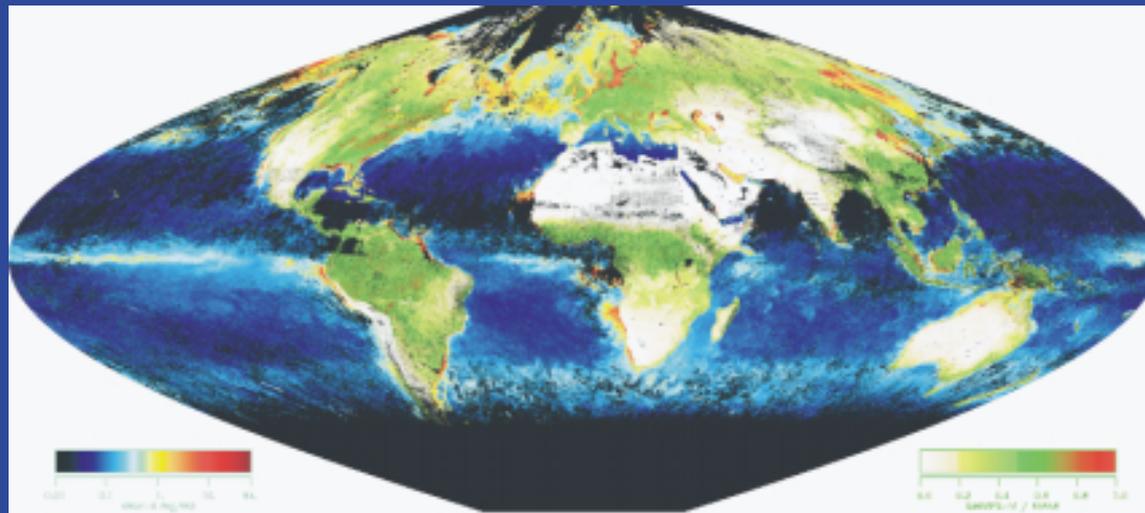


The role of land carbon sinks in mitigating global climate change



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Foreword



*Professor David Read FRS
Chair of working group*

Professor David Read, FRS Chair of the Royal Society working group on land carbon sinks

As evidence for the link between atmospheric greenhouse gases and climate change has increased, international efforts have focused on ways in which anthropogenic emissions of greenhouse gases, particularly carbon dioxide, can be reduced. However attempts to commit countries to reduce their emissions through ratification of the 1997 Kyoto Protocol have been hampered by disagreement about the extent to which land carbon sinks should be considered in meeting these reduction commitments.

In this report we have examined some of the scientific issues underpinning land carbon sinks that have been of concern to policy makers. Throughout we have drawn extensively on the work of the Intergovernmental Panel on Climate Change, the world's most reliable source of information on climate change. It is clear to us that the potential to enhance the land carbon sink through changes in land management practices is finite both in size and duration. Further, the amount of carbon that can be sequestered is small in relation to the ever-increasing global emissions of greenhouse gases. It is of concern to us that measurement techniques currently available are not sufficiently accurate to permit the reliable monitoring of any land carbon sinks that may be designated as part of international agreements such as the Kyoto Protocol. We conclude that projects designed to enhance land carbon sinks should not be allowed to divert financial and political resources away from long-term solutions to the problem of reducing the concentration of greenhouse gases in the atmosphere by reduction in the use of fossil fuels.

I thank the other members of the working group who have worked extremely hard to complete this report in such a short period of time. We owe a particular debt of gratitude to Rachel Quinn (Royal Society, Secretariat) who has provided support and inspiration throughout the project.



*Sir Robert May AC PRS
President, Royal Society*

Sir Robert May, President

There is increasing consensus on the science underpinning predictions of global climate change. Our current knowledge suggests that temperatures will continue to rise, with average global surface temperature projected to increase by between 1.4 and 5.8 °C above 1990 levels by 2100. This increase will be accompanied by rising sea levels, more intense precipitation events in some countries, increased risk of drought in others, and adverse effects on agriculture, health and water resources. It is now evident that human activities are already contributing adversely to this global climate change.

The Royal Society has been an active participant in the debate about the science of climate change and has provided advice on energy policy measures that would ensure that energy supply can meet global demand whilst being economically affordable and sustainable in terms of its global and local environmental impact^{1,2,3}. This report on land carbon sinks is a further contribution to the global discussion on climate change policy and we will continue to facilitate dialogue between scientists and policy makers in this area by convening a major meeting later this year to discuss the current state of knowledge of the science underpinning climate change and what further work must be done in this vital area to ensure that the gaps in our knowledge are reduced.

I am grateful to Professor David Read, the other members of the working group and the secretariat for the very considerable effort that has gone into this report. I commend this report to policy makers so that future policy at a global and local level may be based on sound scientific knowledge. It will also be of interest to anyone who is concerned about the issue of climate change and the steps that must be taken to mitigate its effects.

Cover picture: An image of the fraction of photosynthetically-active radiation absorbed by land and the concentration of chlorophyll in the sea for June 1998. This image has been produced using data from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS). Such data are used to estimate the size and strength of the land carbon sink. SeaWiFS data are provided by NASA's Goddard Space Flight Center, Maryland, USA and processed at the Space Applications Institute of the European Commission Joint Research Centre. We thank Frederic Melin, Nadine Gobron, Bernard Pinty, Ruggero Tacchi and Michel M. Verstraete for providing this image.

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Preparation of this report

This report has been endorsed by the Council of the Royal Society. It has been prepared by the Royal Society working group on land carbon sinks. The members of the working group were:

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Summary

- As evidence for the link between atmospheric greenhouse gases and climate change has increased, international efforts have focused on ways in which anthropogenic emissions of greenhouse gases, particularly carbon dioxide (CO₂), can be reduced. Knowledge that CO₂ is stored within and exchanged between the atmosphere and vegetation and soils has led to the suggestion that soils and vegetation could be managed to increase their uptake and storage of CO₂, and thus become 'land carbon sinks'. Under the terms of the 1997 Kyoto Protocol, signatories can meet part of their obligations to reduce greenhouse gas emissions from fossil fuel consumption by increasing these land carbon sinks. However there have been concerns about the permanence of land carbon sinks and the accuracy with which they can be quantified and verified. This report focuses on the scientific issues underpinning land carbon sinks, particularly in the context of their inclusion in the Kyoto Protocol.
- Terrestrial vegetation and soils are currently absorbing approximately 40% of global CO₂ emissions from human activities. Changes in agricultural and forestry practices and slowing deforestation could increase this, potentially achieving a maximum of 25% of the reductions in CO₂ that are projected to be required globally by 2050 to avoid large increases in temperature. This would however require considerable political will and there is little potential for increasing the land carbon sink thereafter.
- Given that land use changes can make a contribution to reducing greenhouse gases, at least in the short term, we recommend that methods used in the production of forest and agricultural crops should be modified to reflect their potential role in increasing the global land carbon sink. Reform of the European Union's Common Agricultural Policy provides one opportunity to achieve this on agricultural land in Europe. Steps should be taken to ensure that these management changes, along with efforts to reduce deforestation, are compatible with other goals for sustainable development.
- The impact of many management practices on emissions of other trace greenhouse gases such as methane and nitrous oxide is poorly understood and is a priority area for research. Until it is possible to calculate full trace gas inventories we recommend that land carbon sink projects likely to result in significant emissions of trace gases (e.g. the large-scale use of nitrogen-based fertilisers) be avoided.
- There is considerable uncertainty associated with the estimates derived using the techniques that will be required to monitor, quantify and verify land carbon sinks established under the Kyoto Protocol. There is an urgent need to increase the accuracy of these techniques before land carbon sinks are utilised to any significant extent.
- The permanence of the land carbon sink is uncertain with climate models projecting that future warming could cause its magnitude to increase less rapidly, saturate or even be converted to a source of CO₂ later this century. A greater understanding of the interactions between vegetation, soils and climate that underpin these models is urgently required to improve the accuracy of projections of both future climate change and the permanence of the land carbon sink.
- **There is still considerable uncertainty in the scientific understanding of the causes, magnitude and permanence of the land carbon sink. However, our current knowledge indicates that the potential to enhance the land carbon sink through changes in land management practices is finite in size and duration. The amount of CO₂ that can be sequestered in these sinks is small in comparison to the ever-increasing global emissions of greenhouse gases. Projects designed to enhance land carbon sinks must therefore not be allowed to divert financial and political resources away from the restructuring of energy generation and use (e.g. increased use of renewable energy), technological innovation (e.g. increased fuel efficiency, sequestration of CO₂ at source) and technology transfer to less developed countries. It is these that must provide the ultimate solution to the problem of reducing the concentration of greenhouse gases in the atmosphere.**

1 Introduction

As evidence for the link between atmospheric greenhouse gases (GHGs) and climate change has increased, international efforts have focused on ways in which anthropogenic emissions of greenhouse gases, particularly carbon dioxide (CO₂), can be reduced. The 1997 Kyoto Protocol committed the developed nations to reducing their aggregate emissions of greenhouse gases by 5.2% below their emissions in 1990 by 2008-2012. Attempts to pave the way for the ratification of this Protocol have been hampered by disagreement about the extent to which carbon sinks, in the form of agreed land use, land-use change and forestry activities, could be used to meet emission reduction commitments. The Royal Society has previously highlighted the need for action to mitigate the threat of climate change^{1,2,3}. This report evaluates the scientific issues relating to the role of land carbon sinks and seeks to inform the ongoing international debate about their possible use for the mitigation of climate change.

Since 1800 the concentrations of CO₂ in the Earth's atmosphere have increased from around 280 parts per million (ppm) (by volume) to a current value close to 370 ppm. Analyses of CO₂ concentrations in bubbles of air trapped in Antarctic and Arctic ice sheets coupled, since 1957, with direct measurements of CO₂ concentrations in the atmosphere have shown that build up of this greenhouse gas has become progressively more rapid in recent times. The increase coincides with the industrialisation of human society and there is good evidence to show that it is caused by emissions of CO₂ arising from human activities⁴. The most important contributor to the recent increase in the global stock of atmospheric CO₂ is the burning of fossil fuels (e.g. in power stations) and from the deforestation of land, particularly in the tropics⁴. Carbon dioxide, along with a number of other gases present at lower concentrations (so called 'trace gases' such as methane (CH₄) and nitrous oxide (N₂O)), traps thermal radiation emitted from the Earth's surface and so gives rise to warming of the Earth's atmosphere. This warming (known as the 'greenhouse effect'), enhanced by the accumulation of these gases particularly over the 19th and 20th centuries has led to a global mean increase in surface temperature of about 0.6 °C⁴. Projections based upon the trajectories of the ongoing CO₂ emissions have indicated that during the next 100 years the global mean surface temperature is likely to increase by between 1.4 and 5.8 °C⁴.

Palaeoclimatic data indicate that changes of temperature of this magnitude have occurred previously, but the rapidity with which the change is taking place appears to be without precedent during at least the past 10,000 years. In addition, major changes in the distribution and intensity of rainfall, cloudiness and humidity are expected to occur⁴. While such changes cause direct and indirect problems for human societies the rapidity with which they

are occurring also poses a threat to the equilibrium of natural ecosystems.

Increasing recognition of the scale of the problems posed by global climate change has led scientists and policy makers alike to consider approaches to mitigate the warming trend. Recognising that increasing atmospheric CO₂ concentration is likely to be the main driver of climate change⁴, emphasis has been placed upon the possibilities of decreasing emissions of CO₂ and other GHGs on the one hand, or increasing the removal of GHGs from the atmosphere on the other. Clearly, since the use of fossil fuels and various forms of land use and land cover change, particularly deforestation, have been identified as the major anthropogenic sources of CO₂, consideration must be given to restriction of both these activities. Energy generation and use, which currently contributes about 75% of global anthropogenic CO₂ emissions⁴, lies at the heart of economic development, and policies designed to achieve reductions in this area have met with considerable resistance. Consequently, attention has been diverted to the possibility that naturally occurring 'carbon sinks' for CO₂ on land and in the oceans might be manipulated to provide enhanced uptake of this GHG into biological systems. The most important mechanism for this uptake in both terrestrial and aquatic environments is the process of photosynthesis in which CO₂ is converted first to sugars and then to structural plant polymers such as cellulose and lignin. Since virtually all such carbon is eventually returned to the atmosphere in the process of respiration, fixation of this kind is essentially a temporary solution, but the period of carbon sequestration (i.e. uptake and storage) can be maximised by selection of crops and management regimes that provide the longest possible retention times. For this reason forests, in which much of the fixed carbon is retained for decades in tree wood and for centuries in soil organic matter, are natural candidates for possible enhancements of land carbon sinks.

The possibility that forests and agricultural land might be manipulated to mitigate CO₂ emissions was recognised in the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. The Kyoto Protocol in 1997 endorsed the notion not only that governments should employ policies to enhance the land carbon sink capacities of their territories but also that such mitigation could be set against requirements for reductions in emissions from fossil fuel consumption. (See Annex 1.1 for an overview of international agreements on climate change). While recognising that the oceans constitute a potential sink for CO₂, the Kyoto Protocol emphasised terrestrial (land) rather than oceanic sinks largely because issues of ownership and sovereignty are very difficult to resolve in the latter case, but also because land carbon

sinks are more easily manipulated and may also have added value through promoting clean development at community level in less developed countries. Proposals for increasing ocean uptake of CO₂ by fertilisation with

nutrients including iron are extremely speculative, and recent modelling and observations indicate that carbon fixed in this way is rapidly recycled⁵. For these reasons this report considers only land carbon sinks.

2 Global carbon stocks and sinks on land

In this section the current state of knowledge regarding the land carbon cycle is summarised, utilising the latest figures for carbon stocks and fluxes. There is a great deal of uncertainty surrounding estimates of carbon stocks and fluxes often arising from methodological differences in measurements. These are discussed in more detail in Section 5 of this report. This uncertainty means that, throughout this report, it is only possible to provide only a range of values (denoted by \pm) or an approximate estimate rather than to give a single figure. In the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report^{4,6}, which we have referenced extensively in this report, the range is based on \pm one standard deviation. In other cases the method used to generate the range of estimates is described in the references that we have cited.

2.1 Carbon stocks

Globally, vegetation contains 550 ± 100 petagrams⁷ of carbon (PgC), soils contain a much larger amount, 1750 ± 250 PgC. Together, soils and vegetation contain about three times as much carbon as the atmosphere (which contains 760 PgC)⁶. Most of the vegetation carbon is in forests, especially in the tropics, while most of the soil carbon occurs at northern high and temperate latitudes in both forests and grasslands. The ratio of soil carbon to vegetation carbon is about 5 in boreal forests, but less than 1 in most tropical forests (this is illustrated in Figure 1).

2.2 Annual exchange of carbon with the atmosphere

Carbon is actively cycled between the land and the atmosphere⁸ such that the entire atmospheric CO_2 is exchanged with a timescale of about 10 years. Carbon is removed from the atmosphere by plants during photosynthesis (approximately $120 \text{ PgC per year (y}^{-1}\text{)}$). It is returned to the atmosphere by plant respiration (approximately 60 PgC y^{-1}), the breakdown of organic matter by decomposers in the soil (approximately 55 PgC y^{-1}), and combustion by natural and human-induced fires (approximately 4 PgC y^{-1})⁶. Fluxes of a similar magnitude also occur between the oceans and the atmosphere.

2.3 Current perturbation of the carbon cycle

Small imbalances between these fluxes can lead to net uptake or release of carbon from the land of magnitude comparable to current fossil fuel emissions (estimated at $6.4 \pm 0.4 \text{ PgC y}^{-1}$)⁶. Carbon budget constraints (i.e. a consideration of the various sources and sinks of carbon) suggest that the average net uptake of carbon by

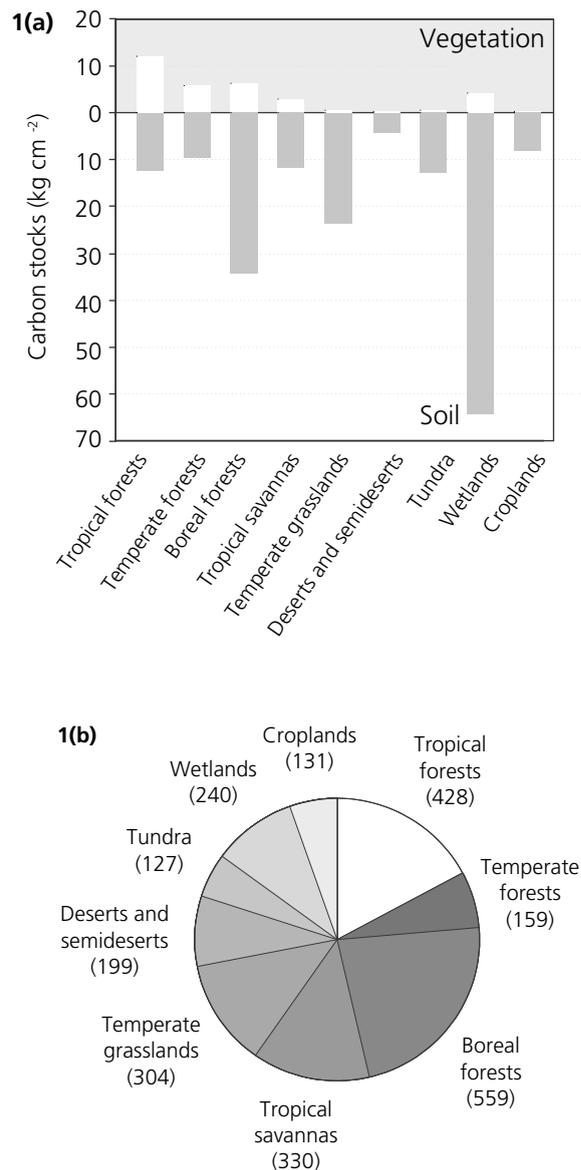


Figure 1. Carbon stocks in soil and vegetation: a) Mass of carbon stored in soils and vegetation per metre square for different terrestrial systems (kg C m^{-2}); b) Relative percentage of carbon in different terrestrial systems, calculated by multiplying the carbon stock by the total area of the terrestrial system. Numbers in brackets are an estimate of the total global carbon stock in PgC.

vegetation and soil was $1.5 \pm 0.7 \text{ PgC y}^{-1}$ through the 1990s. Although vegetation and soil are absorbing around 3.2 PgC y^{-1} , approximately 1.7 PgC y^{-1} is being lost through deforestation, hence the net uptake of around 1.5 PgC y^{-1} (see Section 3 and Figure 2 for more information about how these figures are derived). This net uptake of carbon represents about 23% of the emissions from fossil fuels. The global land carbon sink is therefore a major component of the contemporary carbon budget.

Unfortunately, it is difficult to quantify the size and location of the land carbon sink partly because it displays significant year-to-year variation. These annual variations

are driven primarily by climate anomalies such as those associated with El Niño events or major volcanic eruptions.

3 The current land carbon sink

3.1 Factors affecting the land carbon balance

The net exchange of carbon between the land biosphere and the atmosphere is not in equilibrium (i.e. the fluxes of carbon from the land to the atmosphere are not equal to those from the atmosphere to the land). Several factors contribute to this 'disequilibrium' including direct human influence (e.g. deforestation and reforestation), indirect human influence (e.g. CO₂ and nitrogen fertilisation) and natural factors (e.g. climate variability). These are described below.

Land-use and land cover change is the major direct human cause of disequilibrium, and encompasses deforestation and forest degradation, changes in agricultural practices, reforestation and afforestation, and changes in ecosystem management and fire management. Currently, the most important factors are the rapid clearing of tropical forests (a large source of CO₂ to the atmosphere), the abandonment of agricultural land and the increase in forest land in northern temperate regions (a major land carbon sink for CO₂). The rapid pace of tropical deforestation is currently by far the most important cause of CO₂ release arising from land use and land cover change. Carbon dioxide is released through both the direct burning of vegetation, and the subsequent decomposition of biomass (the organic matter associated with living organisms) and soil organic matter. However there is considerable uncertainty as to the magnitude of this carbon flux, and while the pace of tropical deforestation may have slowed slightly in the 1990s, a complete assessment for the 1990s is not yet available.

In contrast to the CO₂ released from deforestation, some is being absorbed by the regrowth of forests on abandoned agricultural land, particularly in temperate regions, resulting in a net land carbon sink. In temperate regions, the net effect of land use and land cover change alone (i.e. excluding CO₂ and nitrogen fertilisation responses) has been estimated to represent a sink of 0.8 PgC y⁻¹ in the 1990s, with carbon uptake in re-growing forests balanced by the release of CO₂ from the decomposition of wood. The change in forest age structure is a more important factor than expansion in total forest area. The IPCC has estimated that this net land cover change resulted in an overall flux of 1.7±0.8 PgC y⁻¹ from the land to the atmosphere in the 1980s⁹. As indicated above, the majority of this results from tropical deforestation.

CO₂ fertilisation. Increasing the concentration of CO₂ in the atmosphere causes an increase in the rate of photosynthesis of plants, with consequences for the amount of carbon stored in plant biomass, litter and soil organic carbon. Much of this increased photosynthesis is eventually balanced by increased release of CO₂ from plant respiration and microbial decomposition of litter and soil carbon, but until this eventual equilibrium is reached the ecosystem is a net sink for carbon (i.e.

photosynthesis removes more CO₂ from the atmosphere than is returned). The increase in photosynthetic rates is much larger in plants with a photosynthetic mechanism known as C₃ (all trees, nearly all plants of cold climates, and most temperate agricultural crops including wheat and rice) than in plants with a C₄ mechanism (tropical and many temperate grasses, some desert shrubs and some important tropical crops including maize, sorghum and sugar cane), which concentrates CO₂ within the plant cells and is therefore less affected by rising atmospheric CO₂ concentrations. Results from over 100 recent experiments in which young trees have been exposed to double the current atmospheric CO₂ concentration for periods of up to 10 years have demonstrated an increase in tree growth of 10–70%^{10,11}. An important uncertainty is the extent to which this CO₂ fertilisation effect saturates in the longer term. Increased atmospheric CO₂ concentration also increases the water use efficiency of plants and this may enhance the growing season of plants in seasonally dry regions.

Nitrogen(N) fertilisation. Human activity has increased the availability of nitrogen in the terrestrial biosphere through the release of nitrogen oxides during fossil fuel and biomass combustion and the release of ammonia through fertiliser use, animal farming and industry¹². Plant productivity is frequently limited by a lack of available nitrogen and there is evidence that increased nitrogen deposition is enhancing forest growth in temperate regions¹³. Tropical and boreal regions are less affected, being further from nitrogen sources and, in the case of tropical regions, being constrained by lack of other nutrients such as phosphorus and calcium.

Climate variability and climate change. Rates of photosynthesis, plant respiration, decomposition, and fire frequency are affected by climatic factors such as sunshine, temperature and rainfall. Inter-annual variations in climate cause most of the inter-annual variation in the strength of the land carbon sink. In particular, El Niño events are associated with high temperatures and droughts in many tropical regions and, if they increase in frequency, may possibly turn tropical regions into carbon sources.

In the future, human-induced climate change is likely to have a significant effect on land carbon sinks. Satellite sensor data¹⁴ and phenological¹⁵ observations indicate that higher temperatures have already led to longer growing seasons in the boreal zone and temperate Europe, with the potential to increase the land carbon sink. However, measurements of CO₂ fluxes suggest that at high latitudes the enhanced carbon sink in biomass is being offset by release of soil carbon caused by thawing of permafrost¹⁶. In tropical regions changes in patterns of rainfall are likely to be much more important in determining the distribution of carbon sources and sinks.

However, these are much more difficult than changes in temperature to predict from climate models. We discuss climate modelling and the future of the land carbon sink in more detail in Section 6.

3.2 Evidence for the existing carbon sink

The results of a number of different types of studies have provided evidence for a land carbon sink. These studies are reviewed below and include direct measurements of tree size, atmospheric measurements of CO₂ concentrations and computer models. Each of these methods provides evidence for the existence of a land carbon sink although they vary in their estimate of the size of the sink. In Figure 2 we combine estimates of the land carbon sink with estimates of the carbon fluxes resulting from fossil fuel production and land use/land cover change to give a schematic overview of the carbon cycle in the 1990s. In Section 5 we describe the methods used to quantify the size of land carbon sinks in more detail and address some of the uncertainties associated with them.

Carbon exists in two stable forms (¹²C and ¹³C isotopes) in the atmosphere. The burning of fossil fuels and the exchange of carbon between the atmosphere, land and oceans produces differences in the patterns of relative abundance of the two isotopes that can be used to attribute the source of fluxes in CO₂. A recent comparison of results from eight such inversion studies using differing sets of sampling stations, years and calculation method suggests that, in the early 1990s, the annual net carbon flux from the atmosphere to the land was 1.3±0.8 PgC y⁻¹ in the northern temperate and boreal regions and 0.2±1.2 PgC y⁻¹ in the tropics⁶. These net fluxes from atmosphere to land exist despite the release of approximately 1.7 PgC y⁻¹ from land use change (predominately as a result of deforestation in the tropics). This implies a large additional land carbon sink in both tropical and non-tropical regions, most likely caused by CO₂ fertilisation and in temperate and boreal regions, by N fertilisation and perhaps by lengthening of the growing season.

These studies of global patterns of atmospheric CO₂ therefore produce an estimate of the overall land carbon sink of approximately 3.2 PgC y⁻¹ indicating that, about 40% of current human carbon dioxide emissions (fossil fuels, cement manufacture and tropical deforestation) are being absorbed by terrestrial vegetation. If the release of 1.7 PgC y⁻¹ from land use change is taken into account, this implies a net uptake by vegetation and soils of approximately 1.5 PgC y⁻¹.

Inventories of forest biomass in temperate and boreal regions suggest that there has been a substantial increase in the carbon stock in northern forest biomass, of the order of 0.8 PgC y⁻¹¹⁷. This provides further independent evidence of a land carbon sink. Extensive inventories of forest biomass do not exist in most tropical forest regions, but a compilation of results from forest plots in old-growth tropical forests suggests that these forests are increasing in biomass, resulting

in a land carbon sink of 0.85±0.25 PgC y⁻¹¹⁸. The estimates from inventories do not include changes in soil and litter carbon. When forest productivity and biomass is increasing, it is likely that soil and litter carbon reserves are also increasing, in total by up to a similar amount as the reserves in living biomass. This suggests a total sink (excluding land use/land cover change) of 1.4±0.8 PgC y⁻¹ in tropical forests, and 1.35±0.45 PgC y⁻¹ in temperate forests. Other biomes such as savannahs and grasslands may also contribute to the land carbon sink. In total, results from biomass inventories are broadly consistent with results from consideration of global atmospheric CO₂ distribution (see Figure 2). This indicates that without the terrestrial and oceanic sinks, the atmospheric concentration of CO₂ would be increased by 4.9 PgC y⁻¹. The uncertainty associated with the measurements underpinning these estimates is discussed in Section 5.

Computer models of the terrestrial carbon cycle also suggest the presence of significant carbon sinks in boreal, temperate and tropical forests. In recent simulations, CO₂ fertilisation was estimated to account for a net carbon sink of 2.0±1.1 PgC y⁻¹, and N fertilisation for a sink of 0.8±0.6 PgC y⁻¹. Experimental data suggest that there is likely to be considerable synergism between the CO₂ and N fertilisation effects¹⁹.

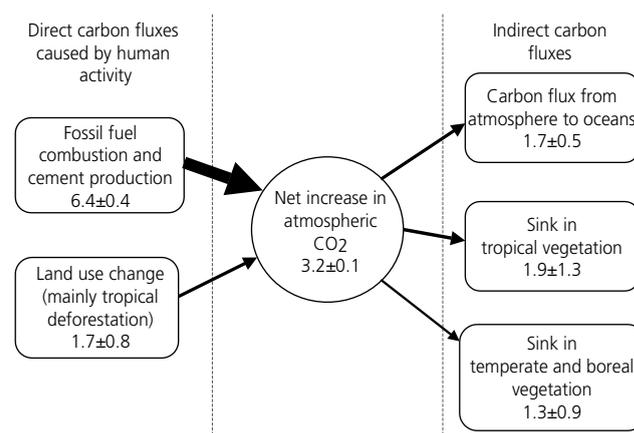


Figure 2. An estimate of the human-induced carbon cycle in the 1990s in PgC y⁻¹. The carbon flows from fossil fuel emissions to the atmosphere, and the net carbon flows to ocean and land, are known with relatively high confidence²⁰. The partitioning of the net land sink between human activity and 'natural' carbon sinks is less certain, as is the partition between tropical and temperate regions. The carbon fluxes to land or oceans can be discriminated by comparing global atmospheric fluctuations of oxygen and CO₂ concentrations. The ocean carbon sink does not affect atmospheric oxygen concentrations, whereas the land carbon sink does⁶. The estimate of the net increase in atmospheric CO₂ concentration has a low margin of error as it is a simple direct measurement of atmospheric CO₂ concentration and not determined from the surrounding values. The carbon source from land use change is modelled from Food and Agriculture Organisation data²¹. The net sinks in tropical and temperate vegetation are derived from inversion studies, and are consistent with results from forest inventories²² (see Section 5 for more details of these methods).

4 Scope for human enhancement of land carbon sinks

4.1 Global estimates of the potential for direct human management of the land carbon sink

Policy and land use changes that enhance the existing 3.2 PgC land carbon sink or appreciably decrease the annual 1.7 PgC emission from land use change (i.e. by reducing deforestation) could mitigate the increase in atmospheric CO₂ from anthropogenic sources (Figure 2). The potential role of land carbon sinks is recognised in the Kyoto Protocol, which allows countries to take into account emissions and sinks resulting from direct human-induced forestry activities (specifically reforestation, afforestation and deforestation) carried out since 1990 in meeting their emissions targets. There is also provision for additional human-induced activities (related to agriculture, land use change and forestry) undertaken since 1990 to be considered but it has not yet been decided how they will be incorporated into a country's emissions targets (see Annex 1.1 for more details). In this section we consider some of the options available for human intervention, together with estimates of what these approaches can be expected to achieve.

Forestry and agricultural activities can reduce atmospheric concentrations of CO₂ by increasing carbon storage (e.g. through planting forests), decreasing emissions at source (e.g. by reducing deforestation) and by modifying agricultural practices to increase the quantity of carbon stored in soil organic matter. In addition, surplus agricultural land could be used for the production of biofuel crops such as willow in short rotation coppice or perennial grasses. These crops, also known as energy crops, can be used to substitute for fossil fuels and thus to decrease emissions at source. This is a benefit that continues indefinitely, in contrast to the increase of managed land sinks that may be limited by factors such as attainment of soil carbon equilibrium.

Attempts to estimate the global potential for increasing land carbon sinks through management are complicated by complex socio-economic and political factors such as the land available for forestation or the rate of uptake of different management options. This leads to considerable uncertainty in estimates²³. However, based on a number of studies, the IPCC has estimated the maximum potential mitigation that could be achieved through changes in agricultural management, forestry practice and through slowing deforestation²³. They estimate that a total of between 1.53 and 2.47 PgC y⁻¹ could be sequestered (i.e. taken up and stored) between 2000 and 2050. Taking the mid-point of this range, suggests that approximately 100 PgC could potentially be captured between 2000 and 2050. We consider this to be very much a maximum estimate of what could be achieved and recognise that it would be very difficult to realise without considerable political will throughout the world.

Figure 3 shows how this mitigation potential is divided between the different agricultural and forestry practices. Changes in agricultural management could sequester 33% of the 100 PgC, with a similar amount being sequestered by a combination of slowing deforestation and allowing the regeneration of trees on previously deforested land. Forestation could account for 28% of the global potential while agroforestry, which combines both agriculture and forestry practices, is projected to play a much smaller role (about 7% of the mitigation potential). More than 50% of the potential for mitigation is in the tropical regions, primarily in the less developed world. Under the Kyoto Protocol the developed world may have the potential to offset some of its emissions through carbon sink projects in the less developed world, using the 'Clean Development Mechanism' (see Annex 1.1 for further details).

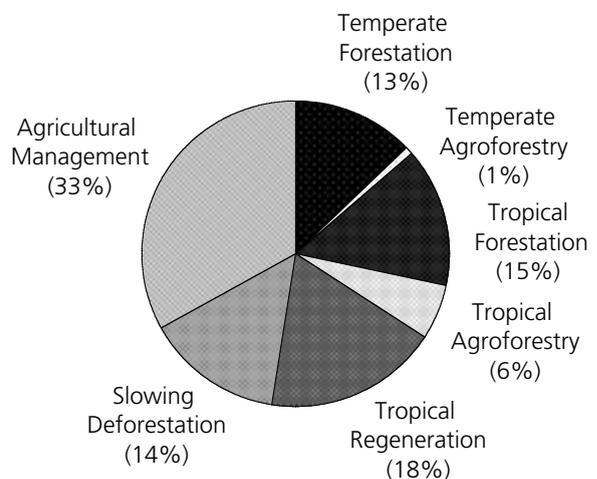


Figure 3. The potential of various land management activities to mitigate global emissions of CO₂ by increasing the carbon sink potential of forestry and agriculture or reducing emissions at source (reducing deforestation). Estimates provided by the IPCC suggest that a maximum mitigation of 100 PgC could be achieved between 2000 and 2050 (see Section 4.1 for further details of how these estimates have been derived).

4.2 Role of forestry in protecting and enhancing the land carbon sink

Forests contain about 45% of the global stock of carbon (Figure 1) so preserving and enhancing this land carbon sink, in both trees and soil, will be the main focus of management strategies aimed at maximising land carbon sinks. These include avoiding deforestation, improved management of timber production forests to reduce carbon loss and restoration of previously degraded forest lands. The latter can be achieved by allowing natural regeneration, actively restoring the land to native forest

or by conversion to plantations. The IPCC estimate that, globally, changes in forestry activities (including agroforestry) could sequester between 54 and 79 PgC by 2050²³, almost 70% of the total potential (Figure 3).

Tropical deforestation is responsible for the majority of the anthropogenic emissions of CO₂ resulting from changes in land use and land cover. Many of the current pilot carbon mitigation projects (so called 'carbon offset' projects) in the tropics aim to reduce rates of tropical deforestation, and thus reduce emissions at source. One of the largest pilot carbon-offset projects is the Noel Kempff Climate Action Project in Bolivia which generates carbon offsets by permanently halting logging in the park expansion area, and protecting these lands from future deforestation. More details of this project can be found in Annex 2.1. Forest based carbon-offset projects such as these can potentially provide many other benefits such as biodiversity conservation, resource conservation, local climate stability and watershed protection. However, there is also a need to ensure they are consistent with other sustainability criteria so that local communities of forest-users do not lose traditional land and rights of forest use as a result of these schemes and to ensure that the deforestation is not displaced elsewhere (i.e. 'negative leakage'). Some of the problems inherent in verifying and monitoring these types of projects are addressed in Section 5 and Annex 1.2.

Current forest management, particularly in the temperate zone, is oriented towards increasing timber production (and thus stocks of carbon within the trees) but takes little account of the often larger carbon stocks in forest soils. For example, the increasing use of heavy machinery in forestry operations is disruptive of the soil and can stimulate loss of carbon through enhanced oxidation of soil organic matter. This can be particularly damaging to the soil carbon stock. Some of the ways in which a new form of forest management, or 'Carbon Forestry', could be achieved are outlined in Annex 2.2. Indirect nitrogen fertilisation is partly responsible for the current land carbon sink in temperate regions so raising fertility could be the most effective way of rapidly increasing the land carbon sink capacity¹³. However, increasing nitrogen availability by sowing nitrogen-fixing leguminous plants or by applications of artificial fertilisers may increase the emissions of trace greenhouse gases such as N₂O, which has a global warming potential over 100 years of around 310 times that of CO₂. Assessments of the effects of management operations on forest carbon sinks are in their infancy and it is not possible at the present time to provide quantitative estimates of the likely consequences of particular management operations. We highlight this as an area requiring future research. In addition to timber production, forests currently provide services to communities in terms of the conservation of wildlife, recreation and amenity. **We recommend that the protection of the existing carbon stocks and enhancement of the land carbon sink capacity be added to the list of services that forests should provide.**

4.3 Role of agriculture in mitigating climate change

Soils that are currently used for agriculture normally contain considerably less organic carbon than an equivalent soil under natural vegetation, such as grassland or forest, because the clearance of natural vegetation leads to a decrease in organic carbon inputs and the accelerated decomposition of organic carbon already in soil. The IPCC estimate that, globally, between 22 and 44 PgC could be sequestered through changes in agricultural methods between 2000 and 2050²³. This excludes the mitigation impact of biofuel crops. In Europe, scenario studies have been employed to predict the potential of changes to agricultural land for carbon mitigation^{24,25} and we outline the results of these studies in Annex 2.3. One scenario in particular combines woodland regeneration and biofuel crops on the 10% of arable land in the EU that is currently under set-aside, with changes in management to the remaining arable land. It is estimated that this could lead to a reduction in GHG emissions equivalent to the EU commitment under the Kyoto Protocol²⁵. Much of this mitigation (about 30%) does not come from increased land carbon sinks in agricultural soils or new forests but from the replacement of fossil fuels with biofuels. For the UK, the opportunities for mitigation from agricultural land are proportionately less than for Europe as a whole because the land area is small compared to the UK's GHG emissions. A scenario study for the UK, which also included some estimation of impacts on the trace GHGs N₂O and CH₄, suggested a total mitigation from agricultural changes plus woodland regeneration and biofuel crops on set-aside land of 0.006–0.008 PgC y⁻¹²⁴. This is equivalent to 4–6% of UK 1990 CO₂ emissions, with about two thirds of the mitigation effect coming from carbon sequestration in trees and soil and the remainder from fossil fuel replacement by biofuels.

Biofuel crops such as perennial grasses (e.g. *Miscanthus*) or short rotation coppice of willow have the potential to provide long-term savings of GHG emissions through their replacement of fossil fuels. In addition, they contribute to the finite increase in the soil carbon sink. Most biofuel crops are perennials and will lead to an increase in the amount of organic carbon stored in the soils in which they are grown, assuming that they are grown on former arable land. This is analogous to increased soil carbon under new forests and arises from a combination of increased carbon input to soil compared to arable crops and decreased decomposition rate because of the elimination of tillage. The fossil fuel offset potential of conversion to biofuels is not included in the global estimates in Figure 3 but it has been suggested that biofuels could offset between 20 and 73 PgC between 2000 and 2050²³, although the cultivation of biofuels may compete with other forestry and agricultural management options in some areas. In the UK, the Royal Commission on Environmental Pollution recently gave one energy scenario for the UK in which

10-15% of the agricultural land of the UK was given over to the cultivation of biofuels²⁶. New schemes to promote the planting of biofuel crops have recently been introduced by the UK government²⁷ as part of their plan to promote renewable energy sources.

These estimates suggest that land management changes can make a significant contribution to reducing atmospheric concentrations of CO₂, at least in the short term. Where land use changes include the cultivation of biofuels there is a potential to deliver CO₂ reductions for an indefinite period through the replacement of fossil fuels by this renewable energy source. **In the light of the proposed reform of the Common Agricultural Policy, we recommend that consideration be given to strategies that encourage the carbon mitigation potential of agricultural land throughout the EU.**

4.4 Putting managed land carbon sinks in perspective

The Kyoto Protocol commits developed nations to reducing their aggregate emissions by 5.2% from 1990

levels by 2008-2012. However, it is clear that much larger reductions will be needed in the future to reduce the risk of major alterations in climate²⁶. The mitigation potential of managed land carbon sinks considered above should therefore be put in the context of the emissions reductions that are likely to be required by 2050. To restrict the rise in global mean surface temperatures to the lower end of the range predicted by the IPCC, the world's population will need to follow one of the lower scenarios of GHG emissions outlined by the IPCC rather than one of the higher ones⁴. We estimate that this will require emissions reductions of about 1000 PgC by 2100, of which about 400 PgC is needed by 2050²⁸. Even if the necessary social, economic and political factors were put in place (and we think that this is unlikely), the mitigation effect of land carbon sinks would amount to 100 PgC by 2050. Changes in forestry and agricultural practices and slowing deforestation can therefore only achieve a maximum of 25% of the required reductions by 2050, with little further potential thereafter (as soil carbon levels equilibrate for example). In Section 7 we briefly discuss the role of land carbon sinks in the context of other mitigation options.

5 Quantifying direct enhancement of the land carbon sink

5.1 Requirements of the Kyoto Protocol

Under the terms of the Kyoto Protocol developed countries will be able to use carbon sequestered on land to offset their commitment to reduce fossil fuel emissions. Furthermore, it was agreed at Kyoto that offsets could be claimed only for land carbon sinks that had been created directly since 1990 (e.g. through afforestation), rather than those created indirectly by changes in the atmosphere (e.g. CO₂ fertilisation) or by previous changes in land cover or land use. The extent to which managed land carbon sinks and other flexibility mechanisms (Annex 1.1) will be allowed to replace domestic emissions reductions is controversial and still under discussion. If land carbon sinks are to be included in the Kyoto Protocol scientific methods are required to quantify, monitor and verify areas of land where changes in land cover, and the associated amount of carbon stored per unit area (carbon density), have been implemented. In addition, there will be a need to assess additionality (i.e. to predict whether the measured changes in carbon density would have occurred without management) and to address concerns about leakage (i.e. when activities to increase carbon storage in one place inadvertently promote activities that either decrease or increase carbon storage elsewhere). These issues are described in more detail in Annex 1.2.

5.2 Methods of quantifying and monitoring land carbon sinks.

In this section we discuss the quantification, monitoring and verification of land carbon sinks and the implications of our conclusions for the inclusion of land carbon sinks under the Kyoto Protocol. We also highlight the large uncertainty associated with these methods and, as a consequence, priority areas for future research.

Measurement of carbon dioxide in the atmosphere

At continental scales, the distribution of 'natural' land and oceanic carbon sinks can be estimated by combining data from monitoring networks around the globe (which provide regular weekly measurements of CO₂, oxygen, carbon (C) isotopes and trace gas concentrations) using mathematical techniques, air mass transport models and knowledge of fossil fuel CO₂ emissions. Recent applications of these studies indicate substantial inter-annual variation in North American and Eurasian land carbon sinks²⁹. The land carbon sink at regional scales can be estimated from continuous measurements of CO₂ concentrations in the planetary boundary layer (PBL), making use of tall towers used for TV transmission, together with air mass transport information. Measurements of relative concentrations of carbon monoxide (CO) and CO₂ in the air can be used to separate out the fossil fuel source from the overall CO₂ exchange

because the CO is almost exclusively a product of anthropogenic combustion processes. Instruments on aircraft and balloons can be used to make sequential measurements of the CO₂ concentrations in the air entering and leaving the PBL. With knowledge of the fossil fuel emissions in the region, the land carbon sink attributable to the vegetation can be inferred.

Measurement of ground-based stocks and sinks of carbon

Determination of the size of carbon stocks and sinks on the ground is achieved by a combination of direct measurement of vegetation and soil at local scales with extrapolation, using Geographical Information Systems (GIS) and/or remote-sensing techniques, to regional and continental scales³⁰. Direct measurements, as applied for example to a forest, involve the assessment over a specified period (five years in the case of the Kyoto commitment period) of changes in the carbon stock of stands of trees using standard forest inventory methods. Accurate estimates of stem volume are obtained from which total tree biomass and carbon content are derived using conversion factors. Similar approaches can be applied to other land cover types, for example to fields in agricultural systems to give 'patch scale' estimates of their carbon sinks. Carbon stocks in soils can also be determined using standard sampling techniques. Because of large spatial variability in biomass and soil carbon contents, very large numbers of samples are required to achieve the precision to be able to measure changes in stock over a period as short as five years.

An alternative approach for deriving soil data, which avoids the need for spatially intensive soil sampling is to use well-validated models of soil/plant carbon dynamics to calculate either the current soil carbon stock or the alteration in soil carbon caused by land-use change. Carbon stock estimates for soil and vegetation can then be 'scaled-up' using a suitable mix of data derived from GIS and/or remote sensing. Alternatively values for baseline stocks could be established by sampling but rely on well-validated models to calculate changes; this avoids the need for repeated local scale sampling that will often be impracticable because of the time consuming nature of the task.

The sizes of carbon sink produced by vegetation at the patch scale can be measured using the micrometeorological technique of eddy covariance. Instruments placed on towers at about twice the height of the vegetation give the net carbon balance continuously every half-hour. Worldwide, over 70 such flux measurement sites are operating at the moment but many more are needed due to the great spatial variability of the carbon balance³¹. This technique provides information with high temporal resolution about the

relationship between net carbon flux and climatic variables at a locality. The measurements can be scaled-up to larger areas using GIS and/or remotely sensed data of the climate, area and land cover. The same approach can be used with the equipment mounted on low-flying aircraft to measure transects of sinks and sources across a landscape, but this technique is less accurate.

Remote sensing (also known as Earth Observation) offers a consistent and readily updated source of information for the quantification, monitoring and verification of above-ground carbon sinks from local to global scales³². In recent years, many satellite/sensor combinations have been developed that record with spatial resolutions of < 1 m to several km, over time periods from minutes to weeks and over a range of off-vertical angles. The resultant data have been used (i) to locate an area on the land surface³⁰; (ii) identify what is present (e.g. land covers of forest, grass, cereal crops); (iii) estimate how much is present (e.g. vegetation amounts such as standing biomass, leaf area index³³) and (iv) to parameterise and drive ecosystem simulation models for the spatial estimation of net primary productivity (NPP) and photosynthetic rate³⁴. Data acquired from these approaches can be used to estimate the strength of the land carbon sink. These stages are usually undertaken sequentially but there is a decrease in technical development and accuracy at each stage. For instance, it is possible to locate and identify land cover classes required for quantification of land cover transitions (e.g. forest to grass), for input to Global Climate Models (see Section 6), with consistently high accuracy. However, the accuracy of estimated vegetation state (e.g. standing biomass) or modelled vegetation process (e.g. NPP) is difficult to determine for the large areas often used in the estimation of land carbon sinks. Refinement of methods to enable improved accuracy of these determinations is a priority for future research.

There are five major challenges to the use of remotely sensed data for the quantification of land carbon sinks: (i) cloud cover restricts the availability of images recorded in optical wavelengths, (ii) remotely sensed data cannot be used to estimate soil organic matter or land use, (iii) it is not possible to estimate the standing stock of mature forests using the visible to middle infrared wavelengths recorded by the majority of Earth Observation satellites, (iv) the ability to utilise data varying in spatial extent from small plots to regions is still rudimentary and (v) some commercial remotely sensed data are very costly. Recent developments have strengthened the remote sensing of carbon sinks, notably advances in the field of geoinformatics (e.g. GIS, Global Positioning Systems, geostatistics, geocomputation)³⁵, an increased availability of synthetic aperture radar data (that are independent of cloud cover), an enhanced ability to estimate a greater number of vegetation state and rate variables, developments in data access, storage and handling and

the launch of new satellites (e.g. Terra in 2000, Envisat in 2001)³⁶.

New methods under development involve the regular (weekly, monthly) assimilation of data into climate system models. Addition of local estimates of photosynthetic activity to remotely sensed estimates of atmospheric CO₂ in the atmosphere (e.g. using SeaWiFS on SeaStar satellite) provides a potentially useful advance. It is hoped that this technique will enable accurate measurements of CO₂ from space and thus allow monitoring of local scale sources and sinks of CO₂ on a daily basis.

Uncertainties associated with methods used for quantifying land carbon sinks

Despite some of the recent advances described above, the uncertainties associated with estimates derived from all of these methods are considerable. A further fundamental problem is that the magnitude of this uncertainty is unknown. In practical terms the most serious uncertainties are those arising from estimates at local scale, because it is upon these estimates that validation of land carbon sink strengths at regional and global scales are based.

Clearly, accurate measurement techniques are vital if we are to monitor the carbon balance of the land surface and thus to quantify and verify land carbon sinks under the Kyoto Protocol. However, uncertainties associated with all measurement techniques at the present time are large enough to prevent the estimation of land carbon sink strength with a level of accuracy sufficient for the reliable monitoring of Kyoto commitments. Scientific research should focus on increasing the accuracy of carbon sink determination; in particular the development of methods for the reliable estimates of the size of land carbon sinks at the local scale. These in turn will place scaling up activities on a more reliable footing. **Because of the uncertainties outlined above, where a value is being put on the size of a land carbon sink, as in the context of the Kyoto Protocol, we recommend that the minimum sink or stock magnitude in the uncertainty range should be used to avoid over-valuation of carbon sequestration.**

5.3 Measuring trace greenhouse gases

Land-use change, land cover change and management practices designed to increase carbon sequestration may either impact positively or negatively on emissions of CH₄ and N₂O. Thus, land-fill burial of organic waste for carbon sequestration may release CH₄. A change of land use from rough grazing to forest will not only result in increased carbon storage but will also reduce CH₄ emissions because of the removal of the ruminants (e.g. cattle). In turn, these additional benefits must be offset against the possible negative effect of increased N₂O production at felling or as a result of fertilisation. Even

the most straight-forward options to increase carbon sequestration, such as low tillage agriculture, may have the unwanted side effect of increasing N₂O emissions²⁴. The calculation of full trace gas inventories of even the most simple land-use/land cover transition or change in agricultural management is complex and the science in this area is still poorly known. We identify this as a major priority area for future research. **Until it is possible to calculate full trace gas inventories, we recommend that carbon offset projects that are likely to result in significant emissions of trace gases (e.g. the large-scale use of nitrogen-based fertilisers) should be avoided.**

5.4 Wider issues

Effects of land use/land cover change on factors other than carbon sequestration have to be considered at local, regional and global scales. These include effects on biodiversity, water resources, soil and water quality, climate (mediated through changes in albedo and hydrology), markets, employment and poverty. Furthermore, any actions must be compatible with goals of sustainable development in a world with an increasing population. Some of these issues are illustrated by the examples in Appendix 2. These problems are complex and are beyond the scope of this report, but they suggest that caution needs to be exercised before employing land use change as a single-focus solution.

6 The future land carbon sink and its permanence

6.1 Modelling the land carbon sink

Model projections of the future land carbon sink are necessary for assessing the likely impacts of future scenarios of climate change and atmospheric CO₂. These predictions are critical for designing mitigation strategies and require a good understanding of the underpinning processes. Until recently, the processes of projecting increases in atmospheric CO₂ and changes in climate were considered quite separate endeavours. This is at odds with observations of the Earth system that show CO₂ and climate varying together on timescales ranging from the glacial-interglacial cycles (tens of thousands of years) to the El Niño Southern Oscillation (that occur within decades). The land carbon cycle is especially sensitive to climate, with patterns of rainfall largely determining the distribution of vegetation across the globe, and temperatures affecting the rate of physiological processes such as photosynthesis and respiration. An array of models have been developed in an attempt to predict how the land carbon sink will respond to the combined effects of increasing atmospheric CO₂ and climate change.

Terrestrial carbon cycle models contain explicit representation of the fluxes of CO₂ between land and atmosphere, arising from photosynthesis, plant respiration and the breakdown of organic matter in the soil. Dynamic Global Vegetation Models (DGVMs) are terrestrial carbon cycle models that also simulate changes in the distribution of natural vegetation³⁷. DGVMs are normally used in a stand-alone mode in which they are driven by prescribed changes in atmospheric CO₂ and climate. However, DGVMs are now beginning to be included as an integral part of General Circulation Models (GCMs) of the climate system.

GCMs include detailed representations of physical processes (e.g. convection, radiation), but typically have non-interactive models of the land-surface and atmospheric CO₂. Coupled climate-carbon cycle models are a new generation of GCMs in which atmospheric CO₂ is treated as an internal model variable, that is updated based on emissions and uptake is modelled by the land and oceans. Coupled climate-carbon cycle models therefore include both DGVMs and ocean carbon cycle models as interactive components.

Below we summarise the results from recent modelling studies.

6.2 Results from dynamic global vegetation models

Figure 4 shows results taken from an inter-comparison of six DGVMs³⁷. Each model was used to estimate changes in land carbon uptake over the 21st century as a result of a

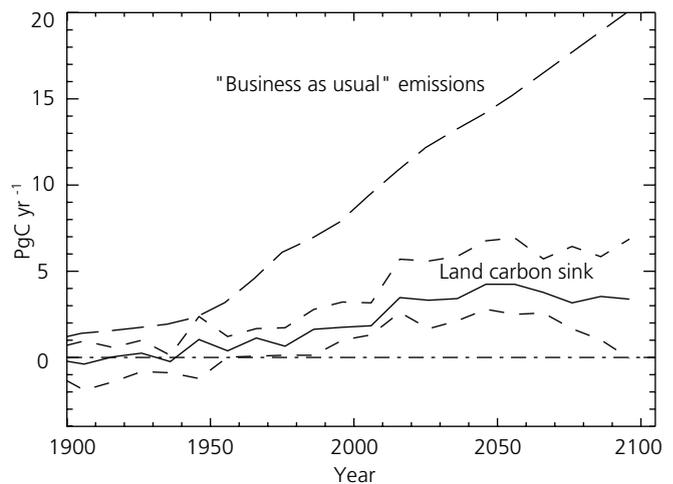


Figure 4. Comparison of modelled carbon uptake by the terrestrial biosphere with assumed CO₂ emissions for the IS92a ('business-as-usual') scenario that represents a central estimate of emissions based on assumptions about economic and population growth³⁸. The lower continuous line shows the land carbon sink every 10 years, as the mean of six DGVM simulations, each subjected to the same changes in CO₂ and climate³⁷. The dotted lines show the upper and lower model projections for each decade illustrating uncertainty in the response of the land carbon sink to these changes. Additional uncertainties are associated with the emissions scenario (which may result in CO₂ emissions in the range 5–30 PgC y⁻¹ by 2100), and the climate model response to a given increase in greenhouse gas concentrations⁴.

specified 'business as usual' increase in atmospheric CO₂³⁸ and an associated climate change (as projected by the 2nd generation Hadley Centre climate model³⁹). In these simulations the terrestrial biosphere is considered pristine, with no land cover changes through human activities.

Although the quantitative predictions from the DGVMs differ (indicating significant uncertainty) the models agree on the following important qualitative aspects:

- The sink capacity of vegetation is currently being stimulated by atmospheric CO₂ increase which enhances photosynthesis.
- Climate warming reduces the sink capacity by enhancing soil and plant respiration.
- The fraction of emissions taken up by the land decreases during the second half of the 21st century, as the rate of soil respiration increases more strongly with temperature than the concurrent CO₂ fertilisation of photosynthesis.
- Although the land carbon sink is important in the context of current emissions, it will rapidly become negligible with respect to future emissions unless additional measures (beyond the reductions set out in

the Kyoto Protocol) are taken to reduce the growth in emissions below this central 'business as usual' projection.

6.3 Results from coupled climate-carbon cycle models

Until recently, GCM predictions of future climate change routinely used standard scenarios of atmospheric CO₂ increase⁴⁰. These scenarios neglected the possible effects of climate change on land and carbon uptake⁴¹. Therefore, climate predictions carried out using these CO₂ scenarios implicitly assume that the carbon cycle and climate system can be decoupled.

Recent work with the first GCMs to include the carbon cycle interactively indicates that by 2100 enhanced effluxes of carbon from the soil (in particular) to the atmosphere cause warming by as much as 1.5 °C globally (and 2.5 °C over land), further reducing the ability of the land biosphere to absorb emissions^{42,43}. The magnitude of this effect varies between the models, ranging from a slight reduction⁴³, to a climate-driven conversion of the global land carbon sink to a source by 2050⁴². If confirmed, the latter result would seriously undermine the use of land carbon sinks as a long-term alternative to cutting emissions. However, the uncertainties in these early climate-carbon cycle predictions are significant and as yet unquantified.

6.4 Common conclusions and key uncertainties from climate modelling

Both the uncoupled DGVMs and the coupled climate-carbon cycle models suggest that the global land carbon sink may saturate sometime during this century. On the whole these models project an increase in land carbon storage as a result of rising CO₂ but a reduction as a result of the associated climate warming (which enhances soil

and plant respiration). To date global models have focused on natural vegetation, but these basic responses are also expected to apply to managed land carbon sinks. The balance between the competing effects of CO₂ increase and climate change is predicted to change as the response of photosynthesis to CO₂ fertilisation slows with increasing CO₂, but respiration is presumed to increase with temperature. As a result the current global land carbon sink is projected to increase less and less rapidly, with some models even predicting its conversion to a source. The wide ranges of projections result from basic differences in the ways that key processes are modelled, and these differences themselves highlight gaps in understanding of basic processes. For example the usual assumption, based on much previous research, that the rate of soil respiration increases significantly with temperature has recently been challenged by new observational evidence⁴⁴. Similarly, there are uncertainties associated with the impact of nitrogen deposition on forests^{12,45}, and the overall impact of land management practices on climate⁴⁶. In all cases these uncertainties project onto predictions of climate change as well as carbon uptake.

Recognition of these critical uncertainties is important as it identifies priority areas for future research. A major uncertainty is the temperature response of soil and plant respiration, both in terms of the temperature coefficient and also in terms of its potential for acclimation to slowly changing temperatures. A further challenge is how to incorporate human impacts, including management, on both land use and land cover, for the past, present and future. Increased use of coupled GCMs and DGVMs will also require more explicit treatment of trace greenhouse gas fluxes, as they have the potential to change climate and feedback onto the carbon cycle. **Research into the interactions between vegetation, soils and climate that underpin these climate models is urgently required to improve the accuracy of projections of both future climate change and the permanence of the land carbon sink.**

7 Conclusions

It is estimated that terrestrial vegetation and soils are absorbing around 40% of current human CO₂ emissions. The magnitude of this 'natural' land carbon sink (which is currently being stimulated by recovery from natural disturbance and fertilisation from atmospheric CO₂ and nitrogen) is estimated at approximately 3.2±1.6 PgC y⁻¹ although there is considerable uncertainty associated with this estimate. Using figures published by the IPCC, we estimate that changes in agricultural and forestry practices and slowing deforestation could enhance this by a maximum of 2 PgC y⁻¹ by the year 2050. Managed land carbon sinks could therefore potentially meet 25% of the reductions in CO₂ projected to be required globally by 2050 to avoid large increases in temperature. However this would require considerable political will and there is little potential for increasing the land carbon sink thereafter.

Given that land use changes can make a contribution to reducing GHGs, at least in the short term, we recommend that methods used in the production of forest and agricultural crops should be modified to reflect their potential role in increasing the global land carbon sink. In addition to timber production, forests currently provide services to communities in terms the conservation of wildlife, recreation and amenity. We recommend that the protection and enhancement of the existing carbon stocks and land carbon sink capacity be added to the list of services that forests should provide. Reform of the European Union's Common Agricultural Policy provides an opportunity to enhance the sink carbon potential of agricultural land in Europe. Biofuel or energy crops such as short rotation willow coppice can reduce CO₂ at source by replacing fossil fuels (for example in power stations). The incorporation of biofuel crops into managed land carbon sinks can therefore further increase their mitigation potential. Steps should be taken to ensure that changes in the production of forest and agricultural crops, along with efforts to reduce deforestation, are compatible with other goals for sustainable development although we recognise that this is complex.

The net contribution to mitigation from land carbon sinks may be reduced if the proposed land use changes increase the releases of other greenhouse gases such as CH₄ and N₂O, which have a greater warming potential than CO₂. The calculation of full trace gas inventories of even the most simple land-use/land cover transition or change in agricultural management is complex and the science in this area is still poorly known. This is a major priority area for future research. Until it is possible to calculate full trace gas inventories, we recommend that land carbon sink projects that are likely to result in significant emissions of trace gases (e.g. the large-scale use of nitrogen-based fertilisers) should be avoided.

Accurate measurement techniques are vital to monitor the carbon balance of the land surface and thus for the quantification and verification of land carbon sinks under the Kyoto Protocol. However, the uncertainties associated with all current measurement techniques mean that they do not appear to be accurate enough for this task. We recommend that scientific research focus on increasing the accuracy of carbon sink determination; particularly in developing methods for the reliable estimates of the size of land carbon sinks at the local scale. These in turn permit improvements in our ability to scale up such measurements and to quantify and monitor larger areas of land carbon sinks. Due to the uncertainties inherent in existing methods, where a value is being put on the size of a land carbon sink (e.g. in context of the Kyoto Protocol) we recommend that the minimum sink or stock magnitude in the uncertainty range should be used to avoid over-valuation of carbon sequestration.

The permanence of the land carbon sink is uncertain with climate models projecting that future warming could cause its magnitude to increase less rapidly, saturate or even be converted to a source of CO₂ in the latter half of this century. These projections have implications for the effectiveness of land carbon sinks created through changes in land management. However there is still considerable uncertainty inherent in these projections. Research into the interactions between vegetation, soils and climate that underpin these climate models is urgently required to improve the accuracy of projections of both future climate change and the permanence of the land carbon sink. There is a particular need to understand the response of soil and plant respiration to increases in temperature. The future development of climate models should focus on the incorporation of human impacts on both land use and land cover (including management) and the more explicit treatment of fluxes of trace greenhouse gases. In the future the relative contribution of managed land carbon sinks to climate change mitigation will decrease as global fossil fuel emissions continue to rise. This is because of both the limited land area that can realistically be managed as a land carbon sink and because the total magnitude of fossil fuel emissions will soon exceed the maximum extra carbon storage capacity of the terrestrial biosphere.

Action to combat climate change should be one of the highest priorities for the UK and all national governments. Land carbon sink enhancement projects (perhaps through an international carbon credit scheme) could enable some countries to meet their short-term emissions reduction goals, such as the 5% emission reductions proposed under the Kyoto Protocol. However the short-term reductions in emissions set out in Kyoto targets alone will not make a significant impact on future CO₂ concentrations. The value of the Kyoto targets lies in

providing an immediate incentive for restructuring energy use (e.g. increased use of renewable energy), technological innovation (e.g. direct physical and chemical sequestration of CO₂ at source and its long-term disposal in suitable geological formations) and technology transfer that will have to be the major component of the long-term solution. Some of these have been addressed in recent reports from the Royal Society^{1,2}.

The primary benefit of land carbon sinks is that they can be effective immediately (i.e. they do not require technological innovation) and can provide a financial incentive for the preservation and sustainable use of forests and agricultural land. However, due to their limited capacity and duration,

land carbon sinks cannot be a major component of the long-term, 21st century, solution to increasing levels of CO₂ in the atmosphere. The main means of achieving this has to be cuts in emissions of carbon dioxide (and other greenhouse gases) primarily through energy saving measures and a major replacement of fossil fuels by renewable or nuclear energy. Land carbon sinks must be seen as additional to these measures but can play a role in the next few decades while long-term measures are developed and implemented. Projects designed to enhance land carbon sinks must not divert financial and political resources away from long-term solutions to the problem of reducing the concentration of greenhouse gases in the atmosphere.

8 References & Notes

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Annex 1 Land carbon sinks and the international climate change process

1.1 Overview of the Framework Convention on Climate Change and the Kyoto Protocol

The *United Nations Framework Convention on Climate Change* (UNFCCC) was opened for signatures in 1992. The UNFCCC aims to stabilise GHGs at a level that avoids dangerous anthropogenic interference with the climate system. With respect to land carbon sinks, signatories (Parties to the Convention) are called upon to promote programmes that mitigate climate change by addressing sources of anthropogenic emissions greenhouse gases and sinks of GHGs. To date 186 countries have signed the UNFCCC.

The *Kyoto Protocol* was adopted in 1997 at the third Conference of the Parties (COP3) to the UNFCCC. The Protocol aims to reduce emissions from developed countries (listed in Annex 1 of the Protocol and therefore referred to as Annex 1 countries) by at least 5% below 1990 levels in the commitment period of 2008-2012 (Article 3.1 of the Protocol). To this end individual countries or groups of countries (such as the European Union) have been assigned emissions targets. The EU's target is a reduction of 8% below 1990 levels. Some countries have been permitted to increase their emissions to allow economic growth.

Articles 3.3 and 3.4 of the Kyoto Protocol make provision for net changes in GHG emissions by sources and removal by land carbon sinks resulting from direct human-induced land use change and forestry activities to be considered in relation to a country's reduction target. Under Article 3.3 this is limited to afforestation, reforestation and deforestation since 1990. Article 3.4 provides the potential for additional human-induced activities (agricultural, land use change and forestry) undertaken since 1990 to be considered but allows subsequent COPs to decide exactly how these should be incorporated into a country's emissions targets. Under both Articles, these direct human-induced activities must be reported in a transparent and verifiable manner.

Countries may also meet their emissions targets through other flexibility mechanisms such as Joint Implementation (JI) and the Clean Development Mechanism (CDM). Under JI (Article 6), emissions reduction units can be exchanged between Annex 1 (developed countries). These units can be gained from projects, including those aimed at enhancing land carbon sinks, providing it can be demonstrated that the mitigation is additional to any that would otherwise occur. Similarly, the CDM (Article 12) allows Annex 1 countries to gain credit for emission reduction projects in developing countries (known as non-Annex 1 countries). Such projects must demonstrate real, measurable and long-term benefits related to the

mitigation of climate change and as with the JI they must show that the mitigation is additional to any that would otherwise occur. Projects that aim to enhance the land carbon sink are not specifically mentioned under Article 12.

Finally, the Kyoto Protocol also commits Annex 1 countries to promote sustainable development in meeting their emissions targets (Article 2). Specifically they are directed to take measures to protect and enhance sinks of GHGs through sustainable agriculture and forestry practices.

The links to the full text of both the UNFCCC and the Kyoto Protocol and lists of signatories can be found at <http://www.unfccc.int/resource/index.html>.

1.2 Issues raised by the inclusion of land carbon sinks in the Kyoto Protocol

This section outlines the requirements that are implicit in the inclusion of land carbon sinks in the Kyoto Protocol. The scientific methods that must be used to meet these requirements, and their associated uncertainties are evaluated in Section 5.

Quantification: In order to become binding commitments, which can be used to offset fossil fuel emission reductions, land carbon sinks need to be quantified with an acceptable degree of accuracy. Methods are needed to quantify (i) areas of land where changes in land use have been implemented, and (ii) the change in amount of carbon stored per unit area (carbon density) over specified periods of time.

Verification: In order to obtain numeric credits for any carbon storage scheme, it is fundamental that a third party is able to verify the claim. In order to verify land areas, the geographic location of land areas needs to be specified, which can be achieved using remote sensing techniques. Carbon density verification requires ground sampling. There can be problems of verifying the historical status; for instance, of soil carbon before afforestation, or the carbon stock before deforestation (i.e. the baseline). In some countries, existing forest inventory procedures could be extended to include repeat soil sampling for soil organic carbon with established quality control and assurance procedures (QCQA). Procedures for sampling carbon within other land uses can be also defined⁴⁷. Certifying that the methods include QCQA within specified standards may be sufficient in some cases. However, difficult decisions need to be made by the Conference of Parties on what types of certification and verification is required, when it is done and by whom.

Additionality: It was agreed at Kyoto that offsets could be claimed only for land carbon sinks that are directly human induced after 1990 and would not occur anyway, such as new afforestation and changes in tillage practices, and not for sinks created by changes in the atmosphere and historic land use. Negotiators wish to know that the action taken will add to any carbon sequestration that would occur anyway. Thus, it is necessary to predict the changes in carbon density that would occur 'for free', as a result of historic land use or changes in the atmosphere.

Leakage: Leakage occurs when activities to increase carbon storage in some places inadvertently promote activities elsewhere which either decrease carbon storage (negative leakage) or increase carbon storage (positive leakage)⁴⁸. Thus, tree planting or regeneration for carbon storage may provide timber which undermines incentives for forestry elsewhere (negative), or lessens the need to destroy or log native forests (positive), or provides an example which others follow (positive). Basically, leakage is caused by a shift in demand for, or supply of, a commodity that then displaces an activity on to other land. The three most important commodities are agricultural products, fuelwood and timber – all of which require land. Locally, leakage is greatest where the demand for the product is inelastic, for example where carbon storage takes land required for staple food crops in populous areas⁴⁹. The leakage problem is complex and can greatly magnify uncertainties in calculating credits or debits. There are two approaches to the leakage problem. First, more extensive carbon accounting lessens the problem by capturing carbon losses and gains within a region or nation. Any enlargement of a

forestry project to include agricultural and fuelwood provision within a region will lessen ('internalise') the problem. Second, where leakage is anticipated, the options are (i) to reduce the credits claimed for a carbon storage activity, or take additional carbon storage measures to compensate, or (ii) to take action outside the boundary of the project to lessen any anticipated shift in level of demand and supply of agricultural products, fuelwood or timber.

Permanence: It is never possible to guarantee the permanence of carbon stored in forests and soils. Losses can occur from fire, insect outbreaks, changes in socio-economic and political circumstances and as a result of climate change. Methods need to be agreed to assess the value of land carbon sinks which evaluate these risks. It would be unwise to store an amount of carbon on land which would pose an unacceptable risk if it were released to the atmosphere at a later date. As outlined in Section 6, climate change will potentially have an impact on the entire land carbon sink. Any release of greenhouse gases from new land carbon sinks created as a result of the Kyoto Protocol e.g. from so called 'Kyoto Forests' will be insignificant in comparison.

Trace greenhouse gases: Land-use change and management practices designed to increase carbon sequestration may either positively or negatively impact on emissions of CH₄ and N₂O. As outlined in Section 5, the calculation of the full trace gas inventories of even the most simple land-use transition is complex and the science in this area is still poorly understood.

References can be found in Section 8.

Annex 2 Examples of management activities to maximise carbon sequestration

2.1 Carbon Offset Project in Noel Kempff National Park, Bolivia

In the Noel Kempff Climate Action Project (NKCAP) the area of the Noel Kempff National Park in Bolivia was approximately doubled in 1996 (to about 1.5 million hectares) to encompass an area of high graded rain forest on which logging rights had previously been granted to three logging companies. This was also an area under threat from a wave of deforestation advancing from the south-west. The project generates carbon offsets by permanently halting forestry operations in the park expansion area, and protecting these lands from future deforestation. The duration of this \$9.5 million project is 30 years, and the money was provided by a number of US energy and oil companies and administered through two non-governmental organisations, the Nature Conservancy in the US and the Fundacion de Amigos de la Naturaleza in Bolivia. The funds were used to compensate the logging companies for giving up their logging rights, to provide personnel to protect the park in the short term (more than half hired from the local community), to establish long-term financing mechanisms, and to fund ongoing carbon monitoring and leakage prevention activities.

Additionality was demonstrated by showing that the Government of Bolivia did not have the resources to expand the park without NKCAP's funds and activities. Studies of logging patterns and deforestation rates in nearby regions convincingly showed that the area was under imminent threat of logging and partial deforestation. A 'without-project' model of forest use was constructed with data from the logging companies and studies of deforestation, and will be continuously compared with data from a nearby non-protected forest area throughout the lifetime of the project. The baseline scenario predicted that without intervention, 13,000 ha of forest would have been cleared by the time that the project is due to end. Carbon storage within the project area was quantified in 625 nested circular sample plots of 14 m by measuring above-ground tree diameters, soil carbon to 30 cm depth, litter stocks and standing dead wood, with the aim of reaching at least 10% precision in all measurements.

At the local level, the minimisation of negative leakage focused on a number of activities to promote sustainable development in local communities, including funding for diversification and improvement of agricultural activities, and assisting indigenous communities to legally obtain land rights and develop forest management plans (an example of positive leakage from the project). The logging companies compensated by NKCAP agreed to allow inspection and monitoring of their activities outside

the park, to assess whether logging rates have intensified elsewhere as a result of the park expansion. Leakage will continue to be monitored throughout the lifetime of the project by directly observing logging company and community activity, and through the use of satellite imagery. To date, no leakage appears to have occurred.

In areas where deforestation is avoided the carbon offset generated is about $0.014 \text{ Tg km}^{-2} \text{ y}^{-1}$ ⁵⁰, where logging is avoided the offset is about $0.0012 \text{ Tg km}^{-2} \text{ y}^{-1}$. Overall, the avoidance of logging is estimated to have generated a carbon offset of 5-6 Tg of carbon, and avoidance of deforestation a further 1.5 – 2.5 Tg (for comparison, the total fossil fuel emissions of the United Kingdom in 1997 were 142 Tg of carbon). These estimates will be revised during the project as the 'without-project' model is updated with data from surrounding regions.

Local communities have benefited through increased land tenure, loans for small-scale businesses, improved health care, water supplies, education and infrastructure facilities, and for indigenous communities, improved land rights.

2.2 'Carbon Forestry'- the direct role of forest management

Forests contain about 45% of the global stock of carbon. A sustainably managed forest, comprising stands representing all stages in the cycle of the forest, operates as a functional system that maintains an overall carbon balance, taking in carbon (as CO_2) from the atmosphere, retaining a part in the growing trees, transferring another part into the soils and exporting carbon as forest products. On a time scale of tens of years, most forests accumulate carbon through growth of the trees and increase in the soil carbon reservoir, until major disturbance occurs. Recently disturbed and newly regenerating areas lose carbon, young stands gain carbon rapidly, mature stands gain carbon at a lesser rate, and over-mature stands may lose carbon.

Forest management operations may increase or decrease these carbon flows. Current forest management is oriented towards increasing timber production, and thus stocks of carbon within the trees, but takes little account of the larger carbon stocks in forest soils. Operations that are disruptive of the soil are likely to stimulate loss of carbon through enhanced oxidation of soil organic matter and may lead to a stand becoming a temporary source of CO_2 , rather than a sink. These operations include site preparation prior to tree planting, such as burning, ploughing, mounding and drainage, all of which lead to considerable disruption of the upper soil horizons rich in soil organic matter.

Thinning (i.e. removing a proportion of the trees and leaving the residues on the ground), re-spacing to waste (i.e. cutting a proportion of young trees and leaving them on the ground) and selective harvesting temporarily reduce uptake of CO₂ from the atmosphere until the canopy has re-grown, at which time the full sink capacity is re-established. Clear felling instantly converts a carbon sink into a carbon source that persists until a vegetation cover is re-established. The increasing use of heavy machinery for these operations can be particularly damaging to the soil carbon stock.

The land carbon sink strength is increased by operations that minimise soil disturbance and increase gross primary productivity. Raising fertility is possibly the most effective way of rapidly increasing carbon sink capacity. Enhancement of nitrogen fixation by free-living soil micro-organisms and by leguminous plants or applications of wood ash and artificial fertilisers, dramatically increases growth and detritus production. In forests at high latitudes in particular, the small stock of nutrients is locked up in wood and soil organic matter and turnover is slow; CO₂ uptake from the atmosphere, tree growth and carbon transfer as detritus to the soil go on at low rates. Low intensity fertiliser applications, coupled with extension of length of the rotation, can partially reverse the age-related decline in growth and productivity and restore the declining carbon sink capacity of ageing forests. We have discussed the possible impacts of enhancing nitrogen fixation on the trace GHG N₂O in the body of the report. In addition, the use of fossil fuels in the industrial production of nitrogenous fertilisers is itself a source of CO₂. Hence we advocate low intensity fertiliser applications.

Alternatively, 'zero management' of degraded forests for natural forest restoration and conservation goals, (i.e. leaving the forest to revert to a natural condition, like that before major disturbance by humans), leads to increase and retention of carbon on the forest floor as coarse woody detritus, and has major additional benefits for biodiversity. However the increase of detritus on the forest floor may also increase the risk of fire, and thus the release of the stored carbon to the atmosphere.

The impact of management operations on the carbon balance of a stand needs to be calculated over the entire management cycle and should take into account the spatial representation of stands at different stages in their life cycle. Assessments of the effects of management operations on forest sinks are in their infancy and it is not possible to provide quantitative estimates of the likely consequences of particular management operations at the present time. However, we estimate that forest management oriented towards protecting and enhancing carbon stocks could lead to enhancement of the global forest carbon sink by up to 0.3 PgC y⁻¹⁵¹.

Forests currently provide services to communities for conservation of biodiversity, for recreation and amenity,

for sport and for landscape, in addition to timber production. To these goals should now be added protection and enhancement of the existing carbon stocks and sink capacity. A new type of forest management, 'Carbon Forestry', is needed to meet this goal. The recent developing emphasis on 'continuous cover forestry' coupled with 'selective harvesting' goes some way in this direction, but not far enough. Positive measures are required particularly to conserve and enhance soil carbon stocks in forests.

2.3 Impacts of changes in agricultural practice or land use on soil carbon stocks

Soils currently used for agriculture, especially for arable crops, normally contain considerably less organic carbon than an equivalent soil under natural vegetation such as grassland or forest. This is because the clearance of natural vegetation normally leads to a decrease in organic carbon inputs and accelerated decomposition of organic carbon already in soil. Indeed the release of carbon when large areas of grassland (e.g. North American Prairies) or forest have been cleared for agriculture has contributed to the increased atmospheric CO₂ concentration. Because part of the carbon held in soil is in long-lived forms there is a reasonable prospect of sequestering carbon in soils in the medium term, e.g. for decades or longer.

Agricultural soils have an equilibrium soil organic carbon content characteristic for a given combination of soil type, cropping systems, management and climate. Following a change in land use or agricultural practice that alters organic carbon input or decomposition rate, carbon content moves towards a different equilibrium level. The time required to change from one equilibrium level to another is often in the range of 10-100 years or even longer. Such changes are documented in long-term agricultural experiments worldwide. Under temperate conditions in the UK, with a major land-use change (arable to woodland), it has been found that half the change in soil carbon content is reached in about 25 years⁵². In practice a true equilibrium content may never be reached as further changes in management often occur during the intervening period.

Predictions of the carbon mitigation potential of different land use strategies is based on the results of agricultural experiments. As with all such studies, care must be taken over the interpretation and extrapolation of the results. For example, within arable agriculture, there is evidence from some studies that a change to minimum tillage (ploughing) can lead to an increase in organic carbon content^{53,54} and this has led some to advocate widespread minimum tillage (ploughing). However other studies have shown little or no net accumulation of soil organic carbon under zero tillage but only a redistribution, with carbon being concentrated near the surface⁵⁵. Where measurements of carbon are made only near the surface

(e.g. 0–15 cm) this has been misinterpreted as a net accumulation of carbon and has led to claims for the carbon sequestration benefits of minimum tillage that are almost certainly exaggerated⁵⁶.

Scenario studies have been employed to predict the potential of changes to agricultural land for carbon mitigation, using the results of long-term agricultural experiments and the best available values for current carbon stocks in agricultural soils. One set of scenario studies has been conducted to provide rough estimates of the potential for carbon sequestration in soils through changes in agricultural practice or land use in the UK and Europe^{24,25}. Currently 10% of arable land in the EU is under 'set-aside', most of it in rotational set-aside schemes. The scenarios studies included considerations of long-term land-use change such that this area is either converted to forest or used for biofuel crops (also known as energy crops) such as short rotation coppice of willow or perennial grasses such as *Miscanthus*. One scenario comprised using 50% of the set-aside area for forest regeneration and 50% for biofuel whilst changes in the remaining agricultural land included more rational use of manures and conversion of all arable land to zero tillage²⁵. This combination gave an estimated annual mitigation of over 0.1 PgC y⁻¹ for Europe, equivalent to more than the EU commitment under the Kyoto Protocol of an 8% decrease compared to 1990 emissions. In this scenario, 27% of the mitigation potential is from fossil fuel replacement by biofuel crops, which would continue

indefinitely. Another 27% is from carbon sequestered in trees and the remainder from carbon sequestered in soil, the latter being estimated to continue for 50 years.

As with all possible responses to climate change, full carbon accounting must be applied to the entire chain of processes. A recent study indicated that even if all biofuel crops in Europe were transported 100 km from the site of production to an electricity generating plant, the saving in fossil fuel from electricity generation greatly outweighed CO₂ emissions from transport⁵⁷. It is also important that combustion of biofuels is efficient wherever it is undertaken on a significant scale to avoid black carbon (soot) emissions that can produce indirect warming. The impacts on trace greenhouse gas fluxes of agricultural and land use changes must also be considered. In the case of the scenario above, the negative impact of trace gases measured was perceptible but not substantial. There will often be additional advantages associated with these changes in agricultural practice. Increased organic carbon content in arable soils almost always causes improved soil quality in terms of physical structure, ease of root penetration, water retention, biological activity and nutrient availability to crops. The use of increased areas of current agricultural land for woodland provides additional habitats for wildlife. Perennial biofuel crops may provide wildlife habitats or corridors; they have also been shown to use nutrients very efficiently and leach very little nitrate to aquifers⁵⁸.

References can be found in Section 8.

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