenergy* 24, 297-310.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotylakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399, 429-436.

Prentice, I.C., Farquhar, G.D., Fasham, M.J.R., Goulden, M.L., Heimann, M., Jaramillo, V.J., Kheshgi, H.S., Le Quéré, C., Scholes, R.J. and Wallace, D.W.R. 2001 *The carbon cycle and atmospheric carbon dioxide.* In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Eds. J. T. Houghton, Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. pp 183-238. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Schlamadinger, B., Grubb, M., Azar, C., Bauen, A. and Berndes, G. 2001. Carbon sinks and the CDM: could a bioenergy linkage offer a constructive compromise? *Climate Policy* 1, 411-417.