Ecological Economics 89 (2013) 61–72

Contents lists available at SciVerse ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Methodological and Ideological Options

Comprehensive carbon stock and flow accounting: A national framework to support climate change mitigation policy

Judith I. Ajani [a,*], Heather Keith [a], Margaret Blakers [b], Brendan G. Mackey [c], Helen P. King [a]

[a] Fenner School of Environment and Society, Australian National University, Canberra ACT 0200, Australia
[b] The Green Institute, GPO Box 557, Canberra ACT 2601, Australia
[c] Griffith Climate Change Response Program, Griffith School of Environment, Griffith University, Gold Coast campus, Griffith University, Queensland 4222, Australia

ARTICLE INFO

Article history:
Received 17 June 2012
Received in revised form 16 January 2013
Accepted 17 January 2013
Available online 17 March 2013

Keywords:
Carbon accounting
Carbon stocks
Carbon carrying capacity
Offsetting
Geocarbon
Biocarbon

ABSTRACT

Greenhouse gas (GHG) inventories underpinning the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol report each country's net annual emissions, that is GHG flows. Yet the UNFCCC's goal is defined as a stock (atmospheric GHG concentration). Flow inventories are apt for the fossil fuel sector where flows are effectively one way, stock changes are almost entirely anthropogenic, and stocks are stable in the absence of human perturbation. For the land sector, flow-based GHG inventories obscure fundamental differences between ecosystems: in their carbon stock stability, restoration capacity, and density. This paper presents a national carbon accounting framework that is comprehensive and includes stocks as well as flows for reservoirs, lands and activities continuously over time. It complements current flow-based inventories under the UNFCCC and Kyoto Protocol. The framework differentiates reservoirs by their role in the global carbon cycle, distinguishing between geocarbon (carbon in the geosphere), biocarbon (carbon in the biosphere) and anthropogenic carbon (stockpiles, products and waste). A reservoir ranking system is proposed based on longevity, reversibility of carbon loss, and carbon density. This framework will support policy makers and researchers grappling with mitigation strategies and competing demands on agricultural land and natural ecosystems.

1. Introduction

The climate change problem is caused by human-induced increases in the stock of greenhouse gases (GHGs) in the atmosphere.[1] The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) is to limit this stock and achieve '… stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (United Nations, 1992, Article 2). Article 3 states that policies and measures to deal with climate change should be 'comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors'. The UNFCCC is implemented largely through the Kyoto Protocol for those Parties that have ratified it (United Nations, 1998), with separate GHG inventories reported for the UNFCCC and the Kyoto Protocol.

In contrast to the UNFCCC objective, which is expressed in stock terms, the mitigation policies and compliance targets determined by UNFCCC negotiations are expressed in terms of GHG flows (UNFCCC, a); that is, reducing emissions from sources (to the atmosphere) and increasing removals by sinks (from the atmosphere). Reducing emissions from fossil fuels was the first main challenge addressed by the UNFCCC. For this, an accounting framework and policy target defined by flows was appropriate as fossil fuel use generates what is effectively a one-way emission to the atmosphere. This focus on flow accounts was continued for the Land Use and Land-Use Change and Forestry (LULUCF) sector but the land–atmosphere interaction is different because flows are two-way with emissions to and removals from the atmosphere. An additional difference in the land sector is that the stability of the carbon stocks depends on characteristics of ecosystems derived from their biological diversity. Stock accounts can capture these characteristics through a classification of ecosystems and reporting the carbon reservoirs for each ecosystem type.

In addition to accounting for stocks, a comprehensive framework for carbon accounting must include all anthropogenic gross flows (as distinct from the current reporting of net flows). However, under the Kyoto Protocol, not all flows, activities and land areas are accounted in the rules, definitions and modalities for LULUCF. These were established by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the UNFCCC and the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2000a), and agreed upon at Marrakesh (United Nations, 2002). The Marrakesh Accords were a politically

* Corresponding author. Tel.: +61 2 6125 4760; fax: +61 2 6125 0746.
E-mail addresses: judith.ajani@anu.edu.au (J.I. Ajani), heather.keith@anu.edu.au (H. Keith), margaret.blakers@bigpond.com (M. Blakers), b.mackey@griffith.edu.au (B.G. Mackey), helen.king@anu.edu.au (H.P. King).

[1] A glossary is presented in the supplementary file accompanying this paper.

0921-8009
http://dx.doi.org/10.1016/j.ecolecon.2013.01.010

negotiated agreement for the LULUCF sector. Since the agreement, unintended and counterproductive consequences for the overall goal of stabilizing atmospheric GHG concentrations have arisen, particularly relating to the treatment of natural ecosystems (Höhne et al., 2007; Schulze et al., 2002).

Accounting in the land sector was used as a means of offsetting fossil fuel emissions without changing the targets (Schulze et al., 2002) with the rules for LULUCF negotiated after the Kyoto Protocol targets for emission reduction had been set. Using the land sector as an offset lessened the incentive to reduce fossil fuel emissions, with the target being reduced from the stated 5% to an effective 2% (Höhne et al., 2007). Offsetting embodies an incorrect assumption that reservoirs and their stocks of GHG precursors are uniform and interchangeable (fungible) from a climate perspective. However, the mitigation value of land carbon is not fungible because, as discussed below, long-lived carbon stocks have a different influence on atmospheric GHG concentrations compared with short-lived stocks.

The aim of this paper is to present a carbon accounting framework for use in climate change mitigation policy, research and public discussion. It complements the flow-based framework that currently underpins the UNFCCC and Kyoto Protocol. The paper focuses on the geosphere and biosphere, which we call primary reservoirs, given that the primary proximate cause of global warming is the release of carbon by human activity from these reservoirs. The accounting framework is based on a scientific understanding of the role of the land carbon reservoir in the global carbon cycle. Such an accounting framework requires comprehensiveness in time and space; inclusion of stocks as well as flows for all sectors, lands and activities associated with the primary reservoirs continuously over time; and recognition of the different characteristics of land carbon stocks. The purpose of GHG accounts and current approaches to collecting and reporting information are reviewed, the reservoirs making up the global carbon cycle are defined and characterized, and criteria are proposed for ranking reservoirs according to their importance for climate change mitigation. The implications of comprehensive stock and flow accounts are greatest for the land sector but also apply to fossil carbon reservoirs, and are discussed in terms of mitigation policies.

2. The Land Sector in the Global Carbon Cycle

2.1. Carbon Reservoirs and their Attributes

This paper focuses on carbon stocks and stock changes within the global carbon cycle because carbon dioxide (CO_2) is the most important anthropogenic GHG (IPCC, 2007). In the time frame of years to centuries, there are four major carbon reservoirs of importance in the global carbon cycle: the atmosphere; ocean water; the geosphere; and the biosphere. We define geocarbon as carbon stored in the geosphere: in fossil fuel reserves, sedimentary rocks including limestone, methane clathrates, and marine sediments. Carbon stored in the biosphere, in living and dead biomass and soils (both organic and inorganic carbon) in terrestrial and marine ecosystems, is called biocarbon.

The characteristics of stability and longevity of reservoirs are important in determining their role in the global carbon cycle with respect to the permanence or rates of exchange of their carbon stocks with the atmosphere. Carbon from different reservoirs of fossil fuels (i.e. coal, oil, gas) is fungible in that all reservoirs have similar characteristics in terms of their stability and longevity in the absence of human perturbation. This is not the case for carbon stocks held in biosphere reservoirs which vary in terms of these characteristics. A primary distinction can be made between ecosystems that are: (i) human designed, engineered and maintained and (ii) products of natural processes (natural ecosystems). The former includes land which is cultivated to grow crops of annual and perennial plants mainly for food, wood and fiber, and increasingly as feedstocks for biofuels and biomaterials, that is agricultural lands (including plantations).

Agricultural lands carry stocks of carbon that, relative to natural ecosystems, are smaller and have shorter lifetimes as the plants are regularly harvested. In a general sense, the aim of human management of agricultural land, including plantations, is to optimize the rate at which new biomass is produced for harvesting at regular periods. One consequence of this optimization goal is a reduction in the size of accumulated carbon stocks, particularly in living and dead biomass.

Natural ecosystems, by contrast, result from ongoing evolutionary, ecological and biological processes within which human cultural and traditional uses also occur. Natural selection, the key process, operates on traits of species and system-level properties over time to create a diversity of characteristics. The species that persist are those best able to utilize the available resources and survive stress periods. Natural selection also optimizes a species' physiological processes (Cowan and Farquhar, 1977). System-level properties that are naturally optimized include canopy density, energy use, nutrient cycling, resilience, trophic interactions and adaptive capacity (Brown et al., 2004). Genetic, taxonomic and functional diversity means the species pool contains plants and animals with varying life histories and niche tolerances to maximize utilization of resources, and natural selection reveals those best suited to new conditions (Hooper et al., 2005).

Ecosystem resilience, the capacity of an ecosystem to persist when subjected to disturbance and environmental change, is a critical property determining the stability of the ecosystem's carbon stock. Resilience is a function of genetic, taxonomic and functional biodiversity that allows micro-evolution to result in populations developing traits that are tailored to local environmental conditions and other selective forces (Bradshaw and Holzapfel, 2006). Characteristics of resilience include regeneration after fire, resistance to and recovery from pests and diseases and adaptation to changes in radiation, temperature and water availability (Mackey et al., 2008; Secretariat of the Convention on Biological Diversity, 2009). These resilience processes, based on the ecosystem's biodiversity, mean that the carbon stocks in natural ecosystems, as distinct from human made or modified ecosystems, are more likely to persist and hence accumulate large carbon stocks in soils and plants, particularly in large, old trees (Thompson et al., 2009).

From the perspective of the carbon cycle, it is the total amount of carbon and the length of time it is stored in the land sector that influence the carbon stock in the atmosphere (under equivalent rates of geocarbon emissions). The importance of distinguishing ecosystem characteristics based on their value for climate change mitigation is well illustrated by comparing plantations and forests used for wood production with natural forest ecosystems. A fast-growing plantation supplying wood for economic production also provides a high annual rate of CO_2 removal. However, the carbon stocks accumulated are relatively small before the plantation is harvested. Similarly in natural forests that are logged periodically for wood, stock levels are kept low but may rebuild with the cessation of wood extraction (Brown et al., 1997; Dean et al., 2012a, 2012b; Diochon et al., 2009; Kanowski and Catterall, 2010; Keeton et al., 2010; Nepstad et al., 2001; Thornley and Cannell, 2000). Being an agricultural system, plantations are efficient in wood production. Natural ecosystems with their biodiversity-based characteristics are effective carbon stock reservoirs. Exploiting these different reservoir characteristics should be of interest to policy makers operating in a world of limits, as discussed in detail in Section 4.5.

2.2. Stock Changes Since 1850

Over the period 1850 to 2000, humans have caused about 275 Pg of carbon emissions from fossil fuel use and cement production

(Houghton, 2007). To date, this geocarbon stock depletion, relative to accessible stocks, has been small (Fig. 1). Over the same period, Houghton (2003, 2007, 2008) estimates a global net biocarbon loss of 156 Pg due to changes in land use and management. Biocarbon stocks have been depleted largely through the clearing of around 50% of the world's natural forests (Archer, 2005; Millennium Ecosystem Assessment, 2005). Houghton (2007) reports significant differences in the estimates of biocarbon stock changes and presents possible explanations including errors in the analyses either in ocean models or the land-use change calculations, or terrestrial carbon flows unrelated to land-use change. This imbalance, meaning the stock change estimates do not align (see Fig. 1), is an important motivation for developing a comprehensive set of carbon accounts.

2.3. Relationship between Geocarbon and Biocarbon

The land sector has two roles in the global carbon cycle that contribute to climate change mitigation; namely, reducing or avoiding further emissions from land-use change and degradation, and removing CO_2 from the atmosphere. The land sector is responsible for an estimated 10–33% of annual human-induced greenhouse gas emissions, the rate of which has varied over time (Houghton, 2007, 2008; Le Quéré et al., 2009; Pan et al., 2011; Raupach and Canadell, 2010; Global Carbon Project, a). The land sector has the potential to provide cost-effective, short-term mitigation options (Benndorf et al., 2007; Nabuurs et al., 2007; Richards and Stokes, 2004) albeit with varying trade-off implications for land use. Such removals are an important component of climate change mitigation because the problem of elevated atmospheric concentrations of carbon will remain for a long time even if fossil fuel emissions cease (Archer, 2005).

The land sector was brought into the global climate change negotiations in a policy frame that recognized removal of CO_2 from the atmosphere by plant photosynthesis as an 'offset' against fossil fuel emissions. The fossil fuel dominated carbon market is now widely perceived as a major new source of funding for maintaining land-based carbon stocks and increasing removals of atmospheric CO_2. However, CO_2 removal by the land sector is essentially recapturing past emissions due to land use or land-use change and therefore does not neutralize fossil fuel emissions.

The role of the land use sector in climate change mitigation is significant but limited. The Global Carbon Project reports human activity caused 10.0 ± 0.9 PgC of carbon stocks to be emitted to the atmosphere in 2010, 9.1 ± 0.5 PgC from fossil fuels and cement and the remainder from the land sector (Global Carbon Project, a). At this rate, a theoretical world-wide return of all land to pre-industrial revolution carbon stock levels (addition of 156 PgC, see Fig. 1), would offset less than two decades of fossil fuel emissions. The land sector, however, cannot return to its full carbon carrying capacity. It is limited by competing food and shelter claims and because soil resources have been permanently degraded in some areas so that revegetation is unlikely to result in carbon stocks returning to their earlier levels. Furthermore, the actual rate at which ecosystems can take up carbon is limited by environmental factors. Significantly, the UNFCCC also permits a second form of offsetting against 'avoided emissions' from deforestation and forest degradation. Taken to the limit, this would allow action to reduce fossil fuel emissions to be deferred for decades.

3. Current Greenhouse Gas Accounting and Reporting Systems

3.1. UNFCCC National GHG Inventories

National greenhouse gas inventories (NGGI) report annual greenhouse gas emissions, consistent with the flow-based approach of the UNFCCC and Kyoto Protocol. The rules for accounting in NGGI are based on frameworks, concepts, definitions and standards prepared by the IPCC which is funded by the United Nations Environment Programme and World Meteorological Organization. NGGI cover sectors and categories based on human activities that generate emissions and removals and report annual net flows of GHG emissions to the atmosphere and removals from the atmosphere (IPCC, 2003, 2006).

Variations occur between the NGGI for the UNFCCC and Kyoto Protocol as they serve different functions. For countries that have ratified the Kyoto Protocol, NGGI are the basis for assessing compliance with emission reduction targets. In UNFCCC inventories, the land sector is divided into six land use categories with parties reporting net emissions from managed lands, considered to be due to anthropogenic activities. In the Kyoto Protocol, the land sector is divided on the basis of activities as well as land use categories. In both

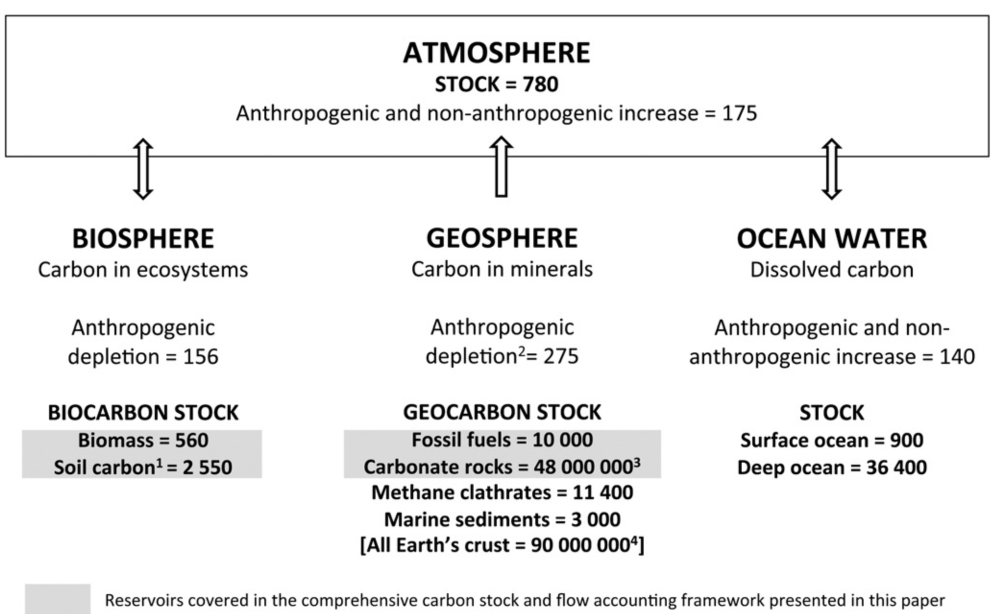

Fig. 1. Carbon stocks in the 1990s and stock changes over the period 1850 to 2000. Units are petagrams of carbon (PgC). Carbon stock estimates are sourced from Holmém, 2000; Kempe, 1979; Lal, 2004; and MacDonald, 1990. Carbon stock changes are sourced from Houghton (2007) who identifies a substantial imbalance in the estimated stock changes. Note 1: measured to 1 metre. Note 2: fossil fuel and cement production. Note 3: carbon accounts would report carbon in carbonate rocks mined or likely to be mined, including for cement or agricultural use. Note 4: indication of carbon stocks in the lithosphere, including all of the above and other components.

cases, emissions and removals from unmanaged lands are presumed to be natural and therefore omitted. These approaches, while pragmatic, generate incomplete inventories of human-induced emissions and removals. For some countries, land sector flow data reported in NGGI is derived using stock information and could be used to help populate complementary carbon stock accounts.

Changes to accounting rules are inevitable as the system evolves, and these can be more readily accommodated in comprehensive accounting frameworks and with lower loss of time series data quality. Conferences of the Parties to the UNFCCC decisions generate NGGI changes for reporting countries. For example, decisions made at the 17th Conference of the Parties to the UNFCCC held in Durban in 2011 (COP17) make it mandatory for Kyoto Protocol countries to report on forest management (Article 3.4). Previously, it was only mandatory to report emissions from land-use change and direct human activities in the form of reforestation, afforestation and deforestation under Article 3.3. Reporting of other Article 3.4 emissions and removals from revegetation, cropland management, grazing land management, and wetland drainage and rewetting remains optional unless a party accounted for them in the first commitment period (United Nations, 2012). New optional rules negotiated at COP17 are expected to introduce new levels of accounting variability between countries. For example, an optional natural disturbance rule will allow for the exclusion of net emissions from natural disturbances above a pre-set disturbance baseline (United Nations, 2012).

Marine ecosystems are not currently included because they fall outside the IPCC's land use categories. Sea grasses therefore are not covered and while, in theory, mangroves and salt marshes could be covered within the forests and grasslands land use categories respectively, the IPCC guidelines do not provide emissions or removal factors (O'Sullivan et al., 2011). The IPCC has proposed increased guidance in marine ecosystem reporting.

Servicing the evolving reporting needs of signatory countries and providing full and consistent time series information for climate change policy requires accounting frameworks with comprehensiveness embedded in them as a core principle.

3.2. Carbon Stock Accounting Systems

The carbon accounting framework presented in this paper builds on the recommendation of the German Advisory Council on Global Change (WBGU) to account for all carbon stocks and flows. WBGU proposed a framework for carbon accounting, reporting and regulation based on the total stock of carbon in the atmosphere (Graâl et al., 2003; Schellnhuber et al., 2009). Termed the 'budget approach', it calculates the global budget of cumulative CO_2 emissions that can be released to the atmosphere if total atmospheric concentrations are to be kept at a level that would prevent dangerous anthropogenic interference with the climate system.

Developing the guidelines for carbon stock accounting forms part of the UN Statistics Division's development of an environmental-economic accounting system. The System of Environmental-Economic Accounting (SEEA) Central Framework was adopted as an international statistical standard by the UN Statistical Commission in 2012 (UN Statistical Commission, 2012). It is a multipurpose conceptual framework for understanding environment-economic interactions, and for reporting stocks and stock changes in resources such as water, wood and fish. The next stage – SEEA Experimental Ecosystem Accounting – includes, among other things, the development of a carbon stock accounting framework. Based on the SEEA Central Framework, the Australian Bureau of Statistics included an unpopulated carbon stock account in their *Completing the Picture — Environmental Accounting in Practice* (Australian Bureau of Statistics, 2012). It combines slightly modified System of National Accounts (SNA) stock change row components and a carbon reservoir classification informed by this paper.

The Global Carbon Project (Global Carbon Project, b) compiles comprehensive data on the flows associated with the global carbon cycle, including geographical and temporal variations, to better understand the drivers of climate change. In 2011, the Global Carbon Project commenced the Earth Carbon Pools Size and Certainty project which aims to present a comprehensive account of all carbon stocks on earth.

A global carbon stock account complements national accounts by enabling reporting of carbon stocks and stock changes in the global commons atmosphere and hydrosphere and helps check aggregated national accounts.

4. The Policy Need for Carbon Stock Accounts

Economic accounting under the SNA, produced and released under the auspices of the United Nations, the European Commission, the Organisation for Economic Co-operation and Development, the International Monetary Fund and the World Bank Group, aims to generate a complete and consistent account of national economic stocks and flows (European Commission et al., 2009). This information is used by governments to develop and monitor policies; researchers for analysis; the public to understand and engage in public debate; and the private sector to identify business and investment opportunities. National carbon accounting systems also need to be comprehensive because they likewise serve multiple objectives: providing information for climate change mitigation policy; monitoring and evaluation; contributing to scientific understanding of the global carbon cycle; informing public debate; and providing data for annual UNFCCC reports.

Opportunities exist (see for example, Schlamadinger et al., 2007) to improve the rules and guidelines for land sector accounting post-2012 through LULUCF (under the Kyoto Protocol), REDD (Reducing Emissions from Deforestation and Degradation in developing countries) and post-Kyoto Protocol negotiations. The stock-based accounting framework presented in this paper works to complement existing flow-based inventories. Grounded from the start in the principle of comprehensiveness, stock-based accounting presents an opportunity to address the gaps in existing flow-based inventories, including through generating flow data in the form of stock changes over defined time periods. Likewise, the classifications and data sets underpinning existing UNFCCC and Kyoto Protocol inventories can inform the construction of stock accounts. Ultimately, policy makers, researchers and the public require comprehensive and linked carbon stock and flow accounts.

4.1. Accounts Linked to UNFCCC Objective

The over-arching goal of the UNFCCC is defined in stock terms (GHG concentrations in the atmosphere). This means stabilizing the concentrations of atmospheric GHGs at a specific quantity (stock) in the atmosphere that avoids dangerous climate change. Carbon stock accounts therefore directly link to the core goal of the UNFCCC. Carbon stock accounts are in accord with the main conclusion of Allen et al. (2009) that, given scientific uncertainty, policy targets aimed at limiting cumulative emissions of CO_2 are likely to be more robust than emission rate or concentration targets. This conclusion is derived from their key finding that the relationship between cumulative emissions of CO_2 and peak warming is 'remarkably insensitive' to the timing or rate of CO_2 emissions. Meeting the UNFCCC objective requires nations to understand the nature of their carbon stocks (carbon being the dominant anthropogenic GHG) and it is therefore logical for them to quantify and report carbon stock levels in their territory.

4.2. Increased Policy Options

Climate change mitigation policy is focused on countries taking responsibility for the emissions occurring in their territory: however policy could also be aimed at countries taking responsibility for the stocks stored in their territory (Davis et al., 2011). Comprehensive accounting of stocks and flows would support policies to reduce emissions by maintaining geocarbon stocks in the geosphere, but would also provide consistent and comparable statistical information to support policies to protect and restore biocarbon stocks in natural ecosystems independent of whether they are currently threatened by degradation or deforestation (the pre-condition for obtaining carbon credits for 'avoided' deforestation or degradation).

Comprehensive carbon stock and flow accounts would support policy interventions at any point along the chain from the primary stocks in the geosphere and biosphere to changes in various anthropogenic stocks (for example, cement in buildings) and eventually emissions to the atmosphere. Bushnell and Mansur (2011) investigated the intersection between the point of regulation and leakage and found that direct regulation at the emission point results in leakage to unregulated countries, whereas a carbon price at source to address emissions from downstream consumption may reduce emissions in other countries, depending on the elasticities of demand and supply.

4.3. Reduced Unintended Consequences

Some land-based mitigation policies result in a long-term increase in atmospheric GHG concentrations (e.g. Searchinger et al., 2009). Such unintended outcomes are the result of incomplete accounts and ignoring the time factor (stock longevity) and the ecosystem characteristics that contribute to biocarbon stock stability. While an accounting system could classify flow data according to these characteristics, the imperative for such a classification becomes clear when preparing a stock framework as discussed in Sections 5 and 6. For example, offsetting fossil carbon emissions by afforestation depletes a highly stable carbon-dense stock (fossil carbon) by building up a less stable, less carbon-dense stock (usually trees, often in plantations subject to regular harvesting at relatively short time periods). Comprehensive carbon accounts would inform policy makers of options to preferentially protect natural ecosystems with stable and carbon-dense stocks relative to afforestation-based stocks.

4.4. Time and Stock Longevity

Time is a crucial dimension to understanding potential solutions to the climate change challenge. Geocarbon stock depletion (e.g. fossil fuel emissions) with corresponding accumulation in the atmosphere is effectively permanent. Injecting CO_2 into underground geological formations (geosequestration) will reduce the rate of atmospheric accumulation, all else being equal, but at the expense of depleting the stock of carbon stored in highly stable and dense carbon reservoirs and increasing the stock of carbon in less stable and less dense carbon reservoirs.

Depletion of biocarbon stocks may be reversible, but removal into the new stock (sequestration) must take into account both the rate at which the stock accumulates and its longevity. Powlson et al. (2011) caution that the use of the term 'sequestration' should be applied only to activities that permanently increase the land carbon stock by removing carbon from the atmosphere. Stock accounts can be constructed to make transparent the relationship between time (stock longevity) and the ecosystem characteristics that contribute to biocarbon stock stability. This can be done by defining and ranking carbon reservoirs such that permanent or long-lived emissions and removals can be distinguished from temporary or shorter-lived stock changes. Alternatively, temporary emissions could be weighted according to the time taken to restore the carbon density of the originating reservoir, but this would be a more complex and contested approach. The question remains open as to the length of time over which 'temporary' stock changes approach 'permanent' with respect to their climate impact.

4.5. Limits

The climate change problem is fundamentally about limits to the magnitude of carbon stocks in the atmosphere, the oceans and also on the land. Stock-based information is needed to explore mitigation options such as: excluding or limiting biocarbon offsets and focusing on fossil fuel emission reduction; allowing fossil fuel emissions to be offset by biocarbon credits; or setting separate rules and targets for geocarbon and biocarbon with an accounting firewall between them.

In the land sector, stocks are limited by land area and maximum carbon densities (Powlson et al., 2011). The carbon stocks found in natural ecosystems and agricultural land derive from net uptake of CO_2 by plants and are a function of both the trajectory of net uptake over time and the asymptote or maximum carbon density. The maximum carbon density is best considered as a dynamic equilibrium where, for the defined ecosystem, short term natural fluctuations and disturbances can be averaged over time and space for accounting purposes, as distinct from a site level carbon density. Carbon carrying capacity is defined as the mass of biocarbon able to be stored under prevailing environmental conditions and natural disturbance regimes, but excluding anthropogenic disturbance (Gupta and Rao, 1994; Mackey et al., 2008). Stock-based carbon accounts can readily accommodate carbon carrying capacity measures. The difference between the carbon carrying capacity and the current carbon stock in ecosystems across the landscape reflects the impact of land use history in depleting these stocks and provides an estimate of the sequestration potential (Keith et al., 2009; Roxburgh et al., 2006). This sequestration potential is affected by rising atmospheric CO_2 levels and by climate change itself which may cause the potential size of the land carbon stock to increase or decrease. For example, the potential carbon carrying capacity and rate of sequestration depends on the direction of changes in the intensity and frequency of droughts and disturbances such as fire and insect outbreaks, limitations to plant productivity by the availability of water and nutrient resources, and rates of soil respiration. The limit of terrestrial carbon sink capacity has been simulated in dynamic global vegetation models of growth processes in relation to environmental conditions, with predictions that the capacity of the earth system to absorb human-induced carbon emissions will be reduced by future climate change (Cramer et al., 2001; Friedlingstein et al., 2006).

Carbon stock accounts that incorporate carbon carrying capacity provide information that is highly relevant to policy related to the demand for food, fiber and fuel from a finite land asset. Policy issues include: (i) estimating the carbon footprint of converting natural ecosystems to agricultural land; (ii) prioritising land for restoration of biocarbon stocks through reforestation, revegetation, restoration or improved land management; (iii) the tradeoffs between managing land to favor carbon stocks or food or fiber production; and (iv) assessing the density and longevity of the carbon stored under different agricultural land uses and the contribution to climate mitigation (Kirschbaum, 2006; Powlson et al., 2011). Stock accounts should clarify the importance of retaining natural ecosystems because of their relative stability and high accumulated carbon densities and because of the long time needed to restore stock levels if these ecosystems are degraded.

4.6. Transparency

UNFCCC methodologies are designed to report net annual GHG emissions rather than emissions and removals separately. Reporting net emissions in the land sector loses information about unidirectional flows, the processes driving them and the characteristics of their precursor stocks. Thus, relatively stable and long-lived stocks can be depleted and the emissions subsequently sequestered into temporary stocks. An example is the conversion of natural grasslands or forests to cropland that may have high rates of production in the short-term but is then harvested. The emission is partly balanced by sequestration in the short-term but the stock of carbon will be reduced, and the change in land use contributes to an increase in atmospheric CO_2 concentrations in the longer term.

For the land sector, reporting emissions and removals separately for each land unit at appropriate time scales is problematic because of concurrent photosynthesis, respiration and decomposition processes. Where anthropogenic influences are in operation, for example harvesting a forest, the accounting challenge is to capture the information needed to support research and policy. The approach taken in the SEEA Central Framework (United Nations Statistical Commission, 2012) of specifying land units is a potential way forward. Each unit would be tagged with a land use history, carbon carrying capacity estimate and annual carbon stock changes (or cumulative stock changes over longer time periods). For land units experiencing degrading human activities during the year (for example, timber harvesting) carbon stocks will be depleted, while in non-harvest years generally stocks will increase with plant growth. This approach provides a more informative data set for aggregation that addresses, albeit partially, the obscuring of spatial and temporal variability through reporting net annual flows.

4.7. Types of Data Fit for the Purpose

Carbon reservoirs have many qualitative differences (Table 1), and hence their quantification is based on different types of data with varying statistical reliability. These differences, notably between geocarbon and biocarbon reservoirs and among different biocarbon reservoirs, require different types of measurements that provide varying levels of accuracy. For inventories serving multiple purposes including policy formulation, these quality differences have to be accommodated within a unified accounting framework.

Geocarbon stocks are inert, incur little or no cost in maintaining their quality, and rarely compete with land uses. Geocarbon stock changes are almost entirely anthropogenic and it is only when the stocks are utilized, for example through mining, that they may compete with other land uses. The number of enterprises and establishments processing geocarbon for energy and other products such as cement is relatively small. Biocarbon stocks encompass the entire landscape, require protection from degrading land uses, and if maintained or increased may compete with alternative land uses. The dynamics of biocarbon stocks and flows are influenced by complex interactions of human activities, natural disturbances and climate variability that can be difficult to separate. Carbon emissions and removals due to human land use activities can occur over many years, whereas most emissions from fossil fuels occur immediately (Höhne et al., 2007). For biocarbon, the number of entities, in terms of spatial units of analysis, is large for both in situ ecosystem stocks and anthropogenic stocks (e.g. wood products). The spatial and temporal variability in biocarbon stocks means that estimation is difficult and comes with relatively large standard errors and confidence intervals that are important to recognize in providing statistically reliable information.

When data from geocarbon and biocarbon stocks are combined and converted to a CO_2-e quantity, substantial underlying differences in stock characteristics and reliability of the data may be masked. Evaluation of these data types, in terms of knowledge gaps, quality of the sources and uncertainties, is important for policy making.

4.8. Carbon Accounts and Climate Change

Carbon accounts cover global warming induced by CO_2, presently the main driver of climate change, and methane (CH_4). In comprehensive accounts the carbon embodied in flows of these gases into and removed from the atmosphere should be disaggregated. Carbon accounts should also be complemented by appropriate accounts for emissions of other greenhouse gases including nitrous oxide, hydrofluorocarbons and the like. While stock and flow carbon accounts are an important information source for policy and research, they do not substitute for scientific assessment of the dynamic relationships between CO_2 levels, other greenhouse gases and the climate.

5. Classification and Ranking of Carbon Reservoirs

5.1. Classification of Carbon Reservoirs

As noted above, different carbon reservoirs vary qualitatively, including in their inherent stability and susceptibility to human perturbation. Carbon accounting therefore requires a reservoir classification system. Following the UNFCCC, “reservoirs” are defined as components of the climate system where a GHG or its precursor is stored. Stocks are the quantity of carbon in a given reservoir. In this proposed framework, top-level carbon reservoirs are: primary (biosphere and geosphere), anthropogenic, atmosphere and ocean water, with subsets of reservoir types (Table 2).

5.1.1. Primary Reservoirs

Primary carbon reservoirs are defined as those in the geosphere (geocarbon) and the biosphere (biocarbon). The release of carbon from these reservoirs by human activity is the primary cause of global warming. The geocarbon reservoir comprises: (i) fossil fuel deposits of coal, oil and gas; (ii) carbonate minerals such as limestone used to produce cement; (iii) marine sediments on the ocean floor; (iv) methane clathrates; and v) Earth's crust (Fig. 1). Anthropogenic CO_2 emissions into the atmosphere occur during cement production, mining, burning fossil fuel for energy and through industrial processes.

The biocarbon reservoir comprises carbon in living and dead biomass (plants and animals) and carbon in soils in terrestrial and marine

Table 1
Qualitative differences in geocarbon and biocarbon.

Attribute	Geocarbon	Biocarbon
Extent	Specific to deposit location	Entire landscape
Stock stability and maintenance cost	Highly stable in the absence of human activity and zero cost to maintain	Ongoing ecosystem management is needed
Competition with other land uses	In situ, nil	Competes with alternative uses of land and water including food production
Cause of stock change	Almost entirely anthropogenic	Stocks vary temporally and spatially to such an extent that statistically reliable estimation is difficult. Distinguishing anthropogenic from non-anthropogenic stock changes is complicated
Number of entities and transaction points	Few owners/extractors of stocks. As carbon-containing products move through the economy, the number of entities and possible transaction points increases	The number of entities is large both for stocks in situ and for anthropogenic stocks

Table 2
Definition of carbon reservoirs based on their role in the global carbon cycle and their physical and ecological attributes.

Carbon Reservoirs	Carbon Cycle Component	Description
Primary Contain carbon stocks that are or can be mobilised in the carbon cycle and whose depletion is the main source of increased concentrations of GHGs in the atmosphere and oceans	**Geocarbon** Carbon reservoirs in the geosphere	**Sediments** Carbon reservoirs in sedimentary rocks and deep ocean sediments
		Fossil carbon deposits Carbon reservoirs in coal, oil and gas deposits including, shale oil and gas
	Biocarbon Carbon reservoirs in the biosphere	**Ecosystems** Carbon reservoirs in terrestrial and marine ecosystems. Includes peat; excludes CO_2 in the oceans
Anthropogenic Contain carbon stocks created by human activity	**Stockpiles** Carbon in stockpiles of materials from primary reservoirs	
	Processed Carbon and other materials transformed by human activities	**Products** Carbon in products in use, e.g. wood, cement, plastics, bitumen
		Waste Carbon in waste created by human activity. Includes solid, liquid and gaseous wastes, the latter including geosequestered CO_2
Atmosphere and Ocean water Contain stocks of CO_2 and other GHGs whose increasing concentration is interfering with the global climate system	**Atmosphere** CO_2, CH_4 and other carbon-based gases in the atmosphere	
	Ocean water Dissolved CO_2 and carbonic acid	Shallow water Deep water

vegetated ecosystems. Biocarbon in different ecosystems is recognized based on environmental and biological attributes, e.g. natural and agricultural ecosystems. Marine vegetated ecosystems include mangroves, saltmarshes and seagrass beds. Although these are currently excluded from NGGI, they are important carbon reservoirs as organic matter decomposes and is stored in shallow sediments where it can remain for millennia (Nellemann et al., 2009). Marine vegetated ecosystems should be identified as a distinct biocarbon reservoir as they have different characteristics to terrestrial ecosystems relevant to mitigation policy options. Peatland is included as a biocarbon reservoir, with peatland vegetation ranging through terrestrial and marine ecosystems including grasslands, forests, mossbeds, mangroves, saltmarshes and paddies. Wetland drainage and peat used for energy can generate significant carbon emissions (see for example, Hooijer et al., 2010).

5.1.2. Anthropogenic Reservoirs

These human-created carbon reservoirs include stockpiles of carbon-containing materials (mined or harvested materials held until the next accounting time period for processing or use); products in use such as concrete, wood and bitumen; and waste reservoirs, including geosequestered GHGs. The carbon stocks embodied in imported and exported products are reported in anthropogenic reservoirs.

5.1.3. Atmosphere and Ocean Water

The atmospheric carbon stock is usually described as a concentration of CO_2. It was 278 ppm prior to human-induced emissions (Global Carbon Project, a) and has been increased by CO_2 emitted from burning fossil fuel and from the land sector. About 40–45% of these emissions remain in the atmosphere with the remainder being taken up by the oceans and terrestrial and marine ecosystems (Le Quéré et al., 2009). The share which is taken up by the biosphere and oceans varies from year to year depending on climatic conditions. Ocean water comprises shallow and deep ocean reservoirs, with the deep ocean being the largest reservoir of carbon in the global cycle, apart from in carbonate rocks and the Earth's crust.

In the framework presented in this paper, we focus on the primary carbon reservoirs of geocarbon and biocarbon whose depletion is the main source of increased concentrations of GHGs in the atmosphere and oceans.

5.2. Ranking of Carbon Reservoirs

The atmospheric concentration of CO_2 is increasing because the rate of anthropogenic emissions exceeds the rate at which natural processes remove CO_2 from the atmosphere (Le Quéré et al., 2009). The life-time of an air-borne pulse of CO_2 is a function of the rate that CO_2 ends up in deep ocean sediments, thereby removing it from exchanges with the atmosphere. Current modelling suggests that about 60% of emissions are removed after 100 years, but there is a long tail which continues to interact with the climate system for millennia (Archer et al., 2009; Prentice, 2007).

Permanent removals from the atmosphere are not sufficient to neutralize emissions. In 2010, anthropogenic net emissions of 10.0 PgC were reported globally with atmospheric CO_2 concentration increasing by 5.0 PgC (Global Carbon Project, a). The difference represents removals of carbon by the biosphere and oceans. Much of this is, however, temporary and only 0.3 PgC a year are removed permanently into ocean sediments (Feely et al., 2004), representing only 3.0% of current annual emissions. This slow removal and the difference between temporary and permanent reservoirs underpin interest in protecting existing stocks of carbon in primary reservoirs: recognising that global terrestrial carbon storage capacity is limited and appreciating that reservoirs have different characteristics. Our ranking of reservoirs allows these distinctions to be readily incorporated in an accounting system.

Primary carbon reservoirs of geocarbon and biocarbon differ fundamentally in the amount and stability of their carbon stocks and the reversibility of stock losses, that is whether the stock can be restored and over what time period (restoration time). They exchange carbon with the atmosphere and thus influence the climate to differing degrees (Prentice, 2007). These physical realities mean that different types of primary carbon reservoirs differ in their priority for protection when considering climate change mitigation policies. For this purpose, reservoirs have higher priority for protection if they are stable in the absence of human activity, if carbon stock losses caused by human action are irreversible or only reversible over a long time period, if carbon stock gains are likely to be permanent, and if they store carbon at high density (Table 3). Reservoir types are evaluated against these criteria below. Reservoirs could be further subdivided and ranked according to characteristics that influence their stability and longevity. For example, remnant natural vegetation in a largely cleared landscape could be considered more at risk from

Table 3
Criteria used to rank primary carbon reservoirs according to their priority for protection from human action that directly affects carbon stocks. The biocarbon reservoir includes carbon in biomass and soils.

Reservoir		Criteria			Rank
		Stability	Restoration Time	Carbon Density	
Geocarbon		High	Geological	High	A. High
Biocarbon	Natural ecosystems	High–moderate	Decades to millennia	High	A. High
	Semi-natural ecosystems	Moderate	Years to centuries	Potentially high	B. Moderate
	Agricultural systems	Low	Annual to decades	Low - moderate	C. Low–moderate

land use impacts and ranked lower than a comparable area embedded within an intact natural landscape.

5.2.1. Geocarbon Reservoirs

Stock losses from geocarbon reservoirs are effectively irreversible over time scales relevant to climate change and human society. Geocarbon reservoirs are generally stable and inert in the absence of human intervention (fugitive emissions from gas deposits and volcanic activity are exceptions). Emissions of CO_2 from geocarbon stocks directly caused by human activities are principally the combustion of fossil fuels and cement production. Changes in the carbon stocks of other geocarbon reservoirs (Fig. 1) may result from indirect impacts of human intervention that alter climate conditions, such as warming of the permafrost (Buffett and Archer, 2004; Harvey and Huang, 1995; MacDonald, 1990), and elevated atmospheric CO_2 that alters ocean chemistry (Feely et al., 2004; Holmém, 2000; Sundquist, 1993). In the absence of action to reduce atmospheric CO_2 these indirect impacts on geocarbon reservoirs have the potential to change carbon stocks substantially. The geocarbon reservoirs (Table 3) have a high priority for protection because they are stable under stable climate conditions, have high carbon densities, and their rate of change is on geological time scales with carbon losses effectively permanent.

5.2.2. Biocarbon Reservoirs

The stability of biocarbon reservoirs (Fig. 1) depends on the interaction of environmental, biological and anthropogenic factors. The size and longevity of biocarbon stocks in an ecosystem fundamentally reflect an environmentally regulated balance between gross primary production (carbon removed from the atmosphere by photosynthesis) and ecosystem respiration (carbon emitted as CO_2) (Keith et al., 2009). Natural processes such as fire and insect attacks are also important depending on ecosystem type (Mackey et al., 2002). Biodiversity in natural ecosystems supports the stability of biocarbon stocks by conferring resilience, and the capacity for adaptation and self-regeneration. The biocarbon stocks of natural ecosystems are in a dynamic equilibrium and relatively stable over long time periods (centuries to millennia). Semi-modified and highly modified ecosystems are likely to be less resilient and less stable (Thompson et al., 2009). On the criterion of reversibility, biocarbon stock losses are in principle recoverable to the extent permitted by land management and prevailing environmental conditions. However, losses from mature natural ecosystems may only be recoverable over centuries to millennia (Righelato and Spracklen, 2007) and in some cases are not completely recoverable (Lindenmayer et al., 2011). On the criterion of carbon density, the current biocarbon stock is influenced by the degree of ecosystem disturbance as well as vegetation and soil condition compared with the carbon carrying capacity. Under common conditions, natural ecosystems have larger carbon stocks per unit area than agricultural systems and semi-natural ecosystems.

Within an ecosystem, a number of carbon pools are usefully recognized, for example in natural forest ecosystems: above ground living biomass; below ground living biomass; dead standing tree biomass; fallen dead biomass (coarse woody debris and litter); and soil (Keith et al., 2009). These pools vary in temporal stability and reversibility of carbon losses. Stock losses from short-lived pools such as leaves and litter are quickly reversible and of less significance from a climate perspective than an equivalent amount of carbon lost from long-lived pools such as the woody stems of trees and soil.

5.2.3. Anthropogenic Reservoirs

The stability of anthropogenic reservoirs varies depending on their susceptibility to decay and to risks such as fire. Anthropogenic carbon may pass through a sequence of reservoirs. For example, some of the carbon in harvested wood may be accounted for successively in a stockpile, a wood product and waste material before reaching the atmosphere.

6. A Framework for Carbon Accounting

The development of systematic and internationally comparable NGGI to support the UNFCCC and Kyoto Protocol is a major achievement of international climate change negotiations. The carbon accounting framework proposed here complements NGGI by incorporating both stocks and flows, effectively introducing a double-entry bookkeeping system. Under the framework, carbon stocks, carbon stock changes, emissions and removals would be estimated for each reservoir for defined time intervals. Emissions would be disaggregated from removals. Movement of carbon, as an emission or removal, would be accounted as changes in the opening and closing stocks over the accounting period, thus accurately tracking all the carbon in the system and incorporating cumulative stock changes. Direct human-induced (anthropogenic) emissions and removals would be distinguished from non-anthropogenic to the extent possible. Data would be reported by reservoir. Fig. 2 illustrates the framework schematically. Further levels of disaggregation of the primary reservoirs would underpin reporting. For example, geocarbon can be disaggregated to account for different fossil fuels. Biocarbon can be disaggregated into ecosystem type with further levels of disaggregation of their soil and biomass carbon pools based on longevity attributes. Anthropogenic reservoirs can be disaggregated by product and aligned to the SNA categories of inventories, fixed assets and consumer durables.

Structurally, the carbon accounting framework presented in this paper aligns with the SNA framework (Table 4). Both aim to generate a complete and consistent account of stocks and flows in their respective domains. Conceptually and in implementation, however, there are important differences. The SNA reports the monetary value placed on goods and services by people; underlying physical changes do not appear in the accounts: a matter being addressed through SEEA (United Nations Statistical Commission, 2012). Carbon accounts, on the other hand, report physical quantities of carbon in different parts of the environment. Attaching 'value' – environmental, economic or social – to specific carbon stocks and stock changes would be a separate exercise. Table 4 compares NGGI and SNA with the framework presented in this paper.

NGGI already collect much of the reservoir and stock change data needed to create comprehensive carbon accounts. Estimates of actual carbon stocks in the different reservoirs at specified dates are more difficult to compile because of information gaps. For geocarbon, they could be derived from environmental accounts as they develop (United Nations Statistical Commission, 2012) and from existing

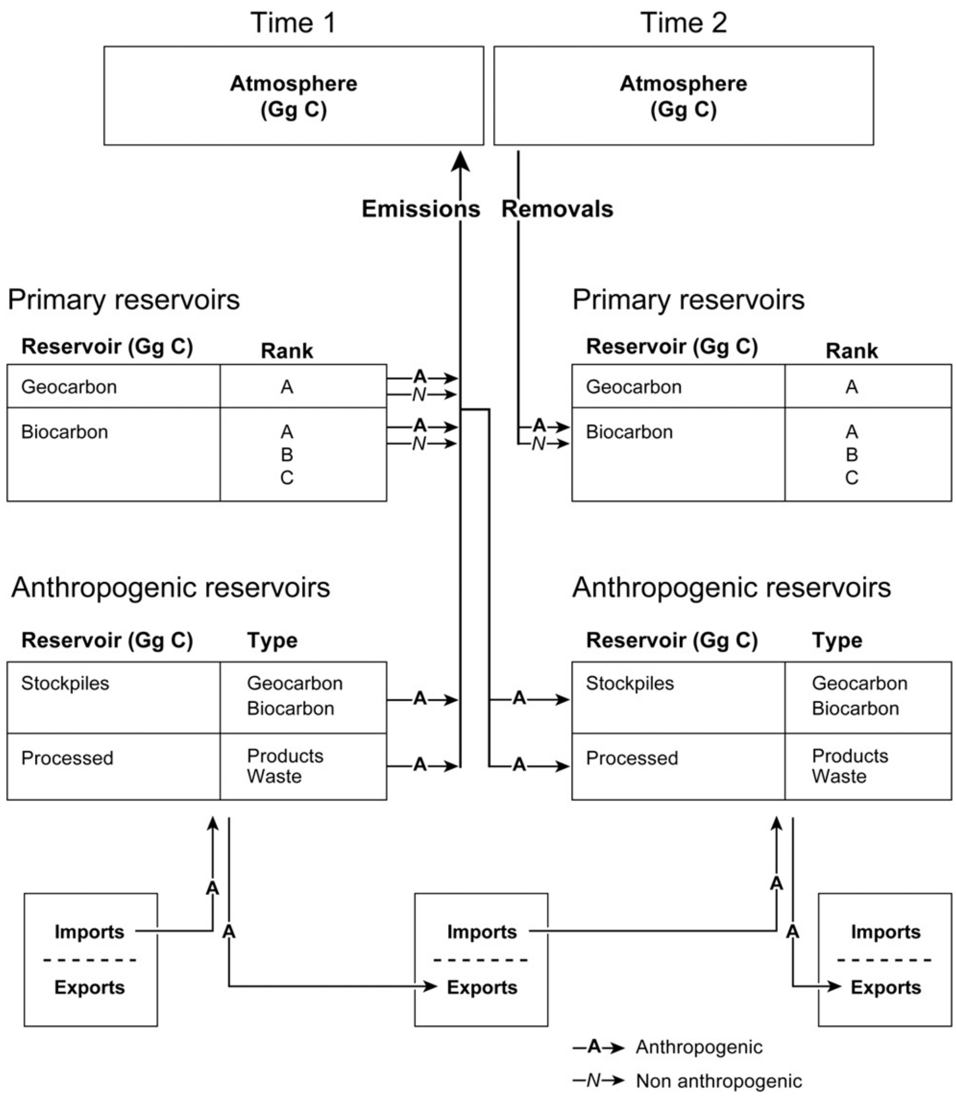

Fig. 2. Carbon stock and flow account framework for a country or region at two time periods. Primary reservoirs are ranked according to their stability-longevity-density as discussed in Section 5.1.1. Primary carbon stocks may be retained in the reservoir, extracted and moved to an anthropogenic reservoir as discussed in Section 5.1.2, or emitted to the atmosphere as a result of human or natural processes. Biocarbon stocks may also be enhanced by removal of atmospheric CO_2 as discussed in Section 2.3. These stock changes, driven by anthropogenic and non anthropogenic factors, and the relationships between the different reservoirs including the atmosphere are depicted in the connecting lines and arrows. The figure presents the framework at an aggregate level. Further levels of disaggregation can be accommodated, for example geocarbon by fossil fuel type and biocarbon into the various carbon pools associated with each ecosystem type.

fossil fuel resource inventories. For biocarbon, the existence of an international standard for carbon stock accounting with consistency in classifications, reporting standards and accounting time periods can be expected to stimulate a complementary research effort to continuously develop biocarbon stock information. Estimates of carbon carrying capacity are important complementary information for policy and research. For biocarbon on land that was forest before the onset of large scale intensive agriculture and the industrial revolution, a first approximation could be obtained from land cover data assembled by the IPCC (Forster et al., 2007). Very few data are available pertaining to non-forest land (see for example, Houghton (2003, 2008) for estimates of soil carbon loss resulting from cultivation of new lands in the 1990s).

The base for constructing comprehensive biocarbon stock and flow accounts is the land unit which includes areas covered by water. Land has a distinct role in the provision of spatial information: the area of land does not generally change significantly even if its use or cover changes (United Nations Statistical Commission, 2012). Within a comprehensive network of land units covering a country or region, each land unit could be separately identified and tagged with information on land use history; ecosystem type and condition; carbon stocks (current and at determined baselines); annual emissions and removals.

Distinguishing direct human-induced changes from indirect changes and natural variability presents similar issues for both stock and flow-based inventories (IPCC, 2010). NGGI use 'managed' land as a proxy assuming all carbon stock changes on such land are human-induced. Carbon stock accounts could take the same approach but smooth the variability by aggregating carbon stock changes over longer time periods. Alternatively, anthropogenic stock changes could be defined as those caused by an agreed set of human activities. These could include: reducing the carbon stock or density of a reservoir through activities like fossil fuel use, forest harvesting or soil disturbance; conversion from a high density to a lower density reservoir such as from perennial grassland to annual crops; conversion to a less stable storage system such as geosequestered carbon captured from fossil fuel use or conversion of a natural forest to a plantation.

The development of the SNA provides valuable lessons for carbon accounting. Most important are the arrangements facilitating constant improvement over the SNAs near 60 year existence. In 2012,

Table 4
Comparison of some features of SNA, NGGI and comprehensive carbon accounts.

	System Of National Accounts (European Commission et al., 2009)	National greenhouse gas inventories (IPCC, 1997, 2000b, 2003)	Comprehensive carbon accounting framework
Jurisdiction	UN Statistical Commission	Intergovernmental Panel on Climate Change	Policy-independent institution
Structure	Stocks and flows	Flows	Stocks and flows
Data	Economic activity	Net CO_2-e emissions	Carbon stocks and stock changes
Place where activity is recorded	Resident nationality of the institutional unit	National territory where emissions and removals occur (with exceptions, e.g. emissions from road fuel use are reported in the country where the fuel is sold)	National territory where stocks are held
Geographic coverage	Complete (all institutional units have a resident nationality)	Incomplete (data on emissions from international transport fuel are collected but not reported in national emissions totals. They are reported as a separate memo item; marine ecosystems are not comprehensively covered, e.g. sea grasses)	Potentially complete (treatment of stocks in international waters needs consideration)
Activity coverage	All economic activities	UNFCCC inventories: net anthropogenic GHG emissions except for 'unmanaged land'. Kyoto inventories: net anthropogenic GHG emissions for elected lands and activities	All carbon stocks and stock changes
Sectors and categories	Industry (International Standard Industrial Classification of All Economic Activities)	Activity (groupings of related processes, sources and sinks: energy; industrial processes and product use; agriculture, forestry and other land-use; waste; other)	Reservoir (geocarbon, biocarbon, anthropogenic reservoirs)

the UN Statistical Commission adopted the SEEA Central Framework as the international statistical standard for environmental-economic accounts (United Nations Statistical Commission, 2012). The Australian Bureau of Statistics (ABS) has applied this framework to develop an illustrative (not populated with data) comprehensive carbon stock account for Australia (Australian Bureau of Statistics, 2012, Appendix 1, Table 44) and preliminary work has commenced to refine the framework, develop the classification systems and populate the account. Such work requires the combined knowledge of scientists in a range of disciplines, statisticians, economists and people engaged in generating the current flow-based NGGI.

7. Conclusion

Because increases in the total stock of GHGs in the atmosphere cause climate change, the UNFCCC has expressed its ultimate objective as limiting and then stabilising the stock of atmospheric GHGs at a level that would prevent dangerous anthropogenic interference with the climate system. Despite both the problem and key policy objective being expressed in stock terms, GHG inventories report net annual flow data. Flow information, when combined with knowledge of underlying processes, is crucial for understanding climate change. It is also appropriate for reporting the fossil fuel sector where flows are effectively one way, stock changes are almost entirely anthropogenic and stocks are highly stable.

Two types of complication arose when the land sector was incorporated into flow-based GHG inventories. First, from a climate change perspective, fundamentally different characteristics between ecosystems have been lost in aggregation, namely differences in carbon stock stability, restoration capacity and density. Adding a stock account to existing UNFCCC flow inventories creates an opportunity to disaggregate land sector carbon information by an ecosystem ranking aimed at retaining key information that links carbon stock stability and density to ecosystem function. The second complication is that biocarbon stocks vary temporally and spatially to such an extent that statistically reliable estimation is difficult. Distinguishing anthropogenic from non-anthropogenic stock changes is also complicated (as it is for reporting flows). Addressing these complexities is vital from a climate change perspective. The magnitude of the carbon stock in each reservoir influences processes such as climate, ocean chemistry or the amount of vegetation. The stability of the biocarbon reservoir is determined by the quality attributes of the carbon stocks, such as the biodiversity of the ecosystem, rather than net flows.

Solving the climate change problem is fundamentally about accepting that there are natural limits; and here comprehensive carbon stock and flow accounts will provide relevant information to assist policy makers, researchers and public discussion in understanding these limits. While offsetting fossil fuel emissions against biocarbon is allowed under the UNFCCC negotiated outcomes, there are limits both in the atmosphere and on the land. Land-based atmospheric CO_2 removal is limited by the sum of the varying carbon carrying capacities of different ecosystems. Even if all degraded ecosystems were returned to their carbon carrying capacity, at current rates of fossil fuel emissions atmospheric CO_2-e concentrations would be 'offset' for less than two decades. Additional offsetting against avoided emissions from the land sector could delay effective action to limit fossil carbon stock depletion. Carbon stock accounts will help inform public debate and policy makers in addressing these challenges over limits.

It is also evident that the land sector cannot return to its full carbon carrying capacity because of competing land use needs and because, in some areas, soil resources have been permanently degraded and carbon stocks are unlikely to return to their earlier levels. Additionally, some ecosystems will have a greater capacity to recover from climate change-induced increases in the frequency of disturbances, such as drought, fire and insect outbreaks, and therefore maintain their carbon stocks at high levels. A land sector ranking system, as proposed in this paper, would tag ecosystems by their stock density and stability attributes and therefore inform land use decision making with its multiple objectives for limited land and water resources.

Acknowledgments

The authors appreciate the comments made by two reviewers of this journal. We thank Michael Vardon, Andrew Cadogan-Cowper and Peter Comisari from the Australian Bureau of Statistics for sharing their statistical methods knowledge. The opportunity for the lead author to participate in the process of developing the carbon stock accounting section of the draft UN SEEA Experimental Ecosystem Accounting and better understand the complexities of asset accounting is gratefully acknowledged as is the funding assistance from the Australian National University HC Coombs Policy Forum, Crawford School of Public Policy.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2013.01.010.

References

Allen, M.R., Frame, D.J., Huntingford, C., Jones, C.D., Lowe, J.A., Meinshausen, M., Meinshausen, N., 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458, 1163–1166.

Archer, D., 2005. Fate of fossil fuel CO_2 in geologic time. Journal of Geophysical Research 110, 1–6.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K., 2009. Atmospheric lifetime of fossil fuel carbon dioxide. Annual Review of Earth and Planetary Sciences 37, 117–134.

Australian Bureau of Statistics, 2012. Completing the Picture, Environmental Accounting in Practice. Australian Bureau of Statistics, Canberra, Australia ([http://www.abs.gov.au/ausstats/abs@.nsf/mf/4628.0.55.001] Last viewed 31August 2012).

Benndorf, R., Federici, S., Forner, C., Pena, N., Rametsteiner, E., Sanz, M.J., Somogyi, Z., 2007. Including land use, land-use change, and forestry in future climate change, agreements: thinking outside the box. Environmental Science and Policy 10, 283–294.

Bradshaw, W.E., Holzapfel, C.M., 2006. Evolutionary response to rapid climate change. Science 312, 147–148.

Brown, S., Schroeder, P., Birdsey, R., 1997. Aboveground biomass distribution of US eastern hardwood forests and the use of large trees as an indicator of forest development. Forest Ecology and Management 96, 37–47.

Brown, J.H., Gillooly, J.F., Allen, A.P., van Savage, M., West, G.B., 2004. Toward a metabolic theory of ecology. Ecology 85, 1771–1789.

Buffett, B., Archer, D., 2004. Global inventory of methane clathrate: sensitivity to changes in the deep ocean. Earth and Planetary Science Letters 227, 185–199.

Bushnell, J.B., Mansur, E.T., 2011. Vertical targeting and leakage in carbon policy. American Economic Review: Papers & Proceedings 101 (3), 1–8.

Cowan, I.R., Farquhar, G.D., 1977. Stomatal function in relation to leaf metabolism and environment. Symposia of the Society for Experimental Biology 31, 471–505.

Cramer, W., Ebondeau, A., Woodward, F.I., Prentice, I.C., Betts, R.A., Brovkin, V., Cox, P.M., Fisher, V., Foley, J.A., Friend, A.D., Kucharik, C., Lomas, M.R., Mankutty, N., Sitch, S., Smith, B., White, A., Young-Molling, C., 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. Global Change Biology 7, 357–373.

Davis, S.J., Peters, G.P., Caldeira, K., 2011. The supply chain of CO2 emissions. PNAS early edition. www.pnas.org/cgi/doi/10.1073/pnas.1107409108 Last viewed 4 May 2012.

Dean, C., Fitzgerald, N.B., Wardell-Johson, G.W., 2012a. Pre-logging carbon accounts in old-growth forests, via allometry: an example of mixed-forest in Tasmania, Australia. Plant Biosystems 146, 223–236.

Dean, C., Wardell-Johnson, G.W., Kirkpatrick, J.B., 2012b. Are there any circumstances in which logging primary wet-eucalypt forest will not add to the global carbon burden? Agricultural and Forest Meteorology 161, 156–169.

Diochon, A., Kellman, L., Beltrami, H., 2009. Looking deeper: an investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens* Sarg.) forest chronosequence. Forest Ecology and Management 257, 413–420.

European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, World Bank, 2009. System of National Accounts 2008. http://unstats.un.org/unsd/nationalaccount/sna2008.asp Last viewed 19 April 2012.

Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J., Millero, F.J., 2004. Impact of anthropogenic CO_2 in the $CaCO_3$ system in the oceans. Science 305, 362–366.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., et al. (Ed.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK and New York.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C., Zeng, N., 2006. Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison. Journal of Climate 19, 3337–3353.

Global Carbon Project, a. http://www.globalcarbonproject.org/carbonbudget/10/hl-full.htm Last viewed 2 March 2012.

Global Carbon Project, b. http://www.globalcarbonproject.org/about/index.htm Last viewed 2 April 2012.

Graâl, H., Kokott, J., Kulessa, M., Luther, J., Nuscheler, F., Sauerborn, R., Schellnhuber, H.-J., Schubert, R., Schulze, E.-D., 2003. Climate protection strategies for the 21st century: Kyoto and beyond. German Advisory Council on Global Change (WBGU) Special Report, Berlin ([http://www.gci.org.uk/Documents/wbgu_sn2003_engl.pdf] Last viewed 2 May 2012).

Gupta, R.K., Rao, D.L.N., 1994. Potential of wastelands for sequestering carbon by reforestation. Current Science 66, 378–380.

Harvey, L.D.D., Huang, Z., 1995. Evaluation of the potential impact of methane clathrate destabilization on future global warming. Journal of Geophysical Research 100, 2905–2926.

Höhne, N., Wartmen, S., Herold, A., Freibauer, A., 2007. The rules for land use, land-use change and forestry under the Kyoto Protocol — lessons learned for the future climate negotiations. Environmental Science and Policy 10, 353–369.

Holmém, K., 2000. The global carbon cycle. Chapter 11. In: Jacobson, M.C., Charlson, R.J., Rodhe, H., Orians, G.H. (Eds.), Earth System Science: From Biogeochemical Cycles to Global Change. Academic Press, London.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H., Jauhiainen, J., 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences 7, 1505–1514.

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setala, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecological Monographs 75, 3–35.

Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus 55B (2), 378–390.

Houghton, R.A., 2007. Balancing the global carbon budget. Annual Review of Earth and Planetary Sciences 35, 313–347.

Houghton, R.A., 2008. Carbon Flux to the Atmosphere from Land-Use Changes: 1850–2005. TRENDS: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA ([http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html] Last viewed 19 April 2012).

IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html Last viewed 31 August 2012.

IPCC, 2000a. Land use, land-use change and forestry. IPCC Special Report. Cambridge University Press, Cambridge.

IPCC, 2000b. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/gp/english/ Last viewed 31 August 2012.

IPCC, 2003. Good practice guidance for land use, land-use change and forestry. In: Penman, J., et al. (Ed.), IPCC National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies, Kanagawa, Japan.

IPCC, 2006. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html Last viewed 19 April 2012.

IPCC, 2007. Fourth Assessment Report: Climate Change 2007. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-human-and.html Last viewed 2 April 2012.

IPCC, 2010. In: Stocker, T.F., Field, C.B., Qin, D., Barros, V., Plattner, G.-K., Tignor, M., Midgley, P.M., Ebi, K.L. (Eds.), Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution Related to Anthropogenic Climate Change. IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

Kanowski, J., Catterall, C.P., 2010. Carbon stocks in above-ground biomass of monoculture plantations, mixed species plantations and environmental restoration plantings in north-east Australia. Ecological Management and Restoration 11 (2), 119–126.

Keeton, W.S., Chernyavskyy, M., Gratzer, G., Main-Knorn, M., Shpylchak, M., Bihun, Y., 2010. Structural characteristics and aboveground biomass of old-growth spruce–fir stands in the eastern Carpathian Mountains, Ukraine. Plant Biosystems 144, 148–159.

Keith, H., Mackey, B., Berry, S., Lindenmeyer, D., Gibbons, P., 2009. Estimating carbon carrying capacity in natural forest ecosystems across heterogeneous landscapes: addressing sources of error. Global Change Biology. http://dx.doi.org/10.1111/j.1365-2486.2009.02146.x.

Kempe, S., 1979. Carbon in the rock cycle. Chapter 13. In: Bolin, B., Degens, E.T., Kempe, S., Ketner, P. (Eds.), The Global Carbon Cycle. SCOPE ([http://www.scopenvironment.org/downloadpubs/scope13/chapter13.html] Last viewed 14 September 2012).

Kirschbaum, M.U.F., 2006. Temporary carbon sequestration cannot prevent climate change. Mitigation and Adaptation Strategies for Global Change 11, 1151–1164.

Lal, R., 2004. Soil carbon sequestration impact on global climate change and food security. Science 304, 1623–1627.

Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R.A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R.A., House, J.L., Huntingford, C., Levy, P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C., Randerson, J.T., Running, S.W., Sarmiento, S.L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G.R., Woodward, F.I., 2009. Trends in the sources and sinks of carbon dioxide. Nature Geoscience 2, 831–836.

Lindenmayer, D.B., Hobbs, R.J., Likens, G.E., Krebs, C.J., Banks, S.C., 2011. Newly discovered landscape traps produce regime shifts in wet forests. PNAS 138 (38), 15887–15891.

MacDonald, G.J., 1990. Role of methane clathrates in past and future climates. Climatic Change 16, 247–281.

Mackey, B.G., Lindenmayer, D., Gill, A.M., McCarthy, A.M., Lindesay, J.A., 2002. Wildlife, a Forest Ecosystem Analysis: Fire and Future Climate. CSIRO Publishing.

Mackey, B.G., Keith, H., Berry, S.L., Lindenmayer, D.B., 2008. Green Carbon: The Role of Natural Forests in Carbon Storage. ANU E Press ([http://epress.anu.edu.au/titles/green-carbon] Last viewed 2 March 2012).

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., Zhang, X., 2007. Forestry. In: Metz, B., Davidson, M.J., Bosch, P.R., Dave, R., Meyer, P.R. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G. (Eds.), 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal ([http://www.grida.no/publications/rr/blue-carbon/] Last viewed 3 April 2012).

Nepstad, D.C., Moutinho, P., Markewitz, R.S., 2001. The recovery of biomass, nutrient stocks, and deep-soil functions in secondary forests. In: McClain, M.E., Victoria, R.L., Richey, J.E. (Eds.), The Biogeochemistry of the Amazon Basin. Oxford University Press, New York, pp. 139–155.

O'Sullivan, R., Chagas, T., Burns, D., Pearson, T., 2011. Blue Carbon Policy Options Assessment, Climate Focus, Washington DC. http://www.climatefocus.com/documents/files/_blue_carbon_policy_options_assessment.pdf Last viewed 11 September 2012.
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S., McGuire, A.D., Pia, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests, 1990-2007. Science 333, 988–993.
Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European Journal of Soil Science 62, 42–55.
Prentice, I.C, coordinating lead author, 2007. The carbon cycle and atmospheric carbon dioxide content, chapter 3, in: Third Assessment Report of Working Group 1 of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
Raupach, M.R., Canadell, J.G., 2010. Carbon and the anthropocene. Current Opinion in Environmental Sustainability 2, 210–218.
Richards, K.R., Stokes, C., 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Climatic Change 63, 1–48.
Righelato, R., Spracklen, D.V., 2007. Carbon mitigation by biofuels or by saving and restoring forests? Science 317, 902.
Roxburgh, S.H., Wood, S.W., Mackey, B.G., Woldendorp, G., Gibbons, P., 2006. Assessing the carbon sequestration potential of managed forests: a case study from temperate Australia. Journal of Applied Ecology 43, 1149–1159.
Schellnhuber, H.J., Messnre, D., Leggewie, C., Leinfelder, R., Nakicenovic, N., Rahmstorf, S., Schlacke, S., Schmid, J., Schubert, R., 2009. Solving the Climate Dilemma: The Budget Approach. Special Report German Advisory Council on Global Change, Berlin ([http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/sondergutachten/sn2009/wbgu_sn2009_en.pdf] Last viewed 3 April 2012).
Schlamadinger, B., Johns, T., Ciccarese, L., Braun, M., Sato, A., Senyaz, A., Stephens, P., Takahashi, M., Zhang, X., 2007. Options for including land use in a climate agreement post-2012: improving the Kyoto Protocol approach. Environmental Science and Policy 10, 295–305.
Schulze, E.-D., Valentini, R., Sanz, M.-J., 2002. The long way from Kyoto to Marrakesh: implications of the Kyoto Protocol negotiations for global ecology. Global Change Biology 8, 505–518.
Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Oberseteiner, M., Oppenheimer, M., Robertson, G.P., Schlesinger, W.H., Tilman, G.D., 2009. Fixing a critical climate accounting error. Science 326, 527–528.
Secretariat of the Convention on Biological Diversity, 2009. Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change: Montreal, Technical Series No. 41 ([http://www.cbd.int/doc/publications/cbd-ts-41-en.pdf] Last viewed 2 March 2012).
Sundquist, E.T., 1993. The global carbon dioxide budget. Science 259, 934–941.
Thompson, I., Mackey, B., McNulty, S., Mosseler, A., 2009. Forest resilience, biodiversity and climate change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Secretariat of the Convention on Biological Diversity, Montreal Technical Series No. 43.
Thornley, J.H.M., Cannell, M.G.R., 2000. Managing forests for wood yield and carbon storage: a theoretical study. Tree Physiology 20, 477–484.
UNFCCC (United Nations Framework Convention on Climate Change), a. Greenhouse gas data from UNFCCC http://unfccc.int/ghg_data/ghg_data_unfccc/items/4146.php Last viewed 22 October 2011.
United Nations, 1992. United Nations Framework Convention on Climate Change. http://unfccc.int/essential_background/convention/background/items/2853.php Last viewed 19 April 2012.
United Nations, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. http://unfccc.int/kyoto_protocol/items/2830.php Last viewed 19 April 2012.
United Nations, 2002. Framework Convention on Climate Change. Report of the Conference of the Parties on its seventh session held at Marrakesh from 29 October to 10 November 2001 ([http://unfccc.int/cop7/] Last viewed 2 April 2012).
United Nations, 2012. Framework convention on climate change. Report of the Conference of the Parties Serving as the Meeting of the Parties to the Kyoto Protocol on its Seventh Session, Held in Durban from 28 November to 11 December 2011 ([http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf] Last viewed 2 April 2012).
United Nations Statistical Commission, 2012. System of Environmental-Economic Accounting Central Framework. http://unstats.un.org/unsd/envaccounting/pubs.asp Last viewed 23 August 2012.