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THE NATURAL FIX?

THE ROLE OF ECOSYSTEMS IN CLIMATE MITIGATION

A UNEP RAPID RESPONSE ASSESSMENT

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WORLD ENVIRONMENT DAY, 5 JUNE 2009

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PREFACE

"Currently the world's ecosystems, instead of maintaining and enhancing nature's carbon capture and storage capacity, are being depleted at an alarming rate."

CARBON CAPTURE AND STORAGE – NATURE'S WAY

One response to the urgent and dramatic challenge of climate change has been a growing interest by governments in carbon capture and storage at power stations. Tens of billions of dollar are being earmarked for a technology that aims to remove greenhouse gases from smoke stacks and bury it deep underground.

In this UNEP-commissioned, Rapid Assessment report we present carbon capture and storage through a Green Economy lens outlining the potential in terms of natural systems – systems from forests to grasslands that have been doing the job in a tried and tested way for millennia.

Currently the world's ecosystems, instead of maintaining and enhancing nature's carbon capture and storage capacity, are being depleted at an alarming rate.

Some 20 per cent of greenhouse gas emissions are coming from the clearing and burning of forests, the vast carbon bank in peatlands and the tundra are threatened by drainage and thawing and many agricultural soils are degraded or degrading.

Safeguarding and restoring carbon in three systems – forests, peatlands and agriculture might over the coming decades reduce well over 50 gigatonnes of carbon emissions that would otherwise enter the atmosphere: others like grasslands and coastal ones such as mangroves are capable of playing their part too.

The multiple benefits of such investments range from improved lives and livelihoods, employment in areas such as conservation, management, monitoring and rehabilitation alongside reversing the rate of loss of biodiversity and improved water supplies up to the stabilization of precious soils.

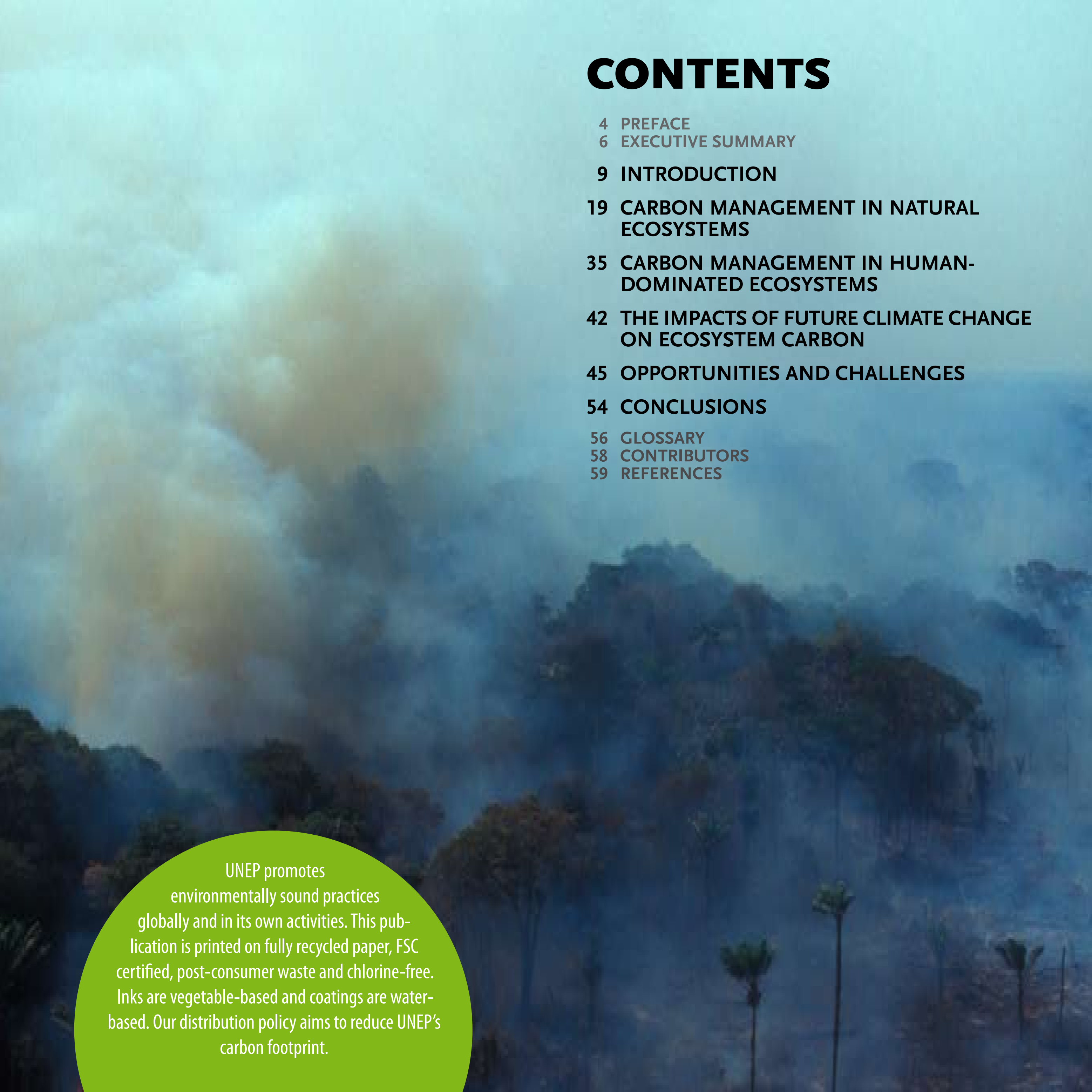
2009 will witness pivotal negotiations surrounding how the world will tackle climate change when governments meet at the crucial UN climate convention meeting in Copenhagen, Denmark this December.

The $3 trillion-worth of stimulus packages, mobilized to reverse the down-turn in the global economy, represents an opportunity to Seal a meaningful climate Deal and perhaps a once in a life time opportunity to accelerate a transition to a low-carbon Green Economy – one that can deal with multiple challenges from food and fuel crises to the climate and the emerging scarcity of natural resources.

There is every optimism governments in Copenhagen will agree to begin paying developing countries for Reduced Emissions from Deforestation and forest Degradation (REDD).

This report, compiled for World Environment Day on 5 June, underlines a far greater potential across a wider suite of natural systems – a potential to not only combat climate change and climate-proof vulnerable economies but to accelerate sustainable development and the achievement of the poverty-related Millennium Development Goals.

Achim Steiner
UN Under-Secretary General and Executive Director, UNEP



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EXECUTIVE SUMMARY

Very large cuts in emissions of greenhouse gases are needed if we are to avoid the worst effects of global climate change. This report describes the vital contribution that ecosystems can and must make to these efforts.

To keep average temperature rises to less than 2°C, global emissions have to be reduced by up to 85% from 2000 levels by 2050 and to peak no later than 2015, according to the IPCC.

But rather than slowing, the rate of greenhouse gas emissions is going up. The most recent estimates indicate that human activities are currently responsible for annual global carbon emissions of around 10 Gt, of which around 1.5 Gt is a result of land use change and the rest from fossil fuel use and cement production (Canadell *et al.* 2007). This has led to an average annual rate of increase of carbon dioxide concentrations in the atmosphere of just under 2 ppm for the years 1995–2005 compared with around 1.25 ppm for the years 1960–1995 (IPCC 2007b).

Vigorous efforts are needed to reverse this trend and doing so will be impossible without addressing carbon losses from ecosystems such as forests and peatlands. Managing ecosystems for carbon can not only reduce carbon emissions; it can also actively remove carbon dioxide from the atmosphere. Restoring some of the large amounts of carbon lost from soils, particularly from agricultural soils and drylands has the greatest potential here. A challenging but achievable goal is to make agriculture carbon neutral by 2030. Currently, this natural fix is the only feasible option for removing carbon from the atmosphere at large; carbon capture and storage technologies are appropriate only for concentrated point sources such as power stations.

Ecosystem carbon management can be a cost-effective approach too. Without perverse subsidies to support alternative land uses, the opportunity cost of reducing deforestation and restoring peatlands can be low. Overall, costs are modest relative to clean energy options.

In many cases there is great scope for achieving other societal goals alongside carbon storage such as improving agricultural soil fertility, creating new employment and income-generating opportunities, and contributing to biodiversity conservation. A clearer understanding of the benefits and costs of ecosystem carbon management is needed to inform land use decisions.

There are risks and uncertainties that need to be taken into account. Some ecosystem carbon stores can be lost through the impact of climate change itself and changes in land use. All stores, except perhaps peat, will eventually reach saturation. There is still uncertainty about the amounts sequestered under different management regimes and considerable variability between areas and much work to be done on how best to manage and monitor carbon. While forests, agriculture and peatland have been highlighted as urgent priorities, the role of other ecosystems is also important and needs to be taken into account.

Implementation of widespread ecosystem carbon management policies presents great challenges, raising significant institutional and regulatory issues and complex political and socio-economic dilemmas. In particular, an effective policy will need to achieve a balance between rural livelihoods and carbon

management policies that may threaten those livelihoods. It is often difficult to ensure that the rewards for good carbon management reach the communities involved. It is crucial that the voices of the rural poor and indigenous people are not lost in a rush to secure carbon gains.

The key messages from this report are:

- It is vital to manage carbon in biological systems, to safeguard existing stores of carbon, reduce emissions and to maximise the potential of natural and agricultural areas for removing carbon from the atmosphere.
- The priority systems are tropical forests, peatlands and agriculture. Reducing deforestation rates by 50% by 2050 and then maintaining them at this level until 2100 would avoid the direct release of up to 50 Gt C this century, which is equivalent to 12% of the emissions reductions needed to keep atmospheric concentrations of carbon dioxide below 450 ppm.
- Peatland degradation contributes up to 0.8 Gt C a year, much of which could be avoided through restoration. The agricultural sector could be broadly carbon neutral by 2030 if best management practices were widely adopted (equivalent to up to 2 Gt C a year).
- It is essential that climate mitigation policy is guided by the best available science concerning ecosystem carbon, and decisions should be informed by the overall costs and benefits of carbon management.
- Developing policies to achieve these ends is a challenge: it will be necessary to ensure that local and indigenous peoples are not disadvantaged and to consider the potential for achieving co-benefits for biodiversity and ecosystem services. Drylands, in particular, offer opportunities for combining carbon management and land restoration.
- The adoption of a comprehensive policy framework under UNFCCC for addressing ecosystem carbon management would be a very significant advance.

INTRODUCTION

THE NEED FOR ECOSYSTEM CARBON MANAGEMENT

The earth's climate is crucially dependent on the composition of the atmosphere, and in particular on the concentration in it of greenhouse gases that increase the amount of the sun's heat that is retained. The two most important of these are carbon dioxide (CO_2) and methane (CH_4). Both gases are naturally present in the atmosphere as part of the carbon cycle but their concentration has been greatly increased by human activities, particularly since industrialisation. There is more carbon dioxide in the atmosphere now than at any time in the past 650,000 years. In 2006 the global average atmospheric concentration of CO_2 was 381 parts per million (ppm), compared with 280 ppm at the start of the industrial revolution in about 1750. The rate at which the concentration is increasing is the highest since the beginning of continuous monitoring in 1959 (Canadell *et al.* 2007).

Note on units and quantities

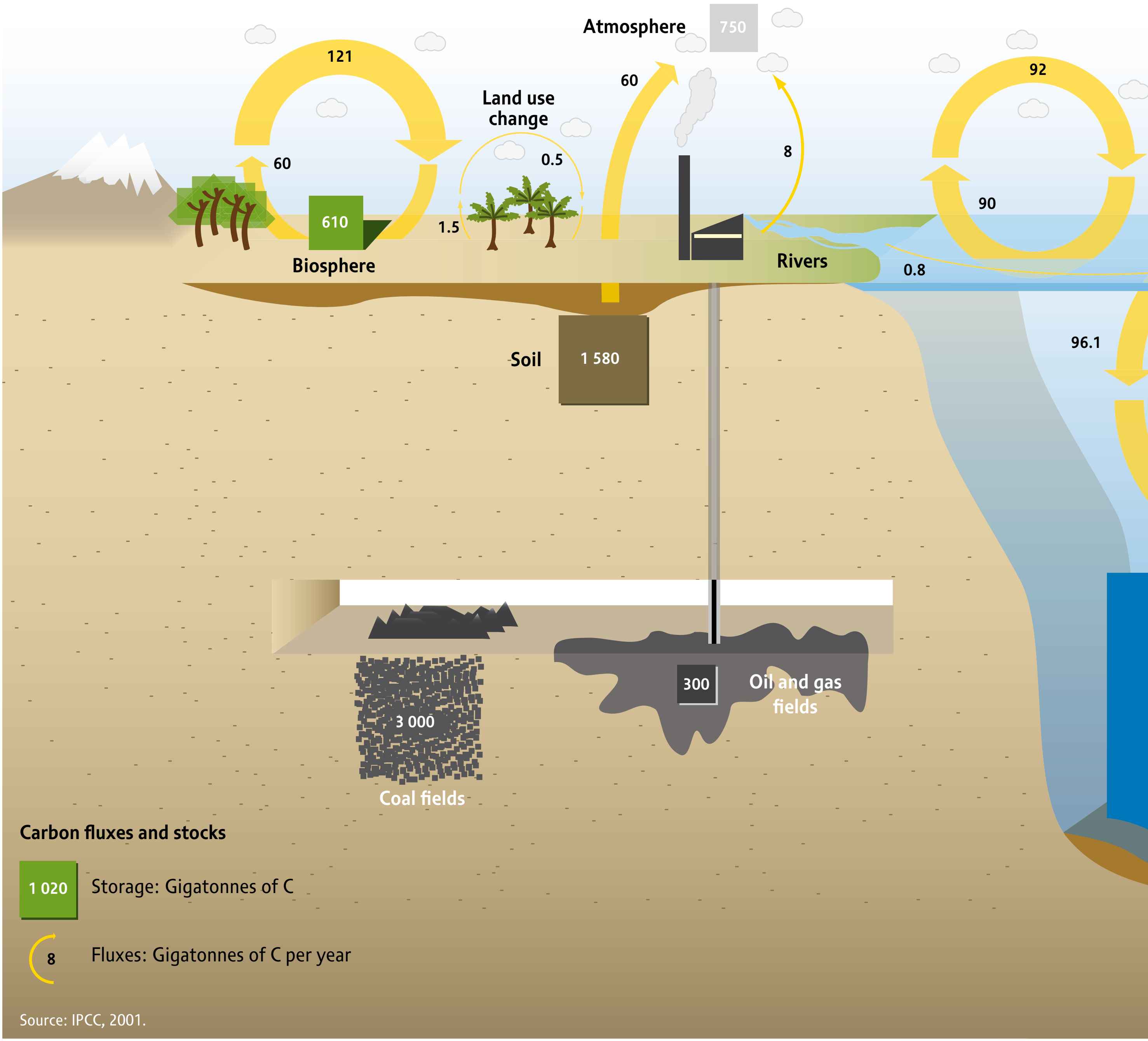
1 gigaton of carbon (Gt C) = 10^9 tonnes of carbon (t C). Carbon (C) or carbon dioxide (CO_2)? It is when carbon is in the form of carbon dioxide gas in the atmosphere that it has its effect on climate change. However, as it is the carbon that cycles through atmosphere, living organisms, oceans and soil, we express quantities in terms of carbon throughout this report. One tonne of carbon is equivalent to 3.67 tonnes of carbon dioxide. The global carbon cycle (see next page) illustrates how carbon moves and is stored in terrestrial and marine ecosystems and the atmosphere.

CO_2 equivalent (CO_2e) is a measure of global warming potential that allows all greenhouse gases to be compared with a common standard: that of carbon dioxide. For example, methane is about 25 times more potent a greenhouse gas than carbon dioxide so one tonne of methane can be expressed as 25 tonnes CO_2e.

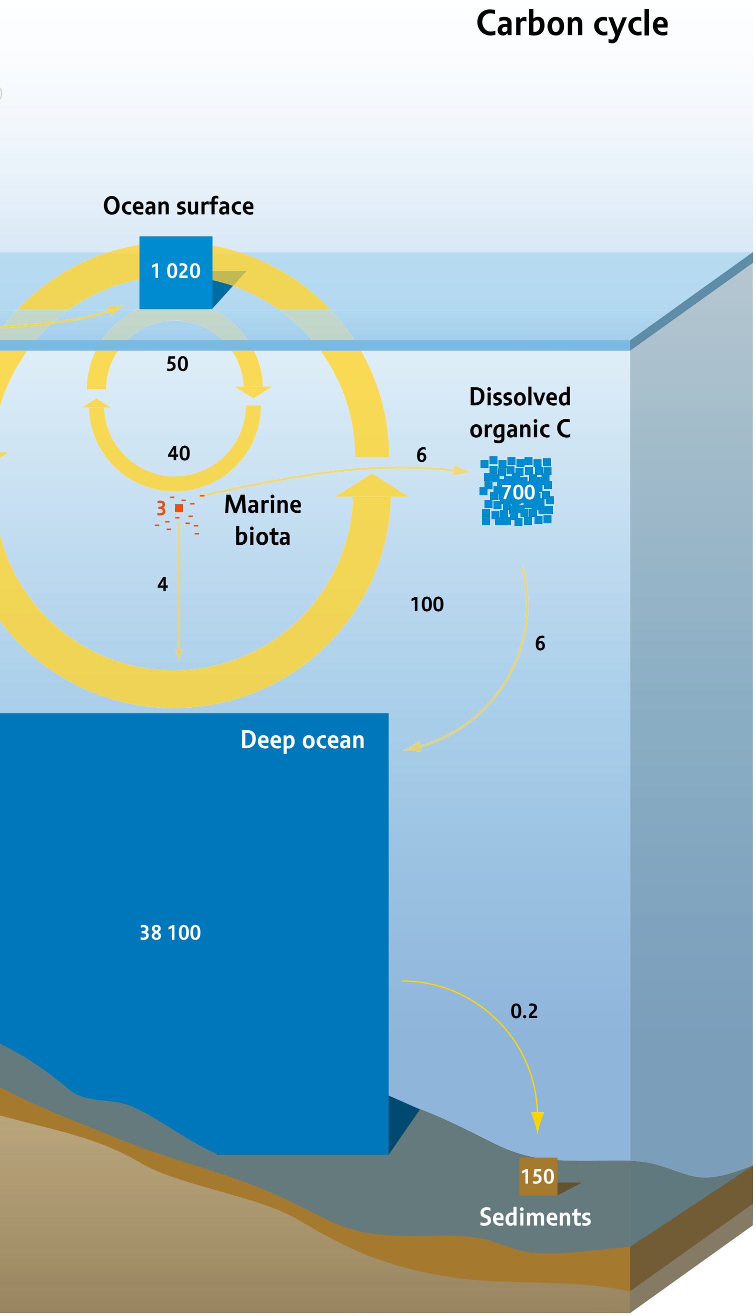
The Intergovernmental Panel on Climate Change (IPCC) has stated that limiting global temperature increase to 2–2.4°C and thereby staving off the worst effects of climate change requires greenhouse gas concentrations in the atmosphere to be stabilised at 445–490 ppm CO_2 equivalent (see box) or lower (IPCC 2007b). As there is presently about 430 ppm CO_2e, this implies limiting future increases to between 15 and 60 ppm (Cowie *et al.* 2007; Eliasch 2008).

CARBON IN LIVING SYSTEMS

Living systems play a vital role in the carbon cycle. Photosynthesising organisms – mostly plants on land and various kinds of algae and bacteria in the sea – use either atmospheric carbon dioxide or that dissolved in sea water as the basis for the complex organic carbon compounds that are essential for life. The vast majority of organisms, including photosynthesising ones, produce carbon dioxide during respiration (the breaking down of organic carbon compounds to release energy used by living cells). Burning of carbon compounds also releases carbon dioxide. Methane is produced by some kinds of microbe as



Source: IPCC, 2001.



a product of respiration in low oxygen environments, such as stagnant marshes and the intestines of ruminants, including cattle, sheep and goats. Methane in the atmosphere is eventually oxidised to produce carbon dioxide and water.

In the biosphere a significant amount of carbon is effectively ‘stored’ in living organisms (conventionally referred to as biomass) and their dead, undecomposed or partially decomposed remains in soil, on the sea floor or in sedimentary rock (fossil fuels are, of course, merely the remains of long dead organisms).

When the amount of atmospheric carbon fixed through photosynthesis is equivalent to the amount released into the atmosphere by respiring organisms and the burning of organic carbon, then the living or biotic part of the carbon cycle is in balance and concentrations of carbon dioxide and methane in the atmosphere should remain relatively constant (although their concentration will be affected by other parts of the carbon cycle, notably volcanic activity and dissolution and precipitation of inorganic carbon in water).

Often, however, the system may not be balanced, at least locally. An area may be a *carbon sink* if carbon is accruing there faster than it is being released. Conversely, an area is a *carbon source* if the production of atmospheric carbon from that area exceeds the rate at which carbon is being fixed there. In terrestrial ecosystems, whether an area is a sink or a source depends very largely on the balance between the rate of photosynthesis and the combined rate of respiration and burning.

The amount of carbon stored, the form that it is stored in and the rate of turnover – that is the rate at which carbon is organically fixed or released as carbon dioxide or methane – vary greatly from place to place. These are dependent on a variety of conditions of which climate (chiefly temperature and, on land, precipitation) and nutrient availability are the most important. Changing climate will itself have an impact on the natural distribution of biomes and ecosystems and on the carbon cycle both globally and locally.

HUMAN IMPACTS ON THE CARBON CYCLE

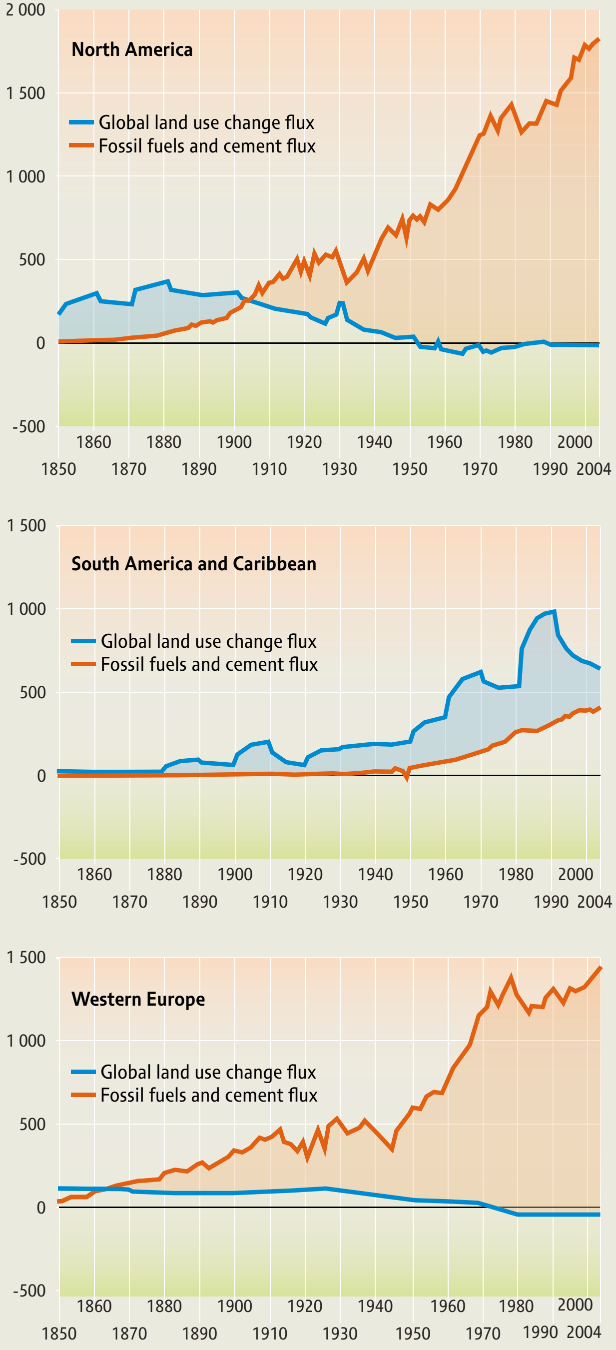
Humans are affecting the carbon cycle in a number of ways. The burning of large amounts of fossil fuels releases long-stored organic carbon into the atmosphere. Production of cement produces atmospheric carbon through the burning of calcium carbonate. Many land-use changes also tend to increase the amount of atmospheric carbon: conversion of natural ecosystems to areas of human use (agriculture, pasture, building land and so forth) typically involves a transition from an area of relatively high carbon storage (often forest or woodland) to one of lower carbon storage. The excess carbon is often released through burning. From the point of view of climate regulation, increasing livestock production, notably of ruminants, has a particularly marked effect as it increases the production of the highly potent greenhouse gas, methane.

Historically, it is estimated that since 1850 just under 500 Gt of carbon may have been released into the atmosphere in total as a result of human actions, around three quarters through fossil fuel use and most of the remainder because of land-use change, with around 5% attributed to cement production. Of the total around 150 Gt is believed to have been absorbed by the oceans, between 120 and 130 Gt by terrestrial systems and the remainder to have stayed in the atmosphere (Houghton 2007).

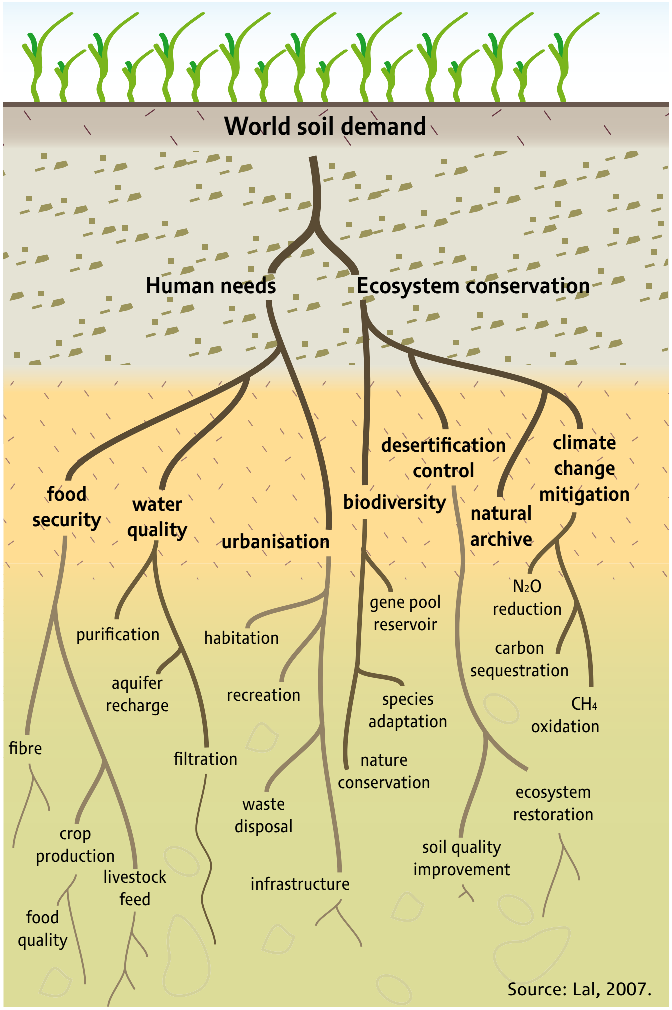
The most recent estimates indicate that human activities are currently responsible for annual global carbon emissions of around 10 Gt, of which around 1.5 Gt is a result of land use change and the remainder comes from fossil fuel use and cement production (Canadell *et al.* 2007). This has led to an average annual rate of increase of carbon dioxide concentrations in the atmosphere of just under 2 ppm for the years 1995–2005 compared with around 1.25 ppm for the years 1960–1995 (IPCC 2007b).

Historic CO_2 emissions by region

Milions of metric tonnes



Source: Carbon Dioxide Information Analysis Center, 2009.



Source: Lal, 2007.

STABILISING OR REDUCING THE AMOUNT OF ATMOSPHERIC CARBON

Stabilising or reducing the amount of atmospheric carbon can be achieved in essentially two ways: by reducing the rate of emission, or by increasing the rate of absorption. Any successful strategy is almost certain to need both approaches, and will require contributions from all sectors (Cowie *et al.* 2007; Eliasch 2008).

Reduction in emissions can be achieved through a reduction in fossil fuel use, in cement production or in adverse (that is carbon-releasing) land-use change, or a combination of these.

Removal of carbon dioxide from the atmosphere can be achieved either mechanically or through biological means. Mechanical removal, referred to as carbon capture and storage (CCS), entails the collection of CO_2 emissions from fossil fuel at concentrated sources such as power stations and cement plants and their storage in geological formations such as spent oil fields (IPCC 2005). Biological mechanisms exploit the ability described above of photosynthesising organisms to capture CO_2 and store it as biomass or as organic matter in sediments of various kinds.

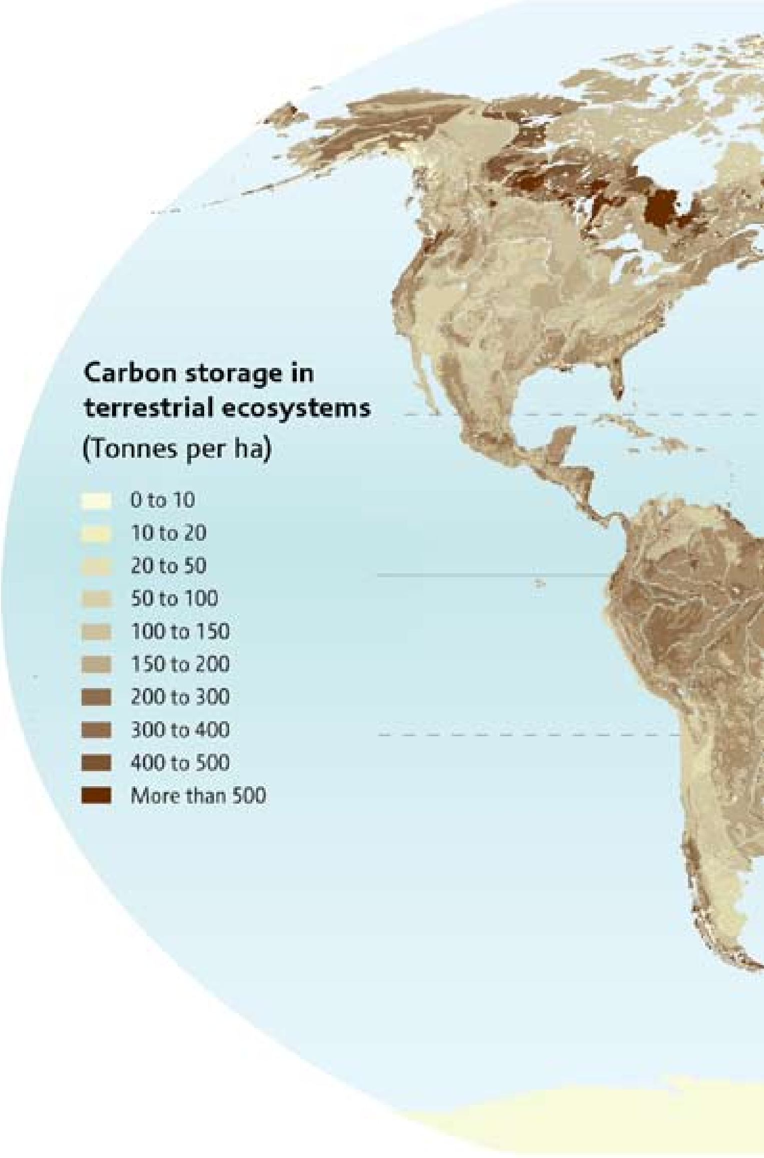
The biological management of carbon in tackling climate change has therefore essentially two components: the reduction in emissions from biological systems and the increase in their storage of carbon. These can be achieved in three ways: existing stores could be protected and the current high rate of loss reduced; historically depleted stores could be replenished by restoring ecosystems and soils; and, potentially, new stores could be created by encouraging greater carbon storage in areas that currently have little, for example through afforestation. In this report, we consider the roles that natural and human-dominated ecosystems can play in reducing emissions and in removing carbon from the atmosphere and we refer to the latter as 'biosequestration'.

If well designed, a biological approach to carbon management can offer other benefits. Natural ecosystems, especially forests, are often rich in biodiversity as well as carbon; protecting one may serve to look after both (UNEP-WCMC 2008; Miles and Kapos 2008); they may also offer a range of other ecosystem services such as soil stabilisation, local climate amelioration and recycling of waste products. Good management of these ecosystems, and of agricultural systems, can pay dividends in terms of water and nutrient availability and reversal of land degradation, having positive impacts on livelihoods and helping in poverty reduction (Lal 2007; Smith *et al.* 2007a).

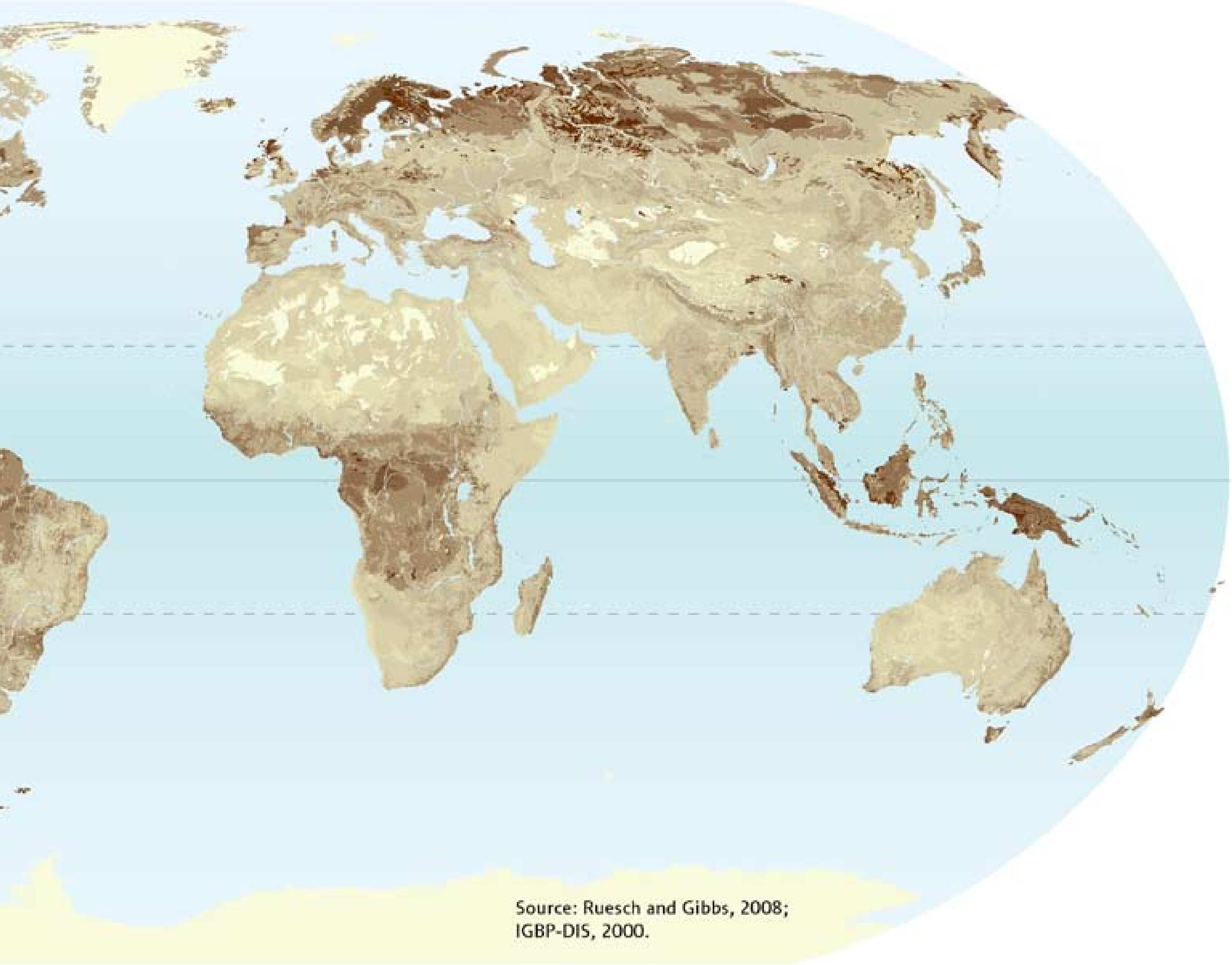
That is not to say ecosystem carbon management is straightforward. There are serious technical, social and economic challenges and some risks of unintended consequences. This report examines the state of knowledge about both its potential and challenges.

CURRENT CARBON STOCKS IN BIOMASS AND SOIL

Terrestrial ecosystems store almost three times as much carbon as is in the atmosphere. Tropical and boreal forests represent the largest stores. The maintenance of existing carbon reservoirs is among the highest priorities in striving for climate change mitigation.



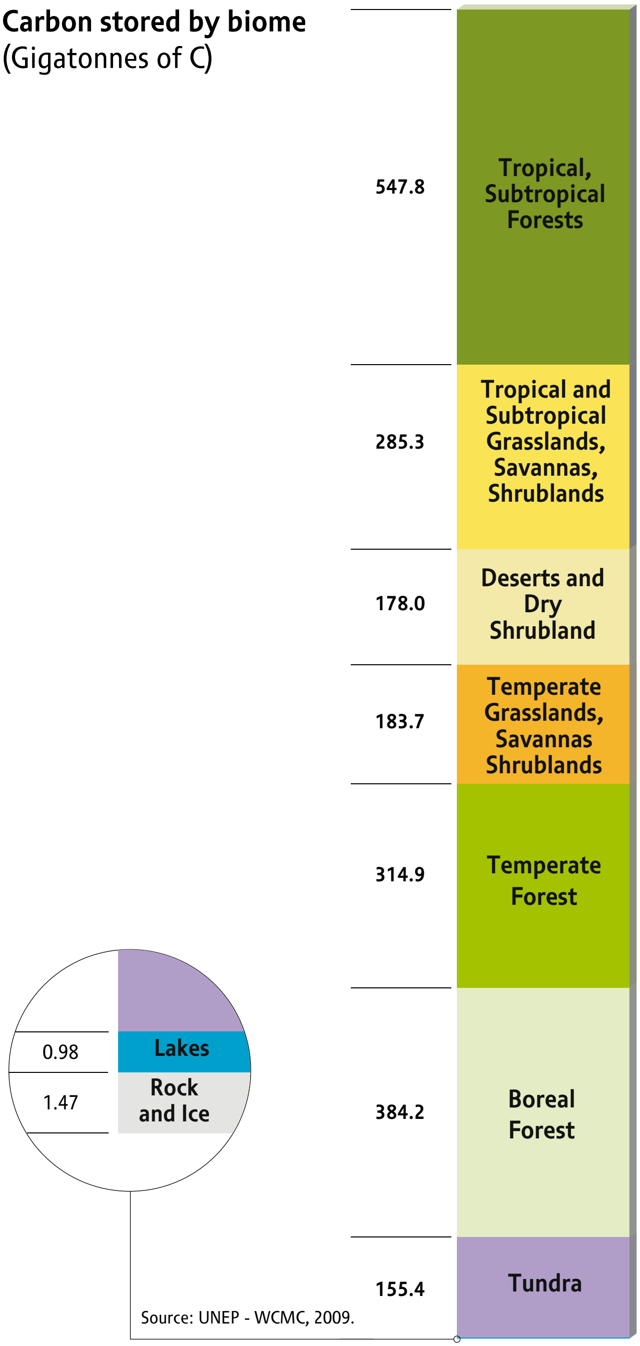
Terrestrial ecosystems store about 2100 Gt C in living organisms, litter and soil organic matter, which is almost three times that currently present in the atmosphere. Different ecosystem types store different amounts of carbon depending on their species compositions, soil types, climate



Source: Ruesch and Gibbs, 2008; IGBP-DIS, 2000.

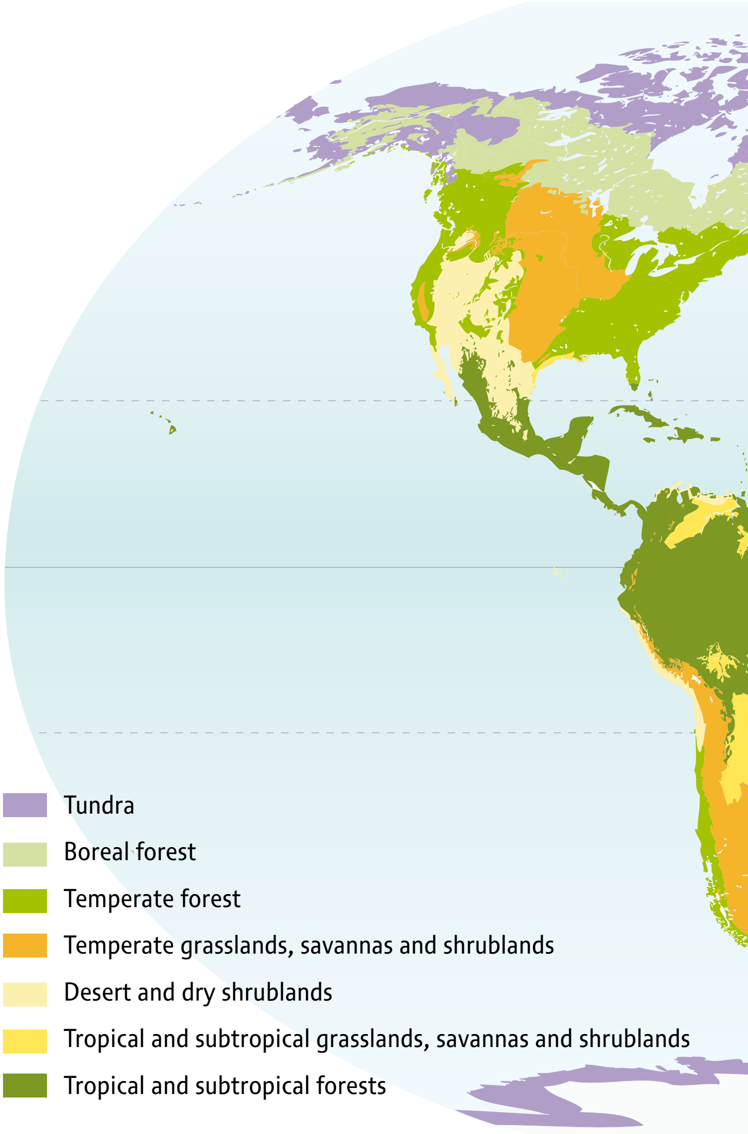
and other features. This map shows today's best available map of the terrestrial distribution of carbon. It combines a globally consistent dataset of carbon stored in live biomass (Ruesch and Gibbs 2008) with a dataset on soil carbon to 1 m depth (IGBP-DIS 2000, this is likely to underestimate carbon stored in peat soils). It shows that the largest amounts of carbon are stored in the tropics, mostly as biomass, and in high latitude ecosystems where the stocks are largely located in permanently frozen layers of soil (permafrost) and in peat.

Carbon stored by biome
(Gigatonnes of C)

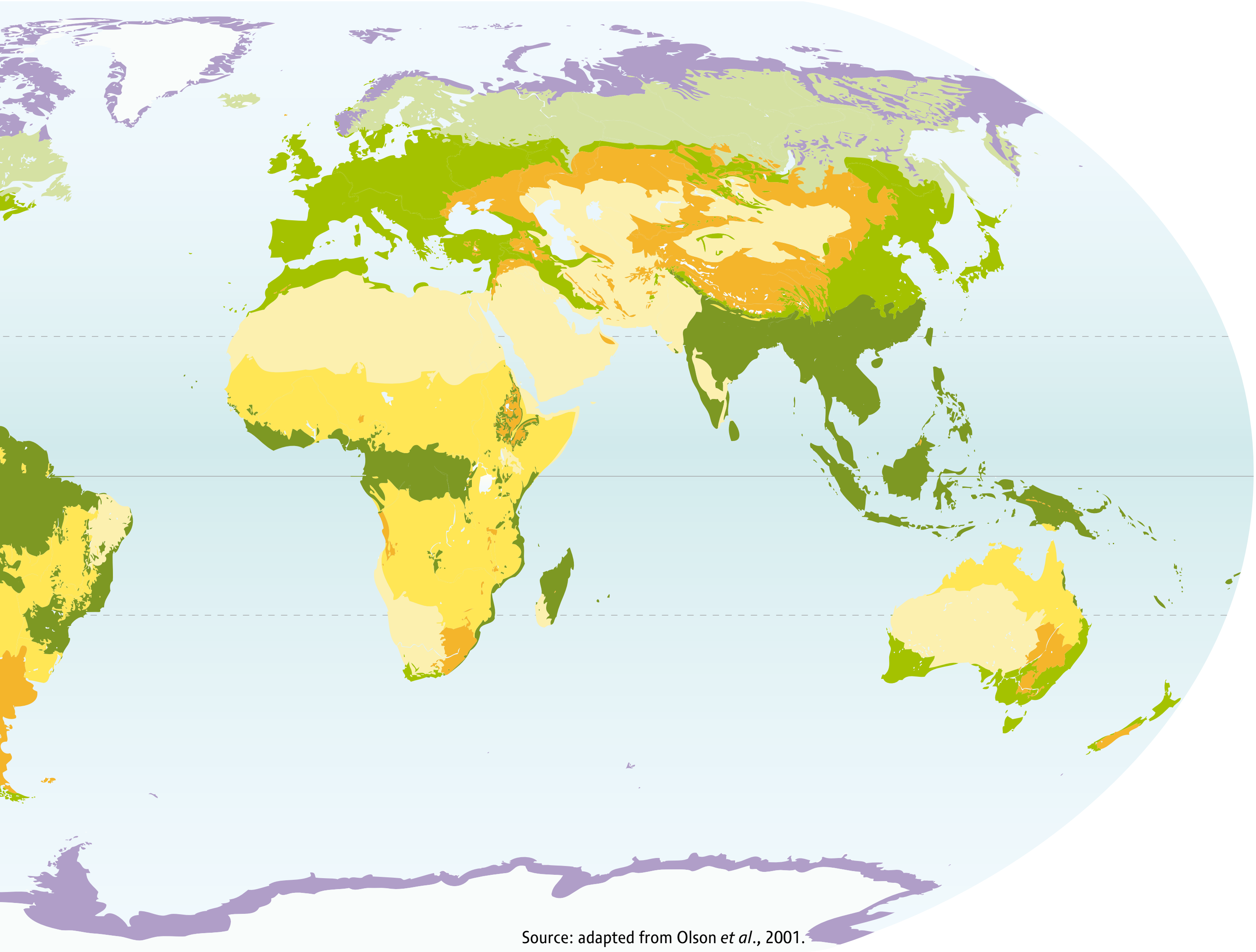


Source: UNEP - WCMC, 2009.

Dividing the world into seven biomes, we estimate that tropical and subtropical forests store the largest amount of carbon, almost 550 Gt. The boreal forest biome then follows with carbon



stocks of approximately 384 Gt. While deserts and dry shrublands have very little aboveground biomass, they are significant soil carbon reservoirs and cover very large areas, so that their overall contribution to carbon storage is notable. Conversely, the tundra biome covers the smallest area, but has the highest density of carbon storage.



Source: adapted from Olson *et al.*, 2001.

CARBON MANAGEMENT IN NATURAL ECOSYSTEMS

Ecosystems can be grouped into biomes, which reflect natural geographic differences in soils and climate, and consequently different vegetation types (Woodward *et al*. 2004). These biomes differ greatly in their capacity to assimilate and store carbon (De Deyn *et al*. 2008). In addition to the balance between carbon gains through growth and losses through respiration, ecosystem carbon balance is also regulated by several other factors including fire, herbivores, erosion and leaching. This section looks at carbon stores and capacity in each biome as well as at peatlands, coasts and oceans and examines the effects that human activities have on those biomes and their role in the carbon cycle.

TUNDRA

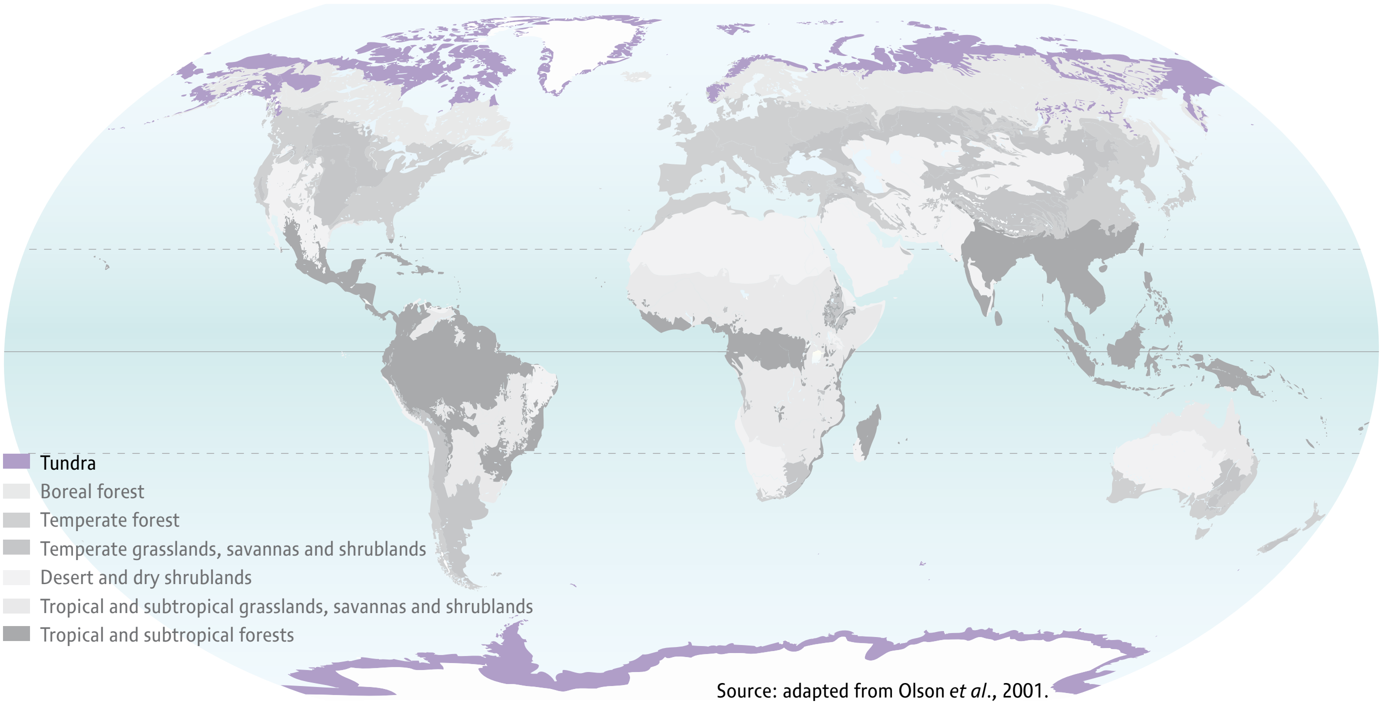
Tundra ecosystems are dense in carbon. They have little potential to gain more carbon but a huge amount could be lost if the permafrost were to thaw. Prevention of climate change is currently the only failsafe method of minimising this loss.

Tundra ecosystems are found in Arctic and mountainous environments, particularly in Northern Canada, Scandinavia and Russia, Greenland, and Iceland. Temperatures are low or very low for most of the year with prolonged periods of snow cover and a short growing season. The active layer of soil, near the surface, tends to be waterlogged in summer and frozen in winter. Diversity of plants and animals is low. The environment selects for slow-growing hardy plants with low biomass above ground. Rates of decomposition are low and large amounts of dead plant material accumulate in the soil (approximately 218 t C per ha, Amundson 2001). The slow decomposition rate means that nutrient recycling is also slow, providing a further limitation on plant growth and leading to tundra plants allocating most of their biomass below ground (De Deyn *et al.* 2008). Total plant biomass is estimated to average 40 t C per ha (Shaver *et al.* 1992).

Below the active soil layer is a perennially frozen layer known as permafrost. Although it is difficult to estimate it is believed that carbon storage in permafrost globally is in the region of 1600 Gt, equivalent to twice the atmospheric pool (Schuur *et al.* 2008).

HUMAN IMPACTS AND IMPLICATIONS FOR CARBON MANAGEMENT

At present, tundra ecosystems are little used by humans and there is also little potential for more carbon capture here under current conditions. However, even a relatively small amount of global warming is expected to have major impacts on these systems. Schuur *et al.* (2008) estimate thawing of the permafrost as a consequence of climate change and subsequent decomposition of soil carbon could release 40 Gt CO_2 into the atmosphere within four decades and 100 Gt CO_2 by the end of the century, enough to produce a 47 ppm increase in atmospheric CO_2 concentration.



Source: adapted from Olson *et al.*, 2001.

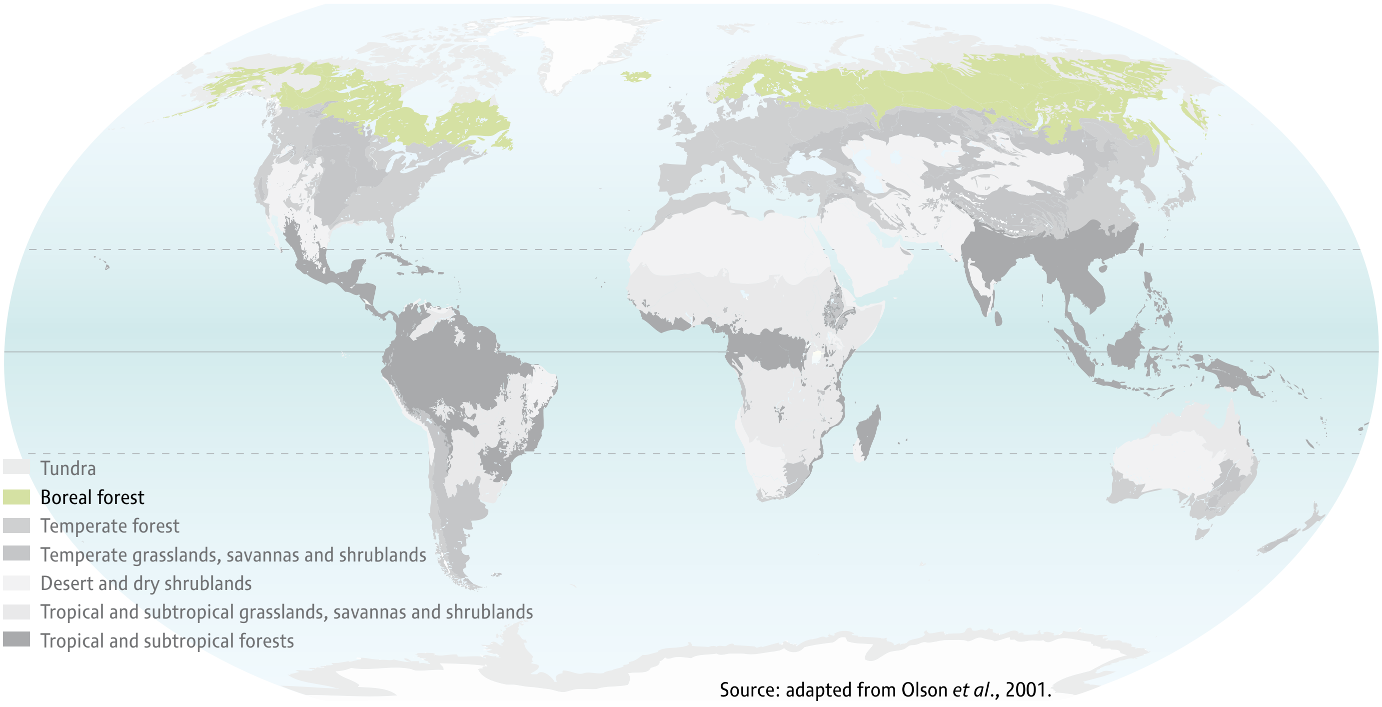
BOREAL FOREST

The boreal forest biome holds the second largest stock of carbon; most of this is stored in the soil and litter. The draining of boreal forest peatlands, inappropriate forestry practices and poor fire management may all cause significant losses of the carbon stored in this ecosystem.

Boreal forests occupy large areas of the northern hemisphere and are mainly found in Canada, Russia, Alaska and Scandinavia. Biodiversity in these forests is generally low. Plant biomass is much higher than in the tundra, with roughly 60–100 tonnes of carbon per hectare, of which around 80% is in the above-ground biomass (Mahli *et al.* 1999; Luyssaert *et al.* 2007). Because of the low temperatures, decomposition in boreal forests is slow. This leads, as in the tundra, to large accumulations of carbon in the soil pool (116–343 t C per ha, Mahli *et al.*, 1999; Amundson 2001). Fire is common in boreal forests and is one of the main drivers of the carbon balance here, with carbon being lost from the system when fire frequencies are high (Bond-Lamberty *et al.* 2007). There is debate about whether the very mature old-growth boreal forests are currently a carbon source or a carbon sink, though recent studies suggest that these old-growth forests may indeed be carbon sinks (Luyssaert *et al.* 2008). In general, due to the low decomposition rates and the extensive peatlands they can grow on, boreal forests are considered to be important carbon sinks.

HUMAN IMPACTS AND IMPLICATIONS FOR CARBON MANAGEMENT

Increasing human pressure on these forests, through logging and mining, and the draining of the peatlands these forests grow on, releases carbon to the atmosphere and significantly reduces their carbon storage capacity. Protection of boreal forests against logging and implementing best forestry practices may therefore reduce carbon emissions, sustain carbon stocks, and maintain uptake by these forests.



Source: adapted from Olson *et al.*, 2001.

TEMPERATE FORESTS

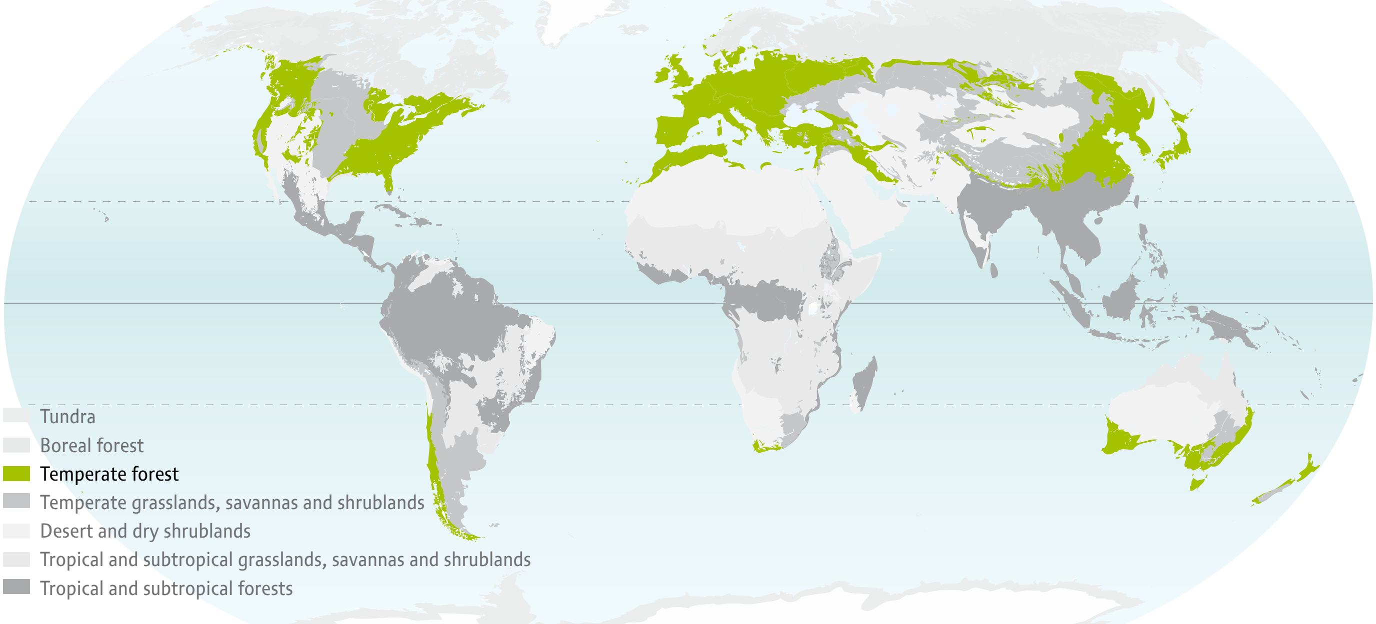
Temperate forests are active carbon sinks and deforestation in the temperate zone has largely stopped. Where demand for land and/or water allows, reforestation would enable carbon sequestration and could provide other benefits including higher biodiversity and recreation opportunities.

Temperate forests are found in climates with four distinct seasons, a well-defined winter and regular precipitation. They occupy large areas of Asia, Europe and North America and are found mostly in developed nations. There are many different types of temperate forests, some dominated by broad-leaved trees and others by coniferous species, and they are generally relatively high in animal and plant diversity. Because the soils they generate are often very fertile much of the area once occupied by temperate forests has been converted to croplands and pasture and is now used for food production.

Plant growth, decomposition and carbon cycling are rapid in temperate forests, with less carbon accumulating in the soil than in boreal forests or tundra. The overall carbon store for these forests has been estimated at between 150 and 320 tonnes per hectare, of which plant biomass, chiefly in the form of large woody above-ground organs and deep, coarse root systems, accounts for around 60% and soil carbon the remainder (Amundson 2001).

HUMAN IMPACTS AND IMPLICATIONS FOR CARBON MANAGEMENT

Temperate forests, notably in Europe and North America, have been increasing in extent for several decades. In many areas, current management practices, such as relatively lengthy cutting cycles and appropriate fire regimes, have led to an enhanced capacity for carbon storage. In consequence, temperate forests are currently considered to be overall carbon sinks. In Europe, forests are estimated to be taking up 7–12% of European carbon emissions (Goodale *et al.* 2002; Janssens *et al.* 2003). Further reforestation and improvements in management could increase carbon sequestration in the short term (Jandl *et al.* 2007).



Source: adapted from Olson *et al.*, 2001.

TEMPERATE GRASSLANDS

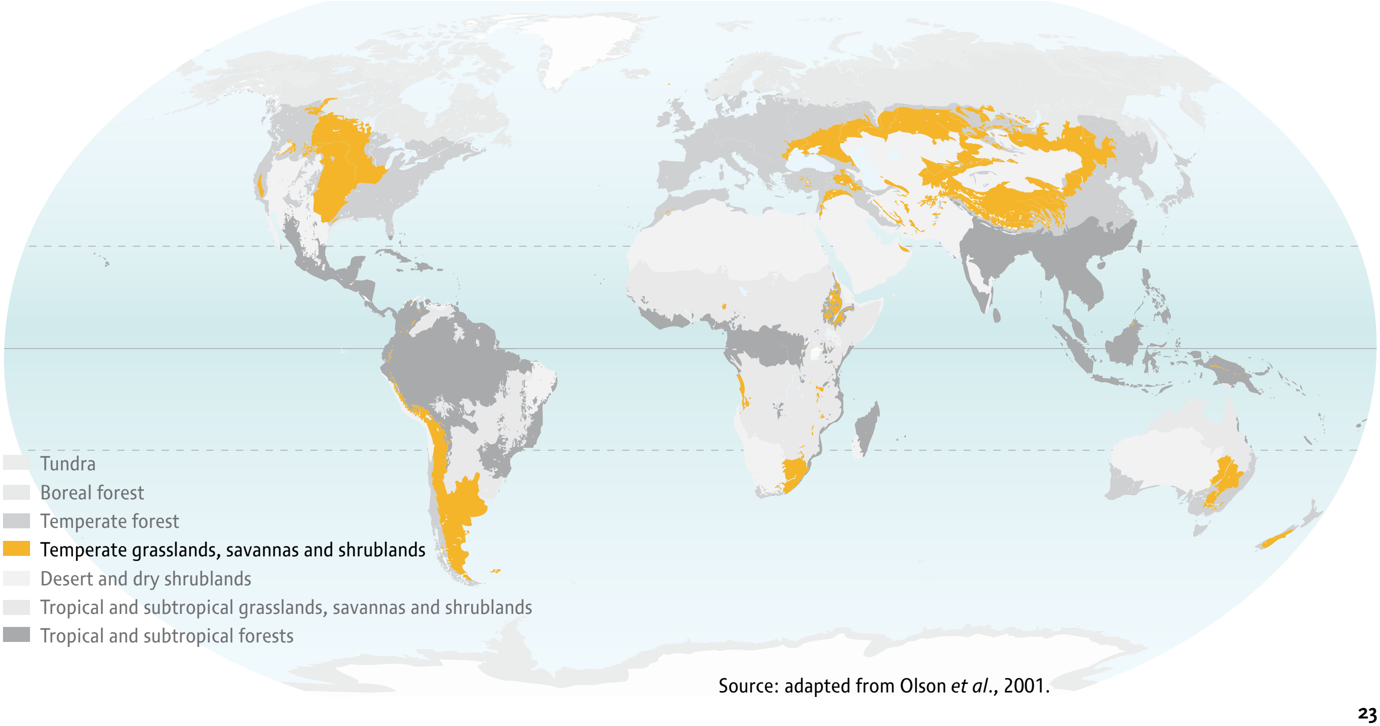
Much of the original area of temperate grassland has been cleared for agriculture. Where natural vegetation remains, minimising human disturbance can prevent further carbon loss.

Grasslands are found across much of the world as an early successional ecosystem in forested regions. They also form the natural vegetation in climates where precipitation levels are inadequate to support trees but higher than those of deserts (Woodward *et al.* 2004). Extensive areas of natural temperate grassland occur in South America, the USA and Central Asia. Plant growth in these grasslands is water and nutrient limited and plants allocate much of their biomass below ground, where they produce slowly decomposing roots. Grazing animals typically play an important role in maintaining grasslands in that they accelerate carbon cycling by consuming and respiring large quantities of leaf biomass and returning some of this to the soil as dung. This is a form of organic carbon that is more decomposable than the leaf and root litter of grasses. In many areas this role is now performed by livestock.

Overall, temperate grasslands have low levels of plant biomass compared with forest or shrubland ecosystems (e.g. 0.68 and 7.3 t C per ha respectively in the temperate steppe of China, Fan *et al.* 2008). However, their soil organic carbon stocks tend to be higher than those of temperate forests (133 t C per ha, Amundson 2001).

HUMAN IMPACTS AND IMPLICATIONS FOR CARBON MANAGEMENT

Despite only having intermediate productivity some temperate grasslands are well suited to crop production and can produce excellent agricultural soils. In much of their natural range, e.g. the prairies of America, these have been cleared to make way for intensive agriculture.



Source: adapted from Olson *et al.*, 2001.

DESERT AND DRY SHRUBLANDS

The large surface area of drylands gives dryland carbon sequestration a global significance, despite their relatively low carbon density. The fact that many dryland soils have been degraded means that they are currently far from saturated with carbon and their potential to sequester carbon can be high.

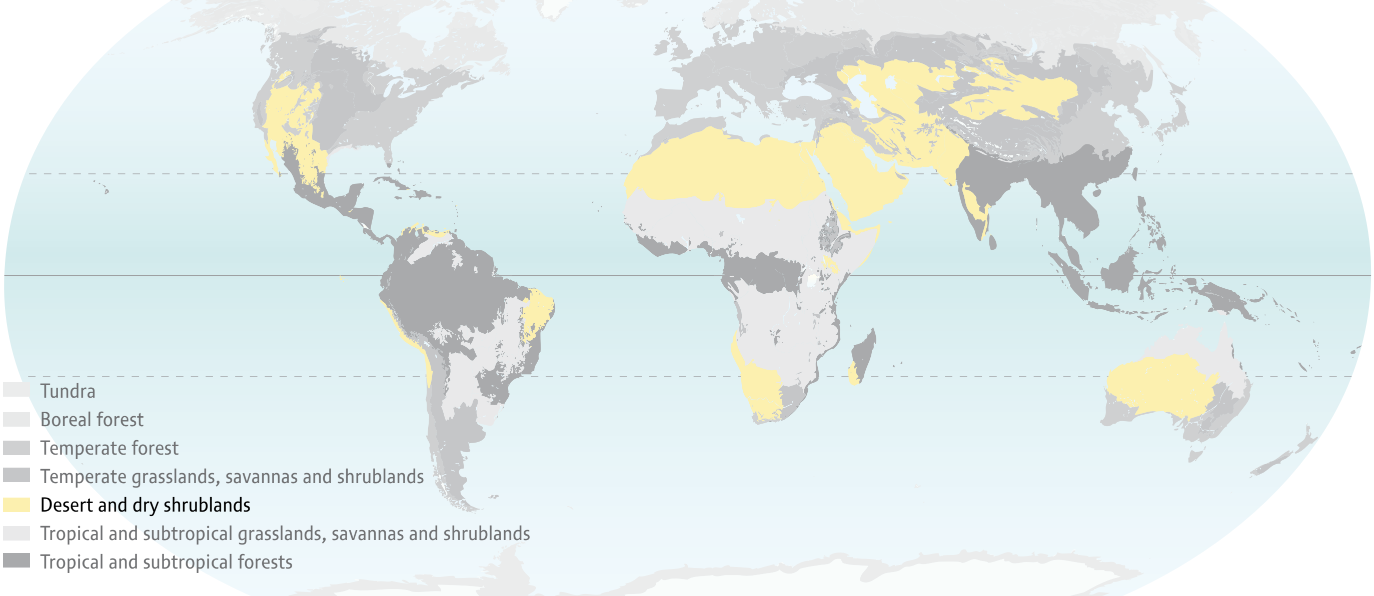
Deserts and dry shrublands occupy regions of very low or highly seasonal precipitation and can be found in numerous regions including many parts of Africa, southern USA and Mexico, parts of Asia and over large areas of Australia. The slow growing vegetation consists mainly of woody shrubs and short plants and is highly adapted to minimise water loss. Like plant diversity, animal diversity is generally low.

The lack of moisture determines the way in which these ecosystems process carbon. Plant growth tends to be highly sporadic and plants invest heavily in protecting themselves against water loss and herbivores by making their tissues tough and resistant to decomposition. Lack of water also slows decomposition rates, leading to the accumulation of carbon-rich dead plant material in the soil. Amundson (2001) estimates carbon content of desert soils as between 14 and 100 tonnes per ha, while estimates for dry shrublands are as much as 270 tonnes per ha (Grace 2004). The carbon stored in the vegetation is considerably lower, with typical quantities being around 2–30 tonnes of carbon per ha in total.

Some recent studies have suggested that carbon uptake by deserts is much higher than previously thought and that it contributes significantly to the terrestrial carbon sink (Wohlfahrt *et al.* 2008). However, considerable uncertainties remain and there is need for further research to verify these results, for example by quantifying above- and below-ground carbon pools over time (Schlesinger *et al.* 2009).

HUMAN IMPACTS AND IMPLICATIONS FOR CARBON MANAGEMENT

As these ecosystems are generally nutrient poor, they tend to make poor farmland and food production on these lands is often at a subsistence level. Land degradation, resulting from inappropriate land uses, leads to carbon loss from the soil.



Source: adapted from Olson *et al.*, 2001.

SAVANNAS AND TROPICAL GRASSLANDS

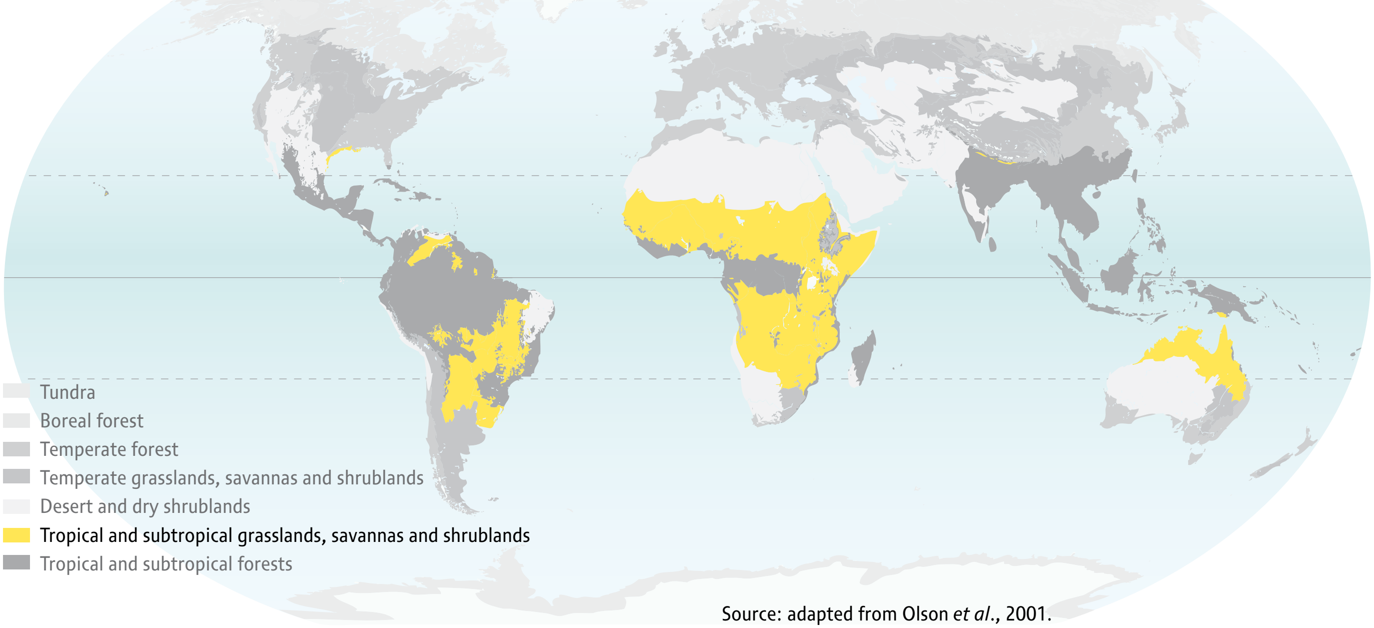
Savannas cover large areas of Africa and South America and can store significant amounts of carbon, especially in their soils. Activities such as cropping, heavy grazing and increased frequency or intensity of fires can reduce carbon stored in these systems.

Savannas are a major component of the Earth's vegetation and occupy large areas in Sub-Saharan Africa and South America. The savanna biome is characterised by the co-dominance of trees and grasses, but ranges from grasslands where trees are virtually absent to more forest-like ecosystems where trees are dominant. Most of the savanna areas are natural ecosystems; however, they can also be formed by the degradation of tropical forests from burning, grazing and deforestation. In Africa savanna areas support a charismatic fauna of large mammals and opportunities for eco-tourism are significant.

The amount of carbon stored above ground depends on how much tree cover there is, and can range from less than 2 tonnes of carbon per ha for tropical grasslands to over 30 tonnes per hectare for woodland savannas. Root carbon stocks tend to be slightly higher, with estimates of 7–54 tonnes of carbon per ha. Soil carbon stocks are high compared to those of the vegetation (~174 t C per ha, Grace *et al.* 2006). Savannas and tropical grasslands are naturally subject to frequent fires, which are an important component in the functioning of these ecosystems. Fire events in savannas can release huge amounts of carbon to the atmosphere (estimated at 0.5–4.2 Gt C per year globally). However, the carbon lost is mostly regained during the subsequent period of plant regrowth, unless the area is converted to pasture or grazing land for cattle (Grace *et al.* 2006) and these ecosystems are considered currently to act overall as carbon sinks, taking up an estimated 0.5 Gt C per year (Scurlock and Hall 1998).

HUMAN IMPACTS AND IMPLICATIONS FOR CARBON MANAGEMENT

Human pressure on these ecosystems is still increasing and it is estimated that more than one percent of global savanna is lost annually to anthropogenic fires, cattle raising and agricultural activities.



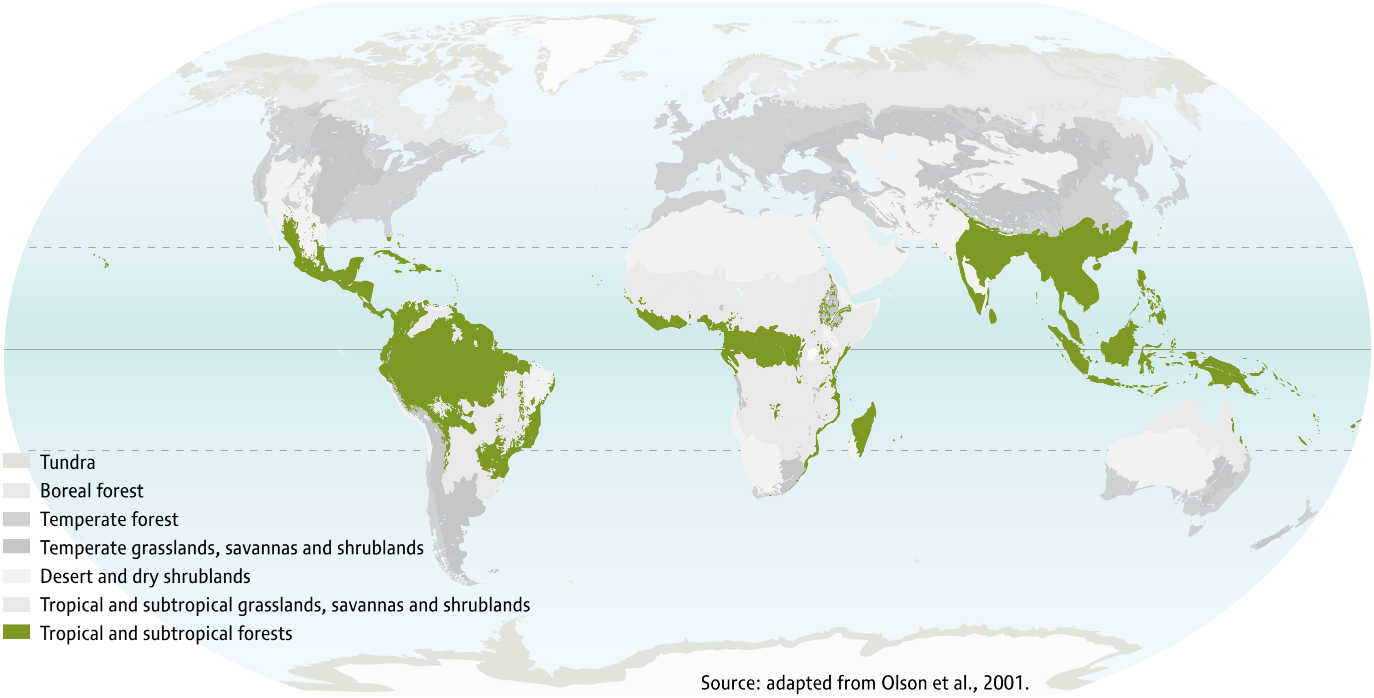
Source: adapted from Olson *et al.*, 2001.

TROPICAL FORESTS

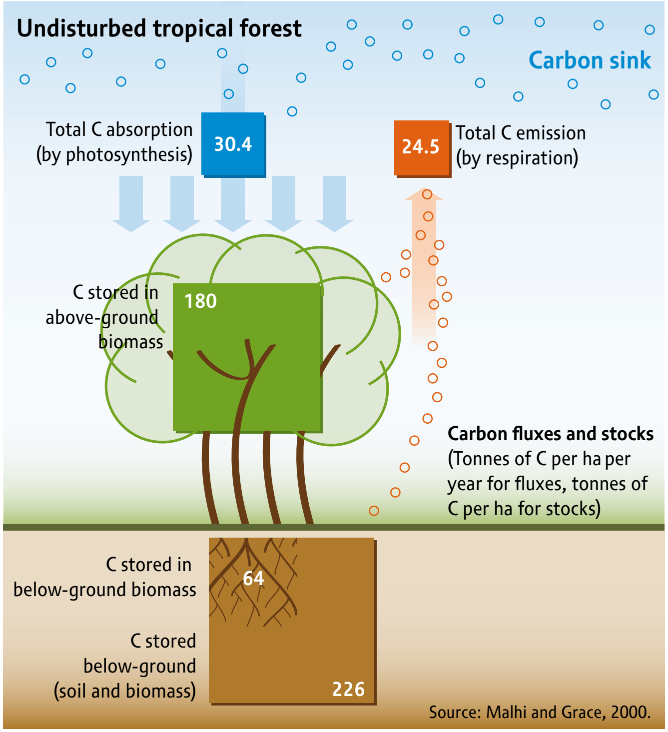
Tropical forests hold the largest terrestrial carbon store and are active carbon sinks. Reducing emissions from deforestation and degradation is a vital component of tackling dangerous climate change. In addition, tackling illegal and ill-managed logging will be an important part of reducing emissions from forestry.

Tropical forests occupy large areas of central and northern South America, western Africa, South-East Asia and north-eastern Australia. Most tropical forests are moist forests, found in areas where annual rainfall normally exceeds 2000 mm per year and is relatively evenly distributed. Such forests have extremely high levels of plant, mammal, insect, and bird diversity and are considered to host the greatest biodiversity of all the Earth's biomes.

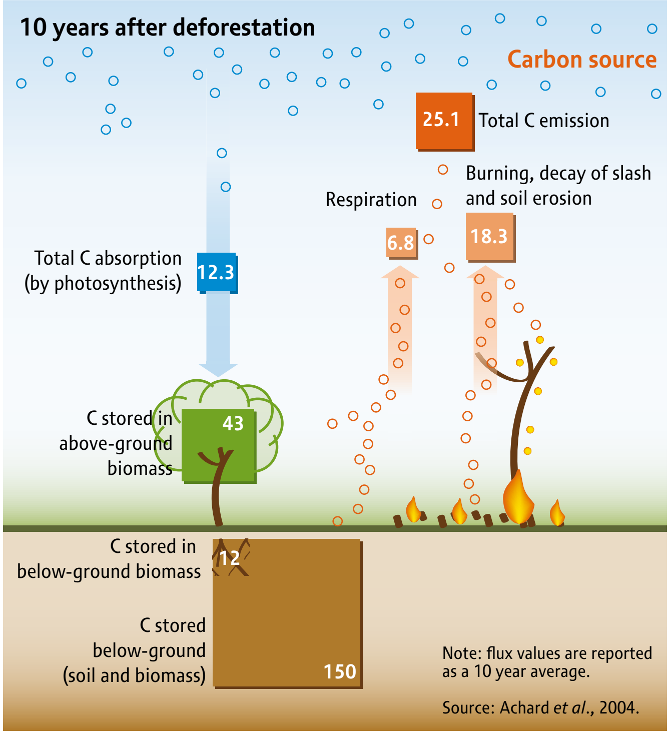
The warm and wet climate of tropical moist forests results in rapid plant growth and most of the carbon can be found in the vegetation, with biomass estimates of 170–250 t C per ha (Malhi *et al.* 2006; Chave *et al.* 2008; Lewis *et al.* 2009). Tropical moist forests can vary considerably in their carbon stocks depending on the abundance of the large, densely wooded species that store the most carbon (Baker *et al.* 2004). On average, they are estimated to store around 160 tonnes per hectare in the above-ground vegetation and around 40 tonnes per hectare in the roots. Soil carbon stocks are estimated by Amundson (2001) at around 90-200 tonnes per hectare, and are thus somewhat lower than biomass stocks.



Source: adapted from Olson et al., 2001.



Source: Malhi and Grace, 2000.



Note: flux values are reported as a 10 year average.

Source: Achard *et al*., 2004.

Globally, tropical forests are considered to be currently carbon sinks, with recent research indicating an annual global uptake of around 1.3 Gt of carbon. Of this forests in Central and South America are estimated to take up around 0.6 Gt C, African forests somewhat over 0.4 Gt and Asian forests around 0.25 Gt (Lewis *et al.* 2009). To put this figure into context, the carbon uptake of tropical forests is equivalent to approximately 15% of the total global anthropogenic carbon emissions. Tropical forests therefore make a significant contribution to climate change mitigation.

HUMAN USE AND CONVERSION OF TROPICAL FORESTS

Tropical forests are being converted to industrial and agricultural (food and biofuel production) land uses at high rate. The causes for tropical deforestation are complex and range from underlying issues of international pressure and poor governance to local resource needs (Geist and Lambin 2001). Global tropical deforestation rates are currently estimated to be between 6.5 and 14.8 million ha per year and these deforestation activities alone release an estimated 0.8–2.2 Gt carbon per year into the atmosphere (Houghton 2005a). Deforestation not only reduces vegetation carbon storage but can also significantly reduce soil carbon stocks.

In addition to deforestation, tropical forests are also being used for the extraction of timber and other forest products. This leads to degradation of the forest and is estimated to contribute globally to a further emission of around 0.5 Gt carbon per year into the atmosphere (Achard *et al.* 2004).

In logging of tropical moist forests, typically only one to twenty trees per ha are harvested. Conventional logging techniques damage or kill a substantial part of the remaining vegetation during harvesting, resulting in large carbon losses. Reduced-impact logging techniques can reduce carbon losses by around 30% during forestry activities compared with conventional techniques (Pinard and Cropper 2000).

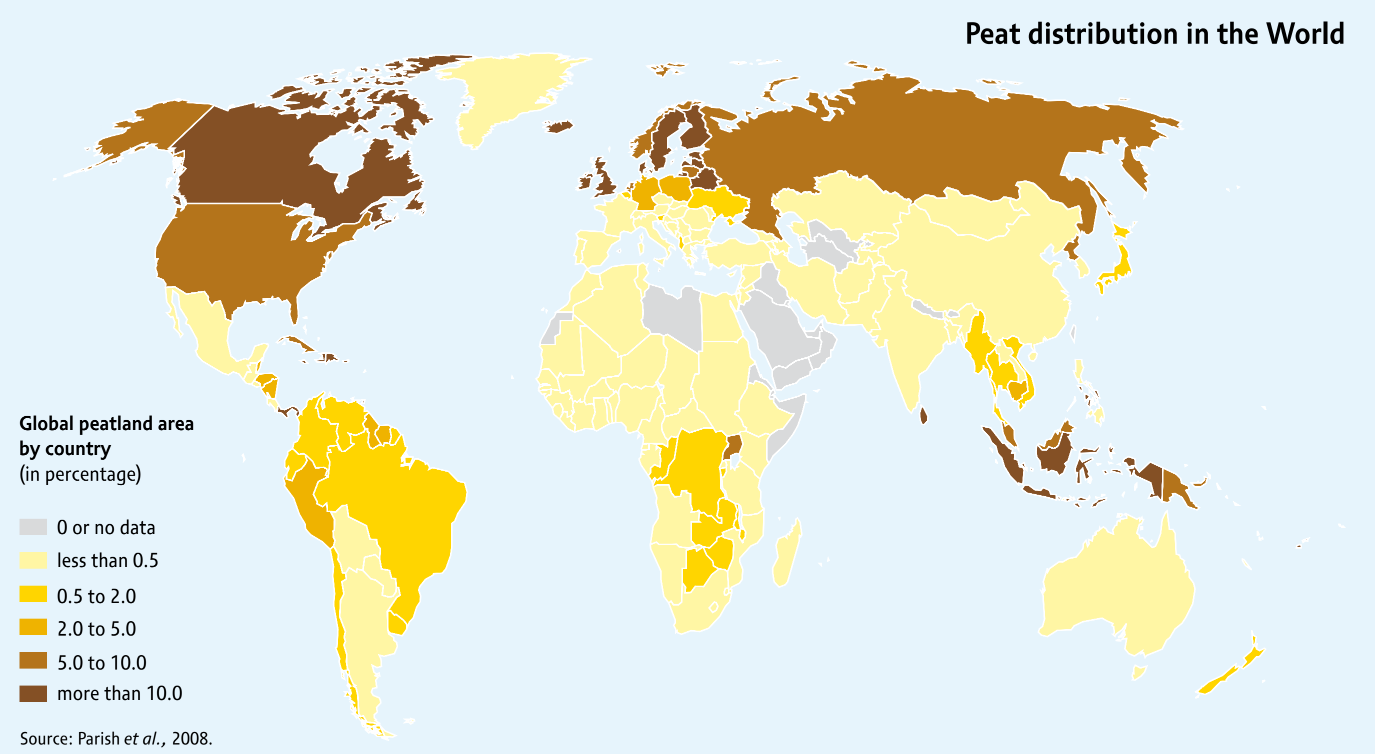
PEATLANDS

Peatland soils store a large amount of carbon but there is a grave risk that much of this will be lost as peatland ecosystems worldwide are being converted for agriculture, plantations and bioenergy. Conservation and restoration of tropical peatlands should be considered a global priority.

While not a true biome, peatlands represent a special case in the management of the global carbon cycle. Peatlands are associated with a range of waterlogged environments in which the decomposition of dead plant material and soil carbon is extremely slow, resulting in the fossilisation of litter inputs and soil with an organic carbon content of over 30%. Although some peat soils can be found in productive ecosystems such as reed and papyrus swamps and mangroves, peat soils are often seen in unproductive environments where plant growth is very slow. Their capacity for storage is huge; with estimates suggesting that ~550 Gt of C is stored globally in peat soils (Sabine *et al.* 2004), and a worldwide average of 1450 t C per ha (Parish *et al.* 2008). These areas are globally widespread but cover a tiny proportion of land area making peatland among the most space effective carbon stores of all ecosystems.

Great quantities of carbon are currently being lost from drained peatlands and unless urgent action is taken this loss will increase further as the area of drained peatlands is steadily increasing. At least half of these losses are currently happening in tropical peatlands. In these areas, which are concentrated in Malaysia and Indonesia, large areas of tropical forest are being drained for palm oil and pulpwood production (Verwer *et al.* 2008). Drainage of peat soils produces an aerobic environment in which peat carbon is respired by soil organisms. Carbon losses are further exacerbated by the increased likelihood of fire outbreak on drained peatlands, with drained peat acting as a fuel source for underground fires.

There is uncertainty over the degree of carbon losses from drained peatlands (Parish *et al.* 2008; Verwer *et al.* 2008) but in all probability losses are already significant (0.5–0.8 Gt C per year) and a significant fraction of overall anthropogenic emissions of greenhouse gasses. Because of these losses, biofuels grown on drained peat soils have a negative impact on the global carbon balance. It is estimated for instance that combustion of palm oil produced on drained peatland generates per unit energy produced 3–9 times the amount of CO_2 produced by burning coal, equating to a carbon debt requiring 420 years of biofuel production to repay (Fargione *et al.* 2008). Such a figure highlights the false carbon economy of cultivating biofuels on drained peatland, the need to conserve pristine peatlands and highlights the potential for emission reduction by rewetting. Rewetting of peatlands restores them to their waterlogged state, re-imposing the anaerobic conditions in which the decomposition of dead plant material is halted, greatly reducing the release of CO_2 and the risk of fire outbreaks.



Peat distribution in the World

Source: Parish *et al.*, 2008.

OCEANS AND COASTS

Without the contribution of oceans and coastal ecosystems to global biological carbon sequestration today's CO_2 concentration in the atmosphere would be much larger than it is. But the uptake capacity of oceans and coasts is both finite and vulnerable. Minimisation of pressures, restoration and sustainable use are management options that can help these ecosystems maintain their important carbon management function.

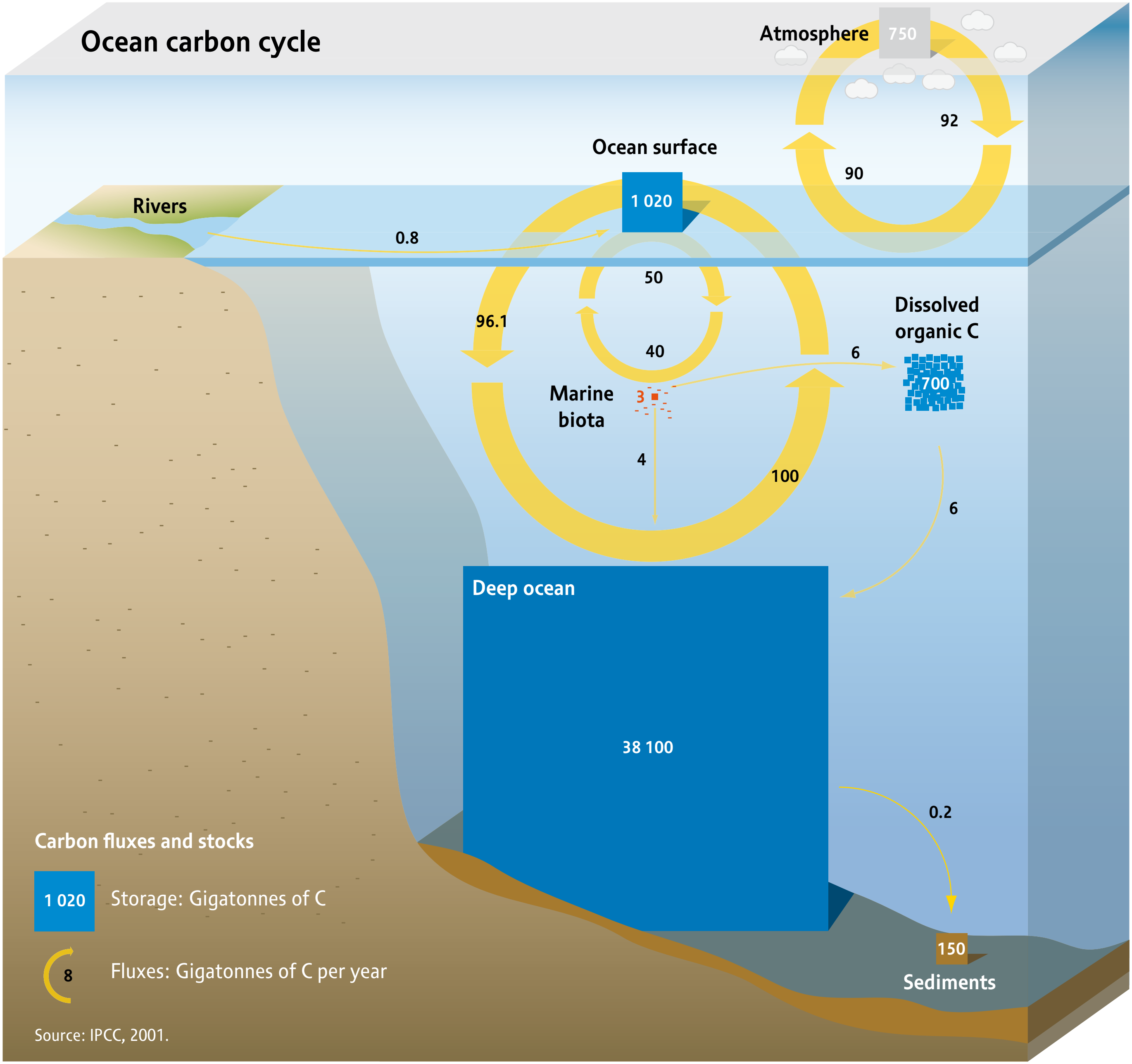
The oceans play a hugely important part in both the organic and inorganic parts of the carbon cycle. They contain dissolved in them about fifty times as much inorganic carbon as is found in the atmosphere, as a complex mixture of dissolved carbon dioxide, carbonic acid and carbonates (Raven and Falkowski, 1999). Carbon dioxide is considerably more soluble in cold water than in warm water, and the relationship between the concentration of carbon dioxide in the atmosphere and of dissolved inorganic carbon in the oceans is therefore heavily dependent on water temperature and ocean circulation. Typically, cold surface waters at high latitudes absorb large amount of carbon dioxide. As they do so they become denser, and sink to the sea-floor, carrying dissolved inorganic carbon with them and creating the so-called solubility pump. As the concentration (or partial pressure) of carbon dioxide increases in the atmosphere, so the oceans absorb more of it. Because of this, the oceans are believed to have absorbed around 30% of human carbon dioxide emissions since industrialisation (Lee *et al.* 2003). The ocean is thus the second largest sink for anthropogenic carbon dioxide after the atmosphere itself (Iglesias-Rodriguez *et al.* 2008). One impact of the extra uptake of carbon dioxide has been a small but measurable acidification of the ocean over this period (Orr *et al.*, 2005).

Dissolved inorganic carbon is translated into dissolved or particulate organic carbon in the open ocean through photosynthesis by phytoplankton. In total, the oceans are estimated to account for just under half of global biological carbon uptake (Field *et al.* 1998). The majority of this fixed carbon is recycled within the photic zone (the depth of the water column that is exposed to sufficient sunlight for photosynthesis to occur), supplying microorganisms that form the basis of the marine food web. Photosynthetic activity in much of the ocean is limited by nutrient availability. Notable exceptions are upwelling zones, where cold nutrient-rich waters are brought to the surface, leading to abundant plankton growth. Phytoplankton here can form large-scale 'blooms' covering hundreds of thousands of square kilometres of the sea surface and influencing important ecological and carbon cycle processes. When remnants of dead plankton sink to the sea floor, organic matter from their biomass is buried as sediments exceptionally enriched in organic carbon – this transfer of carbon from surface waters (and therefore indirectly from the atmosphere) to the deep ocean floor and ultimately through subduction, into the earth's crust, is referred to as the biological pump. Only 0.03% to 0.8% of organic matter in the sea forms sediment (Yin *et al.* 2006), and in order for this to be permanently sequestered, it is necessary that it is not recycled back into the trophic exchange system.

The coastal zone (inshore waters up to 200 metres in depth, which includes coral and seagrass ecosystems) also has an important role in the oceanic carbon cycle. Various estimates indicate that the majority of mineralisation and burial of organic carbon, as well as carbonate production and accumulation takes place in this region, despite the fact that it covers less than 10% of total oceanic area (Bouillon *et al.* 2008). Organic carbon burial here is estimated at just over 0.2 Gt C per year (Duarte 2002).

Coastal wetlands have the potential to accumulate carbon at high rates over long time periods because they continuously accrete and bury organic-rich sediments. For example, Chmura *et al.* (2003), calculated that, globally, mangroves accumulate around 0.038 Gt C per year, which, when taking area of coverage into account, suggests that they sequester carbon faster than terrestrial forests (Suratman 2008). However there is

Ocean carbon cycle



Source: IPCC, 2001.

widespread agreement that if current patterns of use, exploitation and impacts persist, coastal wetlands will become carbon sources rather than sinks (Hoojier *et al*. 2006; Jaenicke *et al*. 2008; Cagampan and Waddington 2008; Uryu *et al*. 2008; Neely and Bunning 2008; Parish *et al*. 2008). Duarte *et al*. (2005) estimate that widespread loss of vegetated coastal habitats has reduced carbon burial in the ocean by about 0.03 Gt C per year.

Some engineering solutions have been proposed to increase the sequestration potential of oceans. Some, such as ocean fertilization using iron, phosphorus or nitrates, increase the biological uptake of carbon. Others, such as injection of CO_2 into the deep sea, use geophysical stores. The rationale for engineering the oceans, which are estimated to have a combined storage capacity of several thousand Gt C, is to accelerate the transfer of CO_2 from the atmosphere to the deep ocean, a process that occurs naturally at an estimated rate of 2 Gt C per year (Huesemann 2008). Some researchers warn that these are unlikely to succeed on a global scale, with many questions remaining over the potential ecological side effects, and the direct impacts these may have on local marine life. Large-scale ocean fertilization experiments are proceeding, but it is difficult to determine the quantity of carbon that is actually sequestered on the ocean floor. With too many unknown variables and the current limitations with models, some are urging a cautious approach be taken with any ocean engineering intervention.

SUMMARY – NATURAL ECOSYSTEMS

The world's terrestrial ecosystems are a vast store of carbon containing more than 2000 Gt C and are acting as a net sink of approximately 1.5 Gt C per year, of which tropical forests account for a large proportion (Luyssaert *et al*. 2007; IPCC 2007b). Sequestration at these levels would be equivalent to a 40–70 ppm reduction of CO_2e in the atmosphere from anthropogenic emissions by 2100 (Canadell and Raupach 2008).

As well as maintaining these stores and sinks, there is significant potential for reducing future emissions of greenhouse gases through restoring degraded environments, for example through re-wetting peatlands and re-planting forests in areas that have been deforested, and reducing the rates of deforestation and loss of peatlands.

Without implementation of effective policies and measures to slow deforestation, clearing of tropical forests is likely to release an additional 87 to 130 Gt C by 2100, corresponding to the carbon release of more than a decade of global fossil fuel combustion at current rates (Houghton 2005b; Gullison *et al*. 2007). Of course if deforestation could be eliminated, these emissions would be avoided. However, even using more conservative assumptions for reductions in deforestation (deforestation rates observed in the 1990s decline linearly from 2010–50 by 50%, and deforestation stops altogether when 50% of the area remains in each country that was originally forested in 2000), a cumulative emission reduction of 50 Gt C could be achieved by 2100 (Gullison *et al*. 2007).

Peatlands are another ecosystem that offers great potential for reducing future emissions. It is estimated that 65 million ha of the global peatland resource is currently degraded, largely as a result of drainage. Peat oxidation from this area is believed responsible for annual carbon emissions of about 0.8 Gt, equivalent to 20% of the total net 2003 greenhouse gas emissions of the Annex 1 Parties to the UNFCCC. Peat fires in Southeast Asia (primarily Indonesia) are responsible for half of these global peatland emissions (Parish *et al*. 2008).

Carbon in natural ecosystems

	Vegetation growth	Vegetation decomposition	C Source or Sink	Current C storage (t C / ha)	Where majority of C is stored	Main threat(s) for potential C emission
Tundra	Slow	Slow	Sink	Approx. 258	Permafrost	Rising temperatures
Boreal Forest	Slow	Slow	Sink	Soil: 116–343; Vegetation: 61–93	Soil	Fires, logging, mining
Temperate Forest	Fast	Fast	Sink	156–320	Biomass above- and below-ground	Historic losses high but largely ceased
Temperate grassland	Intermediate	Slow	Likely sink	Soil: 133; Vegetation: 8	Soil	Historic losses high but largely ceased
Desert and dry shrublands	Slow	Slow	Sink (but uncertain)	Desert soil: 14–102; Dryland soil: < 266; Vegetation: 2–30	Soil	Land degradation
Savannas and tropical grasslands	Fast	Fast	Sink	Soil: < 174; Vegetation: < 88	Soil	Fire with subsequent conversion to pasture or grazing land
Tropical forests	Fast	Fast	Sink	Soil: 94–191; Vegetation: 170–250	Aboveground vegetation	Deforestation and forest degradation
Peatlands	Slow	Slow	Sink	1450	Soil	Drainage, conversion, fire
Oceans and coasts	In terms of plankton: Fast	Fast	Sink	(Total) Surface: 1020 Gt C; DOC: 700 Gt C; Deep ocean: 38100; Sediments: 150	Deep ocean	Not emission but decreasing uptake capacity

CARBON MANAGEMENT IN HUMAN-DOMINATED ECOSYSTEMS

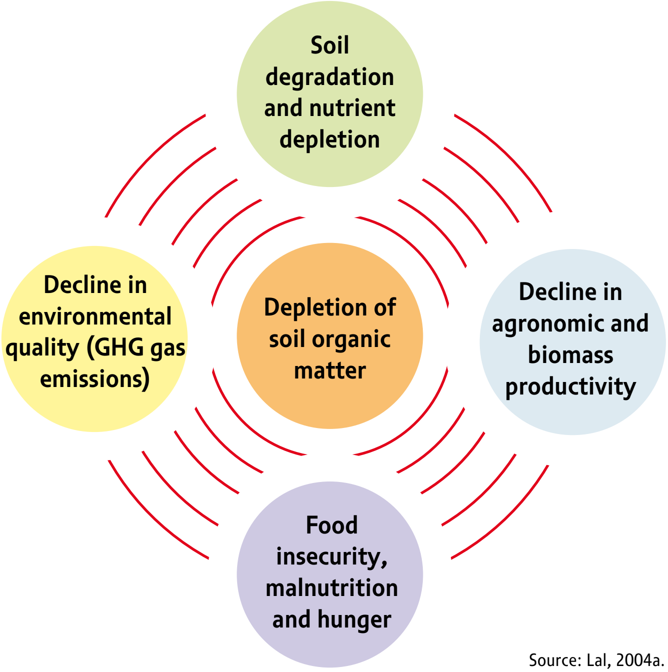
A high proportion of natural ecosystems has already been converted to human-dominated use, such as cropland. There is a range of estimates of the amount of land under agricultural use. The Millennium Ecosystem Assessment found that 24% of the Earth's land surface was under 'cultivated systems' (Millennium Ecosystem Assessment 2005), but Foley *et al.* (2005) report that 40% of the land surface was under cropland and pasture, an area similar to that covered by forest. The following section considers the potential for managing carbon in temperate and tropical agriculture and in plantation forestry.

TEMPERATE AGRICULTURE

There is a good understanding of the best ways of storing carbon in agricultural systems and practices to increase storage can be implemented now. To accelerate this, incentives to promote carbon sequestration in cropland could be considered, but would need to be carefully monitored and include life-cycle level analysis when assessing the real carbon cost of various practices. At the local scale there could be incentives for carbon storing agricultural practices and education regarding the best land management strategies to increase carbon storage.

Agricultural systems in the temperate zone tend to occupy fertile soils that would have formerly supported temperate grassland or forest. Land clearance for croplands and pasture has greatly reduced above ground carbon stocks from their original state and soil carbon stocks are also often depleted as tillage disrupts the soil, opening it to decomposer organisms and generating aerobic conditions that stimulate respiration and release of carbon dioxide. There is large potential for increased carbon storage in such systems. For example, recent estimates indicate that the full application of straw return to Chinese croplands could sequester around 5% of the carbon dioxide emission from fossil fuel combustion in China in 1990 (Lu *et al*. 2008).

The vicious cycle of depletion of soil organic matter



Source: Lal, 2004a.

Carbon losses in agricultural systems can be reduced in many ways, such as through conservation tillage, crop rotation, adoption of appropriate cropping systems, integrated nutrient management using compost and manure, mulching, integrated weed and pest management, and improved grazing (Lal 2008). Optimum management, that is management which best conserves carbon while sustaining food production, will depend on the specific characteristics of the agricultural system in question. Land management policy may therefore be best deployed at a local level. What is clear is that increased stocks of carbon in agricultural systems can represent a win-win situation as high levels of soil organic carbon improve nutrient and water use efficiency, reduce nutrient loss and subsequently increase crop production. Better infiltration and water retention in high organic carbon soils also increases water infiltration, reduces runoff and erosion and helps to avoid drought damage, thus contributing to the sustainability of food production.

Another option is to increase food production on some existing agricultural lands through highly targeted fertilizer and pesticide use, so-called ‘precision agriculture,’ while leaving other areas to return to natural vegetation. Cropland area in the de-

veloped world is already declining and may continue to decline in the future (Balmford *et al.* 2005), potentially freeing up land area that may be used to sequester carbon. Recent evidence shows that carbon gains have occurred in agricultural land abandoned after the collapse of the Soviet Union (soil gains of 0.47 t C per hectare per year, Vuichard *et al.* 2009). This is also known to be true of abandoned lands in Europe and North America as it is in the early stages of succession and forest development that carbon sink strength is strongest.

Biochar: A Panacea?

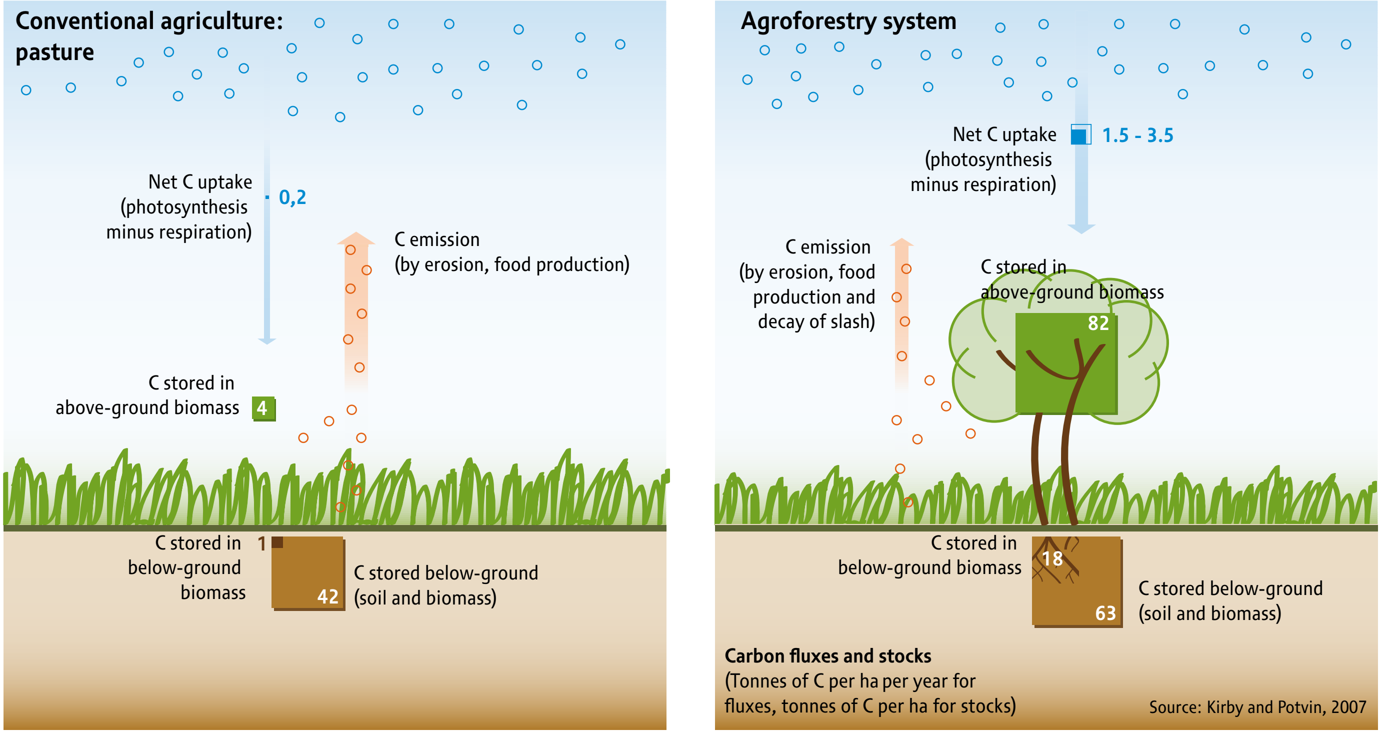
Biochar is a new and poorly understood technology and it is likely that its effectiveness as a carbon storing strategy will depend heavily upon economic and environmental factors. Research is still at a preliminary stage and large-scale biochar deployment is inadvisable until these uncertainties are resolved.

Biochar is an emerging technology in which organic materials are reduced by pyrolosis at temperatures of 350–500°C, producing energy and a carbon rich charcoal that is returned to the soil as a stable form of soil carbon. Research to date has indicated that biochar may have the potential to sequester significant amounts of carbon, while providing benefits to soil fertility and nutrient retention (Lehmann *et al.* 2006)

Nevertheless, the creation of biochar plantations should be approached with great caution. While the use of biochar could be realised in a number of ways including shifting cultivation, charcoal production and the recycling of agricultural wastes (Lehmann *et al.* 2006) the most likely large-scale source of biochar production is from the burning of biofuels. To be justified as a carbon storage strategy, the amount sequestered must exceed that produced in moving it between its site of production, burning and application. In the case of crop residues it must be ensured that biochar addition provides a similar carbon gain to the simple return of these materials at the site of production. The impacts of large-scale biochar production on biodiversity and long-term agricultural sustainability (e.g. nutrient depletion) are unknown.

TROPICAL AGRICULTURE

There is great potential to restore carbon in tropical agricultural soils through management practices that, in the right circumstances, can also increase productivity. Agroforestry can offer particularly large carbon gains, although it can increase water demand. Agricultural carbon sequestration policies will need to be tailored to particular circumstances to allow farmers to benefit.



Carbon fluxes and stocks
(Tonnes of C per ha per year for fluxes, tonnes of C per ha for stocks)

Source: Kirby and Potvin, 2007

Many agricultural areas in the tropics have suffered severe depletion of their soil carbon stocks. Some soils in tropical agricultural systems are estimated to have lost as much as 20 to 80 tonnes of carbon per ha, most of which has been released into the atmosphere (Lal 2004a). Soil erosion, tillage and burning or removal of crop residues and livestock products reduce soil carbon levels and over time the soils have become degraded, often resulting in land abandonment.

As land under tropical agriculture occupies a wide range of soil types and climates, the capacity for carbon sequestration can differ considerably. In hot and dry areas where soil has been degraded, implementation can restore carbon and prevent further losses. In humid climates the potential for carbon sequestration can reach one tonne per ha. According to some estimates, degraded soils represent half of the world's carbon sequestration potential (Lal 2004a).

One management practice with a high potential for carbon sequestration in tropical areas is agroforestry. In agroforestry systems, food production is combined with tree planting. Because of the trees, agroforestry systems store more carbon as plant biomass and have a higher potential for soil carbon sequestration than conventional agricultural systems (Nair *et al.* 2009). Biodiversity benefits may also be realised. Average carbon storage by agroforestry practices is estimated at around 10 tonnes per ha in semi-arid regions, 20 tonnes per ha in sub-humid and 50 tonnes per ha in humid regions, with sequestration rates of smallholder agroforestry systems in the tropics being around 1.5–3.5 tonnes of carbon per ha per year (Montagnini and Nair 2004). In addition, agroforestry systems can reduce the pressure on natural forests thereby having indirectly a positive effect on carbon storage in the latter (Montagnini and Nair 2004).

However, as with conventional agricultural systems, sustainable management practices also need to be adopted in agroforestry systems to ensure carbon sequestration and sustainable water use.

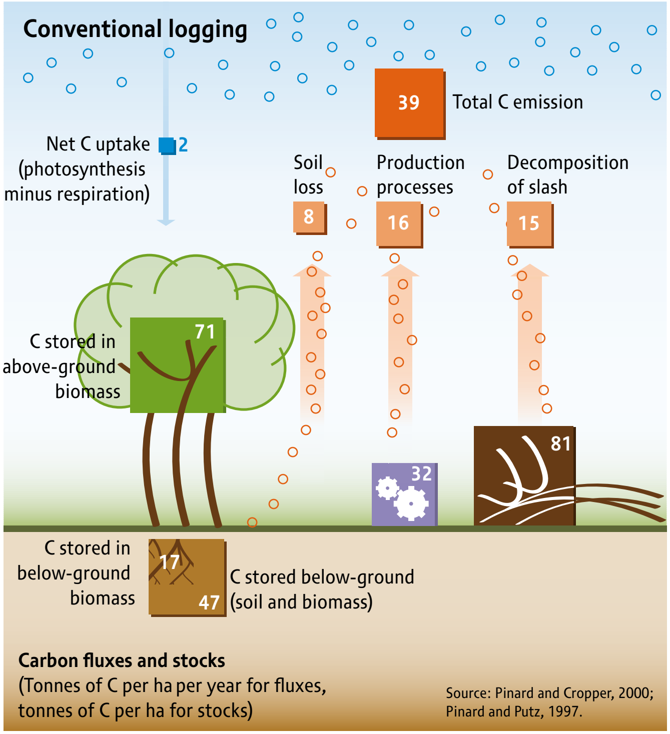
In some systems, interference interactions between crop species and trees planted as part of agroforestry measures may have a negative impact on crop yields (Garcia-Barrios 2003). In these circumstances, compromise solutions may be best, aiming to store reasonable rather than maximum amounts of carbon while still ensuring profitability from crops (Verchot *et al.* 2005).

PLANTATION FORESTRY

Timber forestry can be adapted to increase the amount of carbon held in plantations.

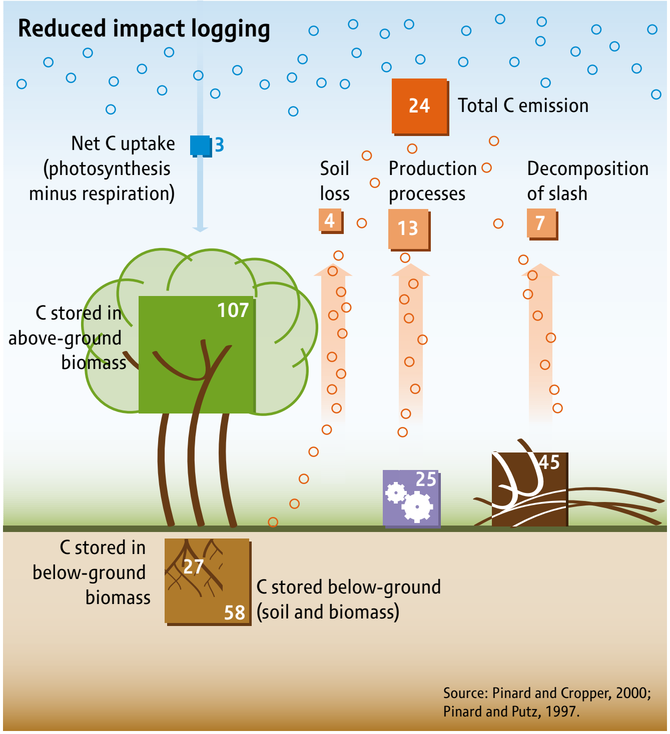
Approximately 4% of the global forest area is represented by plantations (FAO 2006). They supply a substantial proportion of the demand for timber products. Plantations can sequester significant amounts of carbon and are generally considered to be carbon sinks, unless they replace natural forests, which are usually richer in carbon. The largest potential carbon gains for plantations are on marginal agricultural land and degraded soils (Lal 2004b). However, in some cases plantations deplete soil carbon stocks and careful management is therefore necessary. By increasing the rotation period for cutting and implementing site improvement strategies, soil carbon stocks can be replenished and more carbon sequestered by the vegetation. The use of mixed stands instead of monocultures sees beneficial effects on biodiversity and reduces the occurrence of pests whilst enhancing timber production and carbon sequestration (Jandl *et al.* 2007).

There may be other trade-offs too. Tree plantations can support groundwater recharge and upwelling but may also considerably reduce stream flow and salinise and acidify some soils, thus leading to negative effects on water quantity and quality, as well as soil quality (Jackson *et al.* 2005). Negative impacts on groundwater supplies and river flows from afforestation are particularly prevalent in the dry tropics (Bates *et al.* 2008).



Carbon fluxes and stocks
(Tonnes of C per ha per year for fluxes, tonnes of C per ha for stocks)

Source: Pinard and Cropper, 2000; Pinard and Putz, 1997.

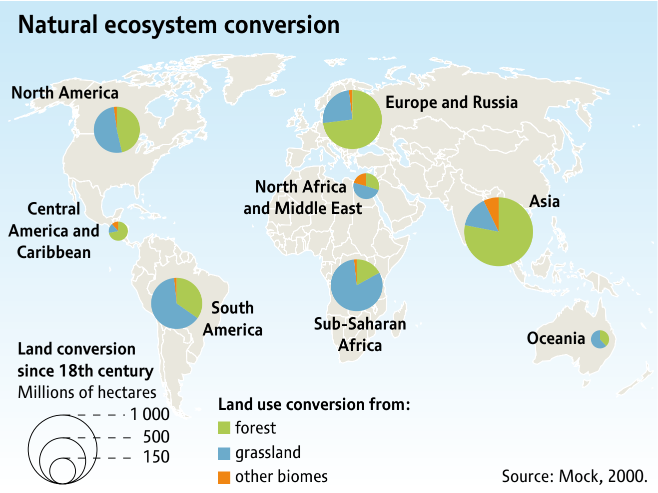


Source: Pinard and Cropper, 2000; Pinard and Putz, 1997.

SUMMARY – HUMAN DOMINATED ECOSYSTEMS

It is clear that much land needs to be kept for agricultural use but it is also possible that the area required for food production will stabilise in the future. The largest readily achievable gains in carbon storage are in agricultural systems where the technical potential for carbon mitigation is significant, estimated at around 0.6 Gt of carbon dioxide equivalent per year by 2030 (Smith *et al.* 2008).

In the agricultural sector, if best management practices were widely adopted, it is estimated that 5.5–6 Gt of CO_2e can be sequestered per year by 2030, which is comparable to emissions from that sector. About 90% of this potential could be achieved through carbon sink enhancement (Smith *et al.* 2007a) and about 10% from emission reductions. The majority of the potential (70%) can be realised in developing countries (Smith *et al.* 2007b). The largest mitigation potential lies in cropland management, grazing land management and the restoration of cultivated organic soils and degraded lands.



Natural ecosystem conversion

Source: Mock, 2000.

THE IMPACTS OF FUTURE CLIMATE CHANGE ON ECOSYSTEM CARBON

Climate change has a major impact on the factors governing the uptake and storage of carbon by ecosystems and therefore plays a key role in the future capacity of ecosystems to sequester carbon.

TERRESTRIAL

Research results from Amazonian and African tropical forests show that carbon storage per hectare has increased over the past few decades, possibly as a result of higher concentrations of carbon dioxide in the atmosphere (Phillips *et al.* 2008; Lewis *et al.* 2009). An increase in vegetation biomass is accompanied by an increase in plant-derived carbon input into soils from leaf and root detritus (Davidson and Janssens 2006). Beyond this, "new" carbon sinks may appear in the arctic and at high altitudes if temperature increases allow vegetation to grow here (Schaphoff *et al.* 2006).

However, a range of models for future changes in biological carbon sequestration project that terrestrial ecosystems will serve as a carbon sink only until 2050. After that, they may become carbon saturated or in the worst case start to act as carbon sources towards the end of the 21st century (White *et al.* 2000; Cox *et al.* 2000; Cramer *et al.* 2001; Joos *et al.* 2001; Lenton *et al.* 2006; Schaphoff *et al.* 2006). Several factors related to climate change have been found to counteract an overall increase in carbon uptake and storage by ecosystems, especially in coaction with other drivers of ecosystem degradation (e.g. Nepstad *et al.* 2008): An increase in temperature accelerates soil carbon decomposition leading to carbon being released more quickly back into the atmosphere (respiration) (Heath *et al.* 2005; Davidson and Janssens 2006). Higher autumn respiration rates and resulting soil carbon loss may turn boreal forest areas into carbon sources (Piao *et al.* 2008). Fertilization experiments in Alaska showed that while annual aboveground plant growth doubled, the loss of carbon and nitrogen from deep soil layers more than offset this increased storage of carbon in plant biomass (Mack *et al.* 2004). Other factors associated with climate change may turn carbon sinks to sources, for example the thawing of permafrost in northern ecosystems (Gruber *et al.* 2004; Johansson *et al.* 2006; Schuur *et al.* 2008), an increase in ozone levels inhibiting photosynthesis (Felzer *et al.* 2005) and changing hydrologic regimes contributing to tropical forest dieback (Fung *et al.* 2005; Hutyra *et al.* 2005; Nepstad *et al.* 2007; Huntingford *et al.* 2008). The serious drought of the year 2005 that hit the Amazon rainforest, for instance, resulted in considerable losses of carbon from aboveground biomass, estimated as in the range of 1.2 to 1.6 Gt (Phillips *et al.* 2009). Moreover, the species composition of tropical forests is likely to change with changing climate, and this may have considerable impact on their carbon storage capacity (Bunker *et al.* 2005).

> *"The vulnerability of many carbon cycle processes and pools depends on the magnitude of future climate change. The magnitude of future climate change, in turn, depends on the vulnerability of the carbon cycle."* (Gruber et al. 2004: 52)

OCEANIC

It is difficult to assess the overall impact of climate change on oceanic carbon uptake capacity. Warming temperatures will certainly affect the uptake of inorganic carbon, because carbon dioxide dissolves less readily in warm water than in cold. Increasing temperatures may also lead to increased stratification of sea waters and a slowing down of turnover between surface and deep waters, leading to less transfer of dissolved inorganic carbon to the ocean bottom. One study predicted that the ability of the oceans to absorb inorganic carbon could peak at around 5 Gt per year, and that this peak could be reached by the end of the 21st century (Cox *et al*. 2000).

Increased presence of dissolved inorganic carbon in sea-water can have a fertilising effect so that the biomass of photosynthetic groups such as brown algae and seagrasses increases when CO_2 does (Guinotte and Fabry 2008). In situ studies recently undertaken at a natural CO_2 vent area in Ischia, Italy, have shown that seagrass communities flourish in increased carbon dioxide environments (Hall-Spencer *et al*. 2008).

Cermeno *et al*. (2009) predict that global warming will lead to an additional decreased efficiency of the so-called biological pump in sequestering carbon due to thermal stratification and a resulting reduction in nutrient supply to the deeper ocean layers. Carbon models have shown that the rate of organic uptake of carbon dioxide by the ocean may be reduced by 9% as a consequence of climate change impacts (through reduction of wind-borne iron supply to the ocean, resulting in a decrease in productivity) (Ridgwell *et al*. 2002). For the Southern Ocean, a weakening of the carbon sink has been observed during the last two decades and whether this trend may continue or reverse is uncertain (Le Quéré *et al*. 2007; Le Quéré *et al*. 2008).

The ecological consequences of ocean acidification caused by increased uptake of inorganic carbon are largely unknown. However, progressive acidification is expected to reduce carbonate accretion of the shells, bones and skeletons most marine organisms possess, having impact on marine food chains from carbonate based plankton up to higher trophic levels (The Royal Society 2005; Nellemann *et al*. 2008).

Overall, while there is agreement between most climate models that both the land and ocean carbon cycles will be affected by future climate change, there is still large uncertainty on the magnitude of these impacts (Friedlingstein *et al*. 2006). There is major uncertainty about the response of South American and African tropical rainforests to continuing climate change, largely depending on the severity of changes in precipitation (Schaphoff *et al*. 2006). Large-scale field experiments, such as FLUXNET, could significantly contribute to improving existing carbon and climate models (Running 2008; Baldocchi 2008).

OPPORTUNITIES AND CHALLENGES

The technical potential for mitigating climate change through biological carbon management, both through storage and sequestration is large. How well that potential can be realised depends on having a suitable policy framework to enable it. This section considers how ecosystem carbon is treated within existing climate policy and some of the opportunities and challenges for increasing the role it can play.

ECOSYSTEM CARBON MANAGEMENT IN INTERNATIONAL CLIMATE POLICY

International climate policy only partly addresses emissions from land use change and does little to support biosequestration activities. The development of a comprehensive policy framework under UNFCCC for addressing ecosystem carbon management would be a very significant advance.

The potential of ecosystem carbon management is recognised in the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol through the LULUCF (Land Use, Land Use Change and Forestry) sector. Under the LULUCF, developed (Annex I) countries must report on carbon stock changes from afforestation, reforestation and deforestation (since 1990), and can also elect to report on the additional activities of forest management, cropland management, grazing land management, and revegetation (Robledo and Blaser 2008). Developing countries have no requirement or opportunity to account for emissions and sequestration activities in the land use sector. Although developed countries can gain credit for forestry projects in developing countries through the Clean Development Mechanism (CDM), the rules are restrictive (Dutschke 2007; Schlamadinger *et al.* 2007) and at the time of writing only three CDM forestry projects had been accepted.

The current policy framework for the land use sector has several shortcomings (Cowie *et al.* 2007; Schlamadinger *et al.* 2007; Hohne *et al.* 2007). One of these is the lack of involvement of developing countries, as described above. Another concern is the incomplete coverage of carbon sources and sinks as Parties are only required to account for forestry activities. All other activities are voluntary and there is no option for wetland accounting (Schlamadinger *et al.* 2007; Henschel *et al.* 2008). Other issues include the complex monitoring and reporting requirements, the requirement to account for managed lands only, and the difficulties in factoring out anthropogenic from natural disturbances (Benndorf *et al.* 2007). Perhaps the biggest criticism is that emissions reductions from the land use sector were not taken into account in the formulation of targets for developed countries, but can still be used to meet them. This has led many to see LULUCF as an offset mechanism, rather than one that achieves overall emissions reductions (Cowie *et al.* 2007; Schlamadinger *et al.* 2007).

These shortcomings mean that ecosystem carbon management is not currently supported by international policy. This could change in the future, as the next climate agreement is currently under discussion. Whether or not a more effective policy framework is created will depend on issues such as whether 'all lands' are included, and whether the perception of LULUCF can be changed from an offset mechanism to a sector capable of bringing about real reductions in emissions (Cowie *et al.* 2007; Schlamadinger *et al.* 2007; Benndorf *et al.* 2007; Hohne *et al.* 2007). The development of new policy is not likely to be simple. LULUCF was developed from a complex political process under considerable scientific uncertainty, and there are a number of factors that make accounting for emissions from land use difficult, such as the issues of permanence, leakage and additionality (see glossary) that will need to be addressed.

Much of the discussion on future land-use based commitments to date has been focussed on forest. The Bali Action Plan, adopted by the UNFCCC at the thirteenth session of its Conference of the Parties (COP-13) held in Bali in December 2007, mandates Parties to negotiate a post-2012 instrument for reduced emissions from deforestation and forest degradation in developing countries (REDD) (Decision 1/CP.13). The Parties specified that the development of such an instrument should take into consideration 'the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries.' The inclusion of REDD in the next climate agreement would partly address emissions from the land use sector in developing countries. The scope of REDD is still to be determined, but could significantly increase the potential for carbon management if it includes carbon stock enhancement (Eliasch 2008).

Although reducing emissions from the forest sector is clearly important, this report has also emphasised the need to reduce emissions through activities in non-forest ecosystems, particularly peatlands and agriculture. This will require the mobilisation of investment in appropriate land use activities (Hohne *et al.* 2007), and there have been some suggestions that non-forest carbon should be included in any successor to the Kyoto Protocol. The Terrestrial Carbon Group advocates the inclusion of all biomass and soil carbon (TCG 2008), the FAO has proposed that agriculture be included on the grounds that its mitigation potential is high relative to the sector's emissions (FAO 2009), and a number of authors have emphasised the importance of complete carbon accounting in the land use sector (Cowie *et al.* 2007; Schlamadinger *et al.* 2007; Benndorf *et al.* 2007; Hohne *et al.* 2007).

Although it is generally agreed that any future climate change agreement should aim to reduce all anthropogenic emissions from the land use sector (through a combination of LULUCF and REDD activities), it is not yet clear if this will be achieved. Improvements in the coverage of land use activities under the LULUCF are under discussion for the next climate agreement, to the extent that there is the option to include reporting on peatlands and wetlands (FCCC/KP/AWG/2009/L.3), and the carbon accounting framework is likely to be made more rigorous. However, most of the additional activities are likely to remain voluntary, as mandatory accounting across all ecosystems appears neither politically or technically feasible. In addition, the relationship between LULUCF and REDD is still to be determined. It does not currently look likely that developing countries will be required to account for emissions from any ecosystem other than forest.

Since any land-based carbon management policy must consider land tenure and enforcement issues, several international human rights instruments become relevant, such as the International Covenant on Economic, Social, and Cultural Rights and the United Nations Declaration on the Rights of Indigenous People (Brown *et al.* 2008). In the context of multilateral environmental agreements, the need to explore synergies between the UNFCCC and the CBD alongside links with national development plans has been recognised (Reid and Huq 2005; Blakers 2008), as well as necessary overlaps with the UNCCD, as desertification, biodiversity and climate change are also closely linked (Lal 2007). However, differences between the conventions in constituencies and administrative arrangements continue to present challenges.

The extent to which climate policy adequately covers land based emissions and removals and achieves real emissions reductions is likely to influence the extent to which countries adopt ecosystem carbon management in practice. Current land use based mitigation policies do not provide the kind of framework that is required to deliver the incentive mechanisms recommended in this report. The development of a comprehensive policy framework under UNFCCC for addressing ecosystem carbon management would be a very significant advance.

WHAT WILL IT COST? HOW CAN WE PAY?

Ecosystem carbon management can be a low cost mitigation activity, but its global potential is likely to be strongly influenced by the financial incentives made available to key stakeholders. These incentives may be derived from a non-market instrument such as an international fund, or from the carbon market or through a combination of both. There are limited opportunities for ecosystem carbon mitigation in the existing compliance markets, although this could change if REDD is linked to the carbon market. The voluntary market is smaller but offers models for including non-forest carbon and rewarding biodiversity conservation. Barriers to including ecosystem carbon include high transaction costs and issues with accounting and permanence. Factors such as governance and subsidies also influence land use decisions and hence affect what happens to ecosystem carbon.

Nations considering how best to mitigate climate change need to consider the cost-effectiveness of the options available to them. Is ecosystem carbon management a good deal?

Costs of carbon mitigation via avoided deforestation, especially of tropical peatland, can be very low in contrast with 'clean energy' options (Spracklen *et al.* 2008). In agriculture, the costs of carbon mitigation vary, but many are low: managing grazing, fertilizers and fire on grasslands costs as little as US$ 5 per tonne of carbon dioxide equivalent per year. Restoration of soils and degraded land cost about US$ 10 per tonne of carbon dioxide equivalent per year (Smith *et al.* 2008). To set these costs in context, the IPCC puts costs of carbon capture and storage (CCS) at US$ 20–270 per tonne of carbon dioxide equivalent (IPCC 2005).

Although ecosystem carbon management is not necessarily very costly, other land uses may offer a better return, at least locally and in the short term. One factor that can shift the balance is the level of incentives made available to landholders. Higher incentives will make carbon management more competitive with other land uses. For example, the economic mitigation potential of forestry would double if carbon prices increased from 20 US$/t CO2e to 100 US$/t CO_2e (IPCC 2007a). These levels of carbon sequestration could offset 2 to 4% of the 20 Gt C per year of projected emissions by 2030 on the basis of current growth rates (Canadell *et al.* 2007; Raupach *et al.* 2007).

For agriculture, the same increase in the price of carbon (from $20 to $ 100 per tonne CO_2e) more than doubles the economic carbon mitigation potential (from 1.5Gt CO_2e per year to 4 Gt CO_2e per year (Smith *et al.* 2007a).

As discussed above, only afforestation and reforestation activities have access to the global carbon market through the Kyoto Protocol's Clean Development Mechanism (CDM) and there are very few forestry projects under way. Voluntary carbon markets are much smaller than the regulatory market, but forestry projects are better represented, making up about a fifth of all transactions (Ebeling and Fehse 2009). Some voluntary markets allow non-forest carbon projects: the Chicago Climate Exchange (CCX) allows offsets through rangeland and agricultural soil management in the United States of America (Chicago Climate Exchange 2008).

Providing direct financial incentives for ecosystem carbon is only one of many policy options and incentives to change land use decisions. For forests, avoided deforestation strategies can include eliminating perverse incentives by changing input subsidies, land titling systems, forest governance arrangements and taxation regimes. Positive incentives can also be implemented to directly or indirectly change drivers of deforestation, including strengthening property rights. For agriculture, some interventions may need no financial incentive as they are beneficial in themselves, but instead require investment in sharing best practice (see below). Even within a financial incentive approach, a broader system of payments for ecosystem services may be more appropriate for some ecosystems and types of agriculture. Selecting the right mix of incentives will depend on what policies and processes are driving land use change.

LAND COMPETITION AND LIVELIHOOD ISSUES

There are competing demands for land use. Any policy that aims to promote ecosystem carbon management must resolve conflicts between different land uses and take care not to disadvantage the poor.

Policies that are to have a positive effect on carbon storage and sequestration in terrestrial ecosystems (both natural and human-dominated) may aim to ensure that existing land-use continues – for example through enhanced protection of set-aside areas that hold significant carbon stores, such as peat-swamp forests – or they may aim to bring about large-scale land use change, for example through changing agricultural practices. Any such policies and their impacts will need to be considered in the context of other, possibly competing needs for and uses of land: for food production, as living space, for maintenance of biodiversity, for recreation and to fulfil aesthetic and spiritual demands (Millennium Ecosystem Assessment 2005).

How, then, can people optimise land use and land management for a variety of needs? One approach is to maximise the efficiency of land-use for one overriding purpose – such as food production or human habitation – in any one place, thereby leaving more land available for other uses (such as recreation, species conservation or carbon sequestration); another is to seek multiple uses or benefits from any one piece of land (Green *et al.*, 2005).

Whichever approach is chosen, trade-offs will almost certainly be necessary and in any individual case, particular people or groups of people will attach different priorities to different kinds of land use. Where there are competing possible land-uses, conflicts are likely to arise, with a strong likelihood that there will be different 'winners' and 'losers', at least in the short and medium term. Without careful planning it is likely often to be the poor and disadvantaged who lose out, for a variety of reasons: they are often highly dependent on local resources, and are not in a position to buy in substitutes; they generally have less of a voice in decision-making at all levels, but particularly national and international; and they may have less knowledge of and ability to make use of laws, regulations and policies to support their needs and aspirations.

Of particular potential concern is the use of various kinds of financial incentive, for example to encourage the cultivation of biofuel crops, or to promote large-scale afforestation for carbon sequestration. Such incentives will in many cases have the effect of increasing the economic value of land hitherto considered of little commercial interest. Sometimes such lands may indeed be marginal; in such cases, there may be little conflict in appropriating the land for such schemes. Sometimes, however, this may not be the case. The land may be of great importance for local people – as rangeland or pasture for livestock, or as a source of wild food or other resources – or it may be important for biodiversity, or both. Appropriation of such land may result in biodiversity losses and in local people finding themselves deprived of traditional benefits with little or no compensation. If this is not to happen, the full spectrum of values of the land should be taken into account in any incentive schemes, and recognition given to customary land tenure and traditional access rights. Local people should be enabled and encouraged to play a full role in decision making (Rights and Resources Initiative 2008).

In any event, incentive-driven measures that do involve local people are likely to have higher transaction costs and are likely to attract less investment. There is also a danger that the poor may agree to activities (such as tree planting) that cost them more to implement than the payments to which they have agreed (Campbell *et al.* 2008; Coad *et al.* 2008). There may in addition be local inequalities, including gender imbalances, whereby benefits do reach the local community, but are unevenly divided within it and the costs fall disproportionately on the very poor (Parasai 2006).

However, with careful planning, there is no intrinsic reason why policies that favour carbon storage and sequestration in ecosystems should not be beneficial locally. This is particularly true for agriculture, where there is great scope for increasing carbon storage in ways that may also enhance long-term productivity. There are, though, often considerable barriers to changing agricultural practice, particularly where farmers have little access to information and resources. Surmounting such barriers is likely to require external input, at the very least in the form of capacity-building and the introduction of appropriate technologies. As discussed in the agriculture section, different ways of increasing soil carbon content will be appropriate in different circumstances. Carbon management policies that are too prescriptive about the choice of technology could lead to pressure on farmers and land managers to adopt methods that are inappropriate for them, with negative consequences for their livelihoods. Experience suggests that farmers prefer a basket of technologies to try out and, very often, adapt. Indeed, some would see this as part of a process by which farmers actually develop the technology (Sumberg and Okali 1997). Many of the agricultural practices that store more carbon can be implemented at little or no cost (Smith 2004) and if farmers decide measures are worthwhile they will keep them when external funding is no longer there, providing a greater mitigation effect than has been paid for.

LIKELY FUTURE TRENDS

Understanding the likely future trends in land use and the influences on those trends is a crucial part of any attempt to manage carbon in ecosystems. The IPCC's fourth assessment report discussed the drivers of land use change in terms of demand for land-based products and services such as food demand, on one hand, and production possibilities and opportunity costs such as technological change, on the other (IPCC 2007a). Population growth and economic development can be seen as the ultimate drivers.

A few global studies have conducted long term land use projections using scenarios of these and other factors, e.g the IPCC's own SRES scenarios, UNEP's Global Environment Outlook and the Millennium Ecosystem Assessment. In the short term, almost all scenarios suggest an increase in cropland (IPCC 2007a).

Longer term scenarios are mixed. Those that assume higher population rates and higher food demands with lower rates of technological improvement and thus lower increases in crop yields suggest a large expansion (up to 40%) of agricultural land between 1995 and 2100. Those that assume smaller populations and a high degree of technological change indicate there could be a reduction in agricultural land by as much as 20% less by the end of the century.

Forest, crops and the people

A land competition conflict in Brazil

Source: based on a map from Nieves Lopez and Riccardo Pravettoni. IBGE, 2008; Commissao Pastoral da Terra, 2008.

BENEFITS FOR BIODIVERSITY AND ECOSYSTEM SERVICES

Implementing policies that protect and restore ecosystem carbon can bring biodiversity and ecosystem service benefits too but are likely to do so only if they are designed with these aims in mind.

Discussions about ecosystem carbon management recognise that it must offer multiple benefits to be politically acceptable. But it cannot be relied on to deliver those benefits in the absence of other policies: priorities will have to be co-ordinated, and cross-cutting international and national policies as well as input from interdisciplinary research are needed (Lal 2007; Miles and Kapos 2008). Carbon management measures have great potential for offering multiple benefits, such as the maintenance of biodiverse areas, and enhancement of ecosystem services such as soil fertility (UNEP-WCMC 2008; Eliasch 2008; Reid and Swiderska 2008).

REDD mechanisms are very likely to benefit biodiversity and can be designed to benefit local resource users at the same time. The challenge is to design regulations that do both, thereby avoiding biodiversity or livelihood trade-offs. In general mechanisms that include reduction in forest degradation are likely to have a greater positive impact on biodiversity than those confined to reducing deforestation. Reforestation activities may also have positive biodiversity impacts (Strassburg 2007; Strassburg *et al.* 2008; TCG 2008). However, afforestation may often have negative impacts on biodiversity.

Various mapping tools are being developed to support site-selection for REDD projects by identifying areas that are rich in both carbon and biodiversity (UNEP-WCMC 2008).

The Climate, Community and Biodiversity (CCB) Standards developed by the CCB Alliance are the most widely used and respected international standards for multiple benefits of land-based carbon projects (CCBA 2008). They aim to encourage the development of LULUCF projects under the Kyoto Protocol with net positive impacts on biodiversity as well as social and economic well-being (Taiyab 2006). Six projects have been approved already, 10 others are currently being reviewed and more than 100 projects intend to also apply the standards (CCBA 2008). Lessons learned from applying these standards could therefore serve as an important input into further policy negotiations on ecosystem carbon management measures.

CONCLUSIONS

The fact that we are having profound and far-reaching effects on the world's climate is no longer in serious doubt. As a result of human activities concentrations in the atmosphere of so-called greenhouse gases, chiefly carbon dioxide (CO_2), methane ($CH4$) and nitrous oxide (N_2O) are currently at levels unseen for at least the last 650,000 years, and are rising at unprecedented rates. Around two-thirds of the increase in greenhouse gases in the last 150 years or so can be ascribed to the burning of fossil fuels. Most of the rest is a result of changes in land-use and a small proportion is the product of burning calcium carbonate to produce cement. Land-use change – most notably deforestation – results in an increase in greenhouse gases chiefly through the release of carbon stored in biomass.

The greenhouse gases emitted as a result of human action enter the carbon and nitrogen cycles. As a result of these cycles, not all the greenhouse gases produced through human action remain in the atmosphere: it is estimated that nearly 30% of these emissions over the past 150 years have been absorbed by the oceans and just under 30% by terrestrial ecosystems.

The Intergovernmental Panel on Climate Change believes that in order to avoid the worst effects of climate change, at the very minimum greenhouse gas concentrations need to be stabilised at 445–490 parts per million carbon dioxide equivalent. The current concentration is around 430 parts per million CO_2e. At current rates of CO_2 emission alone, the threshold of 445 parts per million CO_2e will be reached in a mere seven years, even sooner if the accelerating output observed in the first few years of the present century continues.

Stabilising greenhouse gas concentrations can be achieved either by reducing the rate of emission, or by increasing the rate of absorption of the gases or both. Reduction in emissions from fossil fuel use is clearly of paramount importance. Carbon capture technologies that store the greenhouse gases produced at concentrated emission points such as power stations offer some hope for reducing rates of increase in emissions although their likely overall impact in the short or medium term remains uncertain.

But the management of fossil fuel use and adoption of carbon capture technologies will not in themselves be sufficient to prevent serious climate change in the next few decades. The management of carbon in living systems has a vital role to play: even with drastic cuts in fossil fuel emissions, current land-use practices would still lead to significant increases in greenhouse gas concentrations. Such management has two fundamental components: ensuring that existing carbon stocks held in natural ecosystems and in agricultural areas remain secure; and attempting to increase the rate at which carbon is sequestered in these systems.

Some aspects of the carbon cycle are at present effectively beyond direct policy control or technological intervention – notably the behaviour of the oceans in mediating the carbon cycle and global climate (large-scale fertilisation experiments are being undertaken to try to improve carbon fixing through oceanic photosynthesis, but there can be little human influence on the physical and purely chemical role of the ocean in the carbon cycle). Similarly, warming at high latitudes will lead to at least partial melting of the permanently frozen deep soil layer or permafrost there, releasing a proportion of the vast amount of carbon stored in the permafrost into the atmosphere. At present there are no technologies to prevent this happening: the only certain avoidance measure is to prevent the warming in the first place. Overall, there also appears to be relatively little scope at present for actively increasing carbon storage in most natural or largely natural ecosystems.

There are, however, many areas where appropriate policies and direct interventions could have major impacts. Large amounts of carbon are stored in peat soils worldwide and in remaining tropical moist forests. Protection of these from drainage and clearance would greatly help to slow down the rate of increase of greenhouse gases as well as delivering valuable benefits for biodiversity. Of particular importance are the tropical peat-swamp forests of South-East Asia – ironically under threat of clearance for biofuel production, despite the fact that their value as a carbon store hugely outweighs any possible carbon benefits to be gained from the biofuel crops that are replacing them.

Agricultural systems offer many opportunities for active carbon sequestration and reduction of emissions. They often have highly depleted soil carbon stocks, which could be replenished through the adoption of appropriate techniques, such as conservation tillage and integrated nutrient management using compost and manure. Overall, if best management practices were widely adopted, it is believed that the agricultural sector could become broadly carbon-neutral by 2030.

Not only is this technically possible, it is also economically feasible. Indeed, the IPCC has concluded that at an appropriate level of valuing or costing carbon emissions (US$100 per tonne of carbon dioxide equivalent), in 2030 the agricultural sector would be second only to building as potentially the most important sector for contributing to mitigation of climate change. At this level of carbon pricing, forestry and agriculture combined become more important than any other single sector. Even at lower carbon prices, the two sectors still retain high importance in mitigation.

There still remain many challenges to effective implementation. The greatest potential for increasing carbon storage in agricultural systems is in the developing world, where lack of knowledge and access to appropriate technologies are major barriers to change. Overcoming such barriers will need a commitment to capacity-building on a very extensive scale. Incentive-led systems, to encourage for example the planting of biofuels on marginal lands, need to be very carefully planned and executed if they are not to have adverse impacts on local livelihoods, on biodiversity or even on carbon stocks themselves.

If the global community can rise to these challenges, the Earth's living systems can play a vital role in the struggle to avoid dangerous climate change. Not only that, but measures to manage ecosystem carbon can offer great potential benefits for biodiversity and soil fertility. This opportunity to contribute to so many important environmental goals should not be missed.

GLOSSARY

Acidification
See Ocean acidification

Additionality
Additionality refers to the prevention of carbon emissions that would have occurred in a business-as-usual scenario (Angelsen 2008). This is an issue in the land use sector as the storage of carbon in ecosystems where it would not have been released cannot be compensated as an emissions reduction.

Afforestation
Afforestation is defined under the Kyoto Protocol as the direct human-induced conversion of non-forest land to permanent forested land (for a period of at least 50 years) (Angelsen 2008).

Agroforestry (systems)
Mixed systems of crops and trees providing wood, non-wood forest products, food, fuel, fodder, and shelter (Chopra *et al*. 2005).

Biofuel
Any liquid, gaseous, or solid fuel produced from plant or animal organic matter. E.g. soybean oil, alcohol from fermented sugar, black liquor from the paper manufacturing process, wood as fuel, etc. Second-generation biofuels are products such as ethanol and biodiesel derived from ligno-cellulosic biomass by chemical or biological processes (IPCC 2007a).

Biome
A biome is a major and distinct regional element of the biosphere, typically consisting of several ecosystems (e.g. forests, rivers, ponds, swamps within a region). Biomes are characterised by typical communities of plants and animals (IPCC 2007c).

Biosequestration
The removal of atmospheric carbon dioxide through biological processes, for example, photosynthesis in plants and trees (Department of Climate Change 2008).

Carbon Capture and Storage (CCS)
A process consisting of separation of CO_2 from industrial and energy-related sources, transport to a storage location, and longterm isolation from the atmosphere (IPCC 2007a).

Carbon cycle
The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere (IPCC 2007c).

Carbon sequestration
The process of increasing the carbon content of a reservoir other than the atmosphere (Chopra *et al*. 2005).

Carbon sink
See Sink

Carbon source
See Source

CCS
See Carbon Capture and Storage

CDM
See Clean Development Mechanism

Clean Development Mechanism (CDM)
A mechanism under the Kyoto Protocol designed to assist developed (Annex I) countries in meeting their emissions reduction targets. The mechanism reduces emissions through implementing projects in developing (Annex II) countries which are credited to the Annex I countries who finance and implement the project. The CDM aims to not only reduce emissions or increase sinks but also contribute to the sustainable development of the host country (Peskett *et al*. 2008).

Governance
The exercise of political, economic and administrative authority in the management of a country's affairs at all levels. Governance is a neutral concept comprising the complex mechanisms, processes, relationships and institutions through which citizens and groups articulate their interests, exercise their rights and obligations and mediate their differences (UNDP 1997).

Greenhouse gases
Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere (IPCC 2007a).

Kyoto Protocol
An agreement made under the United Nations Framework Convention on Climate Change (UNFCCC). Countries that ratify this protocol commit to reducing their emissions of carbon dioxide and five other greenhouse gases (GHG), or engaging in emissions trading if they maintain or increase emissions of these gases. The Kyoto Protocol now covers more than 170 countries globally but only 60% of countries in terms of global greenhouse gas emissions. As of December 2007, the US and Kazakhstan are the only signatory nations not to have ratified the act. The first commitment period of the Kyoto Protocol ends in 2012, and international talks began in May 2007 on a subsequent commitment period (Peskett *et al*. 2008).

Land Use, Land Use Change and Forestry (LULUCF)
A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities (UNFCCC 2009).

Leakage
In the context of climate change, carbon leakage is the result of interventions to reduce emissions in one geographical area (subnational or national) that lead to an increase in emissions in another area. For example, if curbing the encroachment of agriculture into forests in one region results in conversion of forests to agriculture in another region this is considered to be 'leakage'. In the context of REDD, leakage is also referred to as 'emissions displacement' (Angelsen 2008).

LULUCF
See Land Use, Land Use Change and Forestry

Mitigation
A human intervention to reduce the sources of or enhance the sinks for greenhouse gases (Department of Climate Change 2008).

Ocean acidification
A decrease in the pH of seawater due to the uptake of anthropogenic carbon dioxide (IPCC 2007c).

Permanence
The duration and non-reversibility of a reduction in GHG emissions (Angelsen 2008). This is an issue in the land use sector as carbon stored and sequestered in ecosystems is theoretically always vulnerable to release at some undetermined point in the future.

Precision agriculture
A suite of technologies that promote improved management of agricultural production by accounting for variations in crop performance in space. Also sometimes called "precision farming", "site-specific management" or "information-intensive farming" (Robertson *et al*. 2007).

Reduced-impact logging
Intensively planned and carefully controlled implementation of harvesting operations to minimize the impact on forest stands and soils, usually in individual tree selection cutting (FAO 2004).

Reforestation
Reforestation is 'the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested, but that has been converted to non-forested land'. In the first commitment period of the Kyoto Protocol, reforestation activities have been defined as reforestation of lands that were not forested on 31 December 1989, but have had forest cover at some point during the past 50 years (Angelsen 2008).

Respiration
The process whereby living organisms convert organic matter to carbon dioxide, releasing energy and consuming molecular oxygen (IPCC 2007c).

Sequestration
The removal of atmospheric carbon dioxide, either through biological processes (for example, photosynthesis in plants and trees, see Biosequestration), or geological processes (for example, storage of carbon dioxide in underground reservoirs) (Department of Climate Change 2008).

Sink
Any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere (IPCC 2007c).

Source
Any process, activity or mechanism that releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol into the atmosphere (IPCC 2007c).

Sustainability
A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs (Chopra *et al*. 2005).

United Nations Framework Convention on Climate Change (UNFCCC)
The United Nations Framework Convention on Climate Change (UNFCCC) is the first international climate treaty. It came into force in 1994 and has since been ratified by 189 countries including the United States. More recently, a number of nations have approved an addition to the treaty: the Kyoto Protocol, which has more powerful (and legally binding) measures (Kirby 2008).

UNFCCC
See United Nations Framework Convention on Climate Change

Zero tillage
In zero-tillage agriculture, the soil is never turned over, and soil quality is maintained entirely by the continuous presence of a cover crop (FAO 2008).

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