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