QUANTIFYING, UNDERSTANDING AND MANAGING THE CARBON CYCLE IN THE NEXT DECADES

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Abstract. The human perturbation of the carbon cycle via the release of fossil CO_2 and land use change is now well documented and agreed to be the principal cause of climate change. We address three fundamental research areas that require major development if we were to provide policy relevant knowledge for managing the carbon-climate system over the next few decades. The three research areas are: (i) carbon observations and multiple constraint data assimilation; (ii) vulnerability of the carbon-climate system; and (iii) carbon sequestration and sustainable development.

Introduction

Human perturbation of the global carbon cycle occurs via the release of fossil CO_2 into the atmosphere, and via land-use and land-cover transformations. This perturbation induces a complex response of the natural carbon pools and fluxes, which together result in an increased atmospheric CO_2, the main cause of climate change (Houghton et al., 2001). This has resulted in a need for a better understanding of the dynamics of the carbon cycle and the extent to which it can be managed to help stabilize atmospheric CO_2 concentrations.

The research community has responded to this challenge by establishing a comprehensive coordinated framework to understand the multiple components of the global carbon-climate-human system and their interactions (Global Carbon Project, 2003); and to deploy denser and more systematic observations of the changing fluxes and pools (IGCO, 2004). The three main axes of this research framework are: (i) patterns and variability of carbon sources and sinks, (ii) attribution of the various fluxes to processes and interactions with climate, and (iii) future dynamics of the carbon-climate system resulting from biospheric dynamics and human actions purposefully taken to manage the carbon cycle. Together they form a critical component of the knowledge base required to develop sound international and national climate mitigation policies.

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For this paper, we have chosen three fundamentally important research areas which will require major development over the next decade if humankind is to develop a capability to sustainably manage the climate-carbon system. These three research areas are:

- Carbon observations and data assimilation
- Vulnerability of the carbon-climate system
- Carbon sequestration and sustainable development

Observations and Multiple Constraint Data Assimilation

MULTIPLE CONSTRAINT DATA ASSIMILATION

Over the last decade carbon observations have increased enormously with the development of *in-situ* measurements and the launch of a number of space missions that have together yielded large amounts of data relevant to carbon processes, fluxes and stocks. The growing body of systematic carbon observations includes: extensive forest biomass and soil carbon inventory data, Eddy covariance flux measurements, atmospheric CO_2 and tracers concentrations, nutrient fluxes and stocks (particularly N), and remote-sensing products relevant to Gross Primary Production (GPP), land cover and land-use changes, fire disturbances, and forest biomass and structure.

The wealth of data presents new opportunities to quantify and understand the dynamics of the carbon cycle. A central challenge concerns the synthesis of observations of different nature and scales to produce best estimates of the dynamic evolution of carbon stocks and fluxes, at a resolution sufficient to uncover the various processes that control them. Formally, the "top-down" integrated atmospheric concentration information needs to be integrated with the "bottom-up" knowledge of the land and ocean reservoirs as delivered by *in-situ* and remotely-sensed data.

To answer this need, multiple constraint Carbon Cycle Data Assimilation (CCDAS) is emerging as a powerful approach to model-data synthesis which offers the possibility of fully exploiting the wealth of carbon observations within a mechanistic model structure (Kaminski, 2002; Global Carbon Project, 2003; IGCO, 2004; Raupach et al., 2004a).

Such multiple constraint approaches are innovative because they exploit streams of data not only to validate model outputs (e.g., from mechanistic carbon models), or to directly infer fluxes (as in atmospheric inversions), but principally to constrain internal model parameters to optimal values (i.e. parameter estimation). Different data streams constrain different components of a model which is able to assimilate data across a range of space and time scales. For instance, remotely sensed *Normalized Difference Vegetation Index* (NDVI) can constrain GPP at a few hundred meters to 1 km pixel and with time resolutions of up to every 2 weeks; *atmospheric* CO_2 *concentrations* of air taken in flasks constrain the inverse calculation of regional net exchanges on carbon at a semi-continental scale and about 1 month intervals;

and *Eddy covariance fluxes* determine Net Ecosystem Exchanges (NEE) at a scale of a few km^2 and in a continuous time mode.

Another distinctive characteristic of multiple constraint assimilation is that uncertainties associated with the observation, techniques, processing, representativeness, and accuracy are as important in determining the final outcome as the measured values themselves (Raupach et al., 2004a). Thus, uncertainty estimates, for both measurements and model parameters, take on even greater importance within the context of CCDAS.

An important effort needs to be placed on the development of more realistic process-driven models to allow the handling of diverse resolutions and scales, and on assimilation methods to allow the efficient processing of large amounts of data, particularly when using remote-sensing observations. A number of developments on these techniques are now underway and components of a bigger system have already demonstrated their value (e.g., Wang and Barret, 2003; Wang and McGregor, 2003).

There are a number of directions to follow to improve current carbon models, so as to enable them to better use the available data streams within carbon cycle data assimilation systems. The diversity of existing carbon models and their different fields of application, makes it difficult to elaborate an exhaustive list of improvements. Yet, global terrestrial models are generally very crude in their description of the following processes:

- Forest growth and management
- Carbon cycling over cultivated lands
- Carbon cycling over wetlands
- Soil organic matter decomposition
- The effects of land-use change and fire
- The coupling between carbon and nutrients cycling
- The absorption of radiation by canopies
- The effects of biodiversity

Global process-driven models of anthropogenic emissions, fossil and land use, are rarely coupled with spatially explicit ocean and land carbon models.

Ultimately, it is desirable that such future carbon cycle data assimilation systems could also incorporate socio-economic information to better understand proximal and distant controls of carbon fluxes and stock changes. This would allow moving towards a full system capability to explore points of intervention and windows of opportunity for carbon mitigation.

A better knowledge of the present-day state of the carbon cycle perturbation as constrained by measurements and models will be extremely valuable to reduce uncertainties in the future evolution of atmospheric CO_2 and climate as projected in coupled carbon-climate simulations (Cox et al., 2000; Dufresne et al., 2002).

CARBON OBSERVATIONS

Despite the wealth of carbon observations available, most of the data are not collected on a long-term systematic basis. A more operational system of carbon measurements (like that maintained to support weather forecasting) would allow the development of carbon data assimilation systems, as described above; would assist with the management and monitoring of carbon mitigation approaches; and would help meet the data needs of the carbon cycle research community.

A typical resolution at which it is desirable to obtain accurate estimates of the global CO_2 fluxes in the coming decade is $\approx$50 km over land and $\approx$500 km over the oceans on a weekly basis (IGCO, 2004). Possibly higher-resolution fluxes could be determined over regions where denser networks will be established (North American Carbon Plan, CARBOEUROPE).

To reach this goal, a substantial effort is needed to enhance *in-situ* networks (biomass inventories in the tropics, atmospheric observations within continental air sheds, Eddy covariance assets expanded over a wider range of ecosystems, ocean surveys generalized to poorly observed gyres, etc.), to ensure the continuity of present-day remote sensing carbon measurements, and to develop new remote-sensing techniques (e.g., atmospheric CO_2, forest biomass). At present, near all systematic carbon observations are carried out on a research basis.

Thus, an important challenge for this coming decade is to move from the present *ad-hoc* systems of carbon observations to one that operationalises a number of measurements including the standardization of data harvesting techniques, processing, archiving, and making data available to end users. This is not trivial, as many of the relevant carbon observations are difficult, expensive and require skilled personnel to achieve the necessary high level of accuracy.

Some of the critical measurements and challenges are (TCO, 2002; IGCO, 2004):

- *Forest biomass inventories*. To harmonize the diverse methodologies of data collection and interpretation, to create a geo-reference coverage, and to expand to non-commercial forest and woodlands, and tropical forests. To further develop remote-sensing techniques such as LiDAR and Radar with great potential to measure forest biomass in a consistent way for large regions.
- *Eddy covariance flux network*. To ensure continuity of the present network to cover at least 10-year periods. To expand the network in poorly sampled biomes (e.g., savanna), ecosystems undergoing recovery after disturbances (e.g., fire, agricultural land abandonment) and agriculturally used land areas.
- *Soil carbon surveys*. To standardize methodologies and data, fully exploit the resource, and ensure that bulk density and soil profiles are properly measured in addition to carbon concentrations.
- *Land-use change and fire*. To monitor land-cover change at 5-year intervals at 1-km spatial resolution, fire hot spots (daily resolution), and burned areas (monthly resolution) using an operational and consistent system of satellites.

Forest/non-forest transitions are critical and require higher-spatial resolution (25 m).

- *Lateral transport.* To better estimate carbon and nutrient transport by rivers into coastal zones. To develop a gridded erosion model to allocate spatially the sources of the riverine carbon. To quantify transport of wood and food products through the international trade circuits in a spatially gridded form.
- *Geo-reference fossil fuel emissions*. To measure fossil fuel emissions at 10 km or smaller spatial scales, and with a temporal resolution of hours to days to resolve differences with daily biospheric dynamics.
- *Nutrient fluxes to ecosystems*. To have better and more systematic nutrient measurements (N, P, Si, and Fe) such as production rates, changes in soil stores, export to atmosphere, and subsequent deposition on land and oceans.
- *Non-CO_2 components of ecosystem respiration*. To collect more systematic measurements of non-CO_2 components, particularly CO, CH_4 and VOCs from terrestrial ecosystems.
- *Atmospheric CO_2 from space*. New space missions hope to deliver global column integrated CO_2 density which will dramatically improve the accuracy of estimates of carbon sources and sinks. The measurements need to have a precision of 0.3% (1 ppm for the OCO mission planned in 2007), with a spatial resolution of 100 km, and a temporal resolution of a week or better.

Vulnerability of the Carbon-Climate System

Over the last decade, a great deal of effort has focused on quantifying the strength and location of the current carbon sources and sinks. The wide research community that has reached agreement that the Northern lands are responsible for the largest portion of the net terrestrial carbon sink (Houghton et al., 2001) with a comparable spread among North America, and Eurasia but with uncertainties on the order of the mean (Schimel et al., 2001; Gurney et al., 2002). The net terrestrial sink strength is highly variable from one year to the next, because the carbon balance of terrestrial ecosystems strongly responds to climate variability (Bousquet et al., 2000; Rödenbeck et al., 2003) and to interannual changes in fires (Van der Werf, 2004). The average global terrestrial net uptake was -0.2 PgC y^{-1} for the 1980s, and -1.4 PgC y^{-1} for the 1990s (Houghton et al., 2001) subsequently corrected to -1.2 PgC y^{-1} after a new estimate of ocean uptake (Le Quere et al., 2003; Sabine et al., 2004).

Inverse CO_2 atmospheric calculations further suggest that the tropics are approximately neutral, albeit with large uncertainties, (Houghton et al., 2001; Prentice et al., 2001). Given land-use change is responsible for 2.2 PgC y^{-1} emissions into the atmosphere during the 1990s, mostly in the tropics (Houghton, 2003), this implies that tropical regions must also include biological gross sinks of a similar magnitude to compensate the carbon emissions from deforestation. Other authors have estimated smaller global emissions from land-use change of -0.9 PgC y^{-1} (DeFries et al., 2002) and -1.0 PgC y^{-1} (Archard et al., 2002), which would imply a somewhat smaller inferred tropical gross sink.

These are a set of quite robust and well-agreed conclusions on the current knowledge on the global carbon budget, although there is still the need to further reduce uncertainties in these global quantities, particularly emissions from land-use change, and increase their spatial and temporal resolution.

Much larger uncertainties, however, are associated with the future dynamics of the carbon cycle. The first climate model simulations to include the carbon cycle as an interactive element suggest that the current land carbon sink may be vulnerable to climate change, but the magnitude of this effect differs markedly amongst the existing climate-carbon cycle models (Cox et al., 2000; Dufresne et al., 2002). In the most extreme case the global land carbon sink was projected to convert to a source in the middle of the 21st century, increasing the modelled CO_2 concentration at 2100 by about 250 ppmv, and providing a significant acceleration of anthropogenic climate change (Cox et al., 2000). The primary reason for this drastic land sink-to-source transition can be traced to the model assumption that the rate of soil heterotrophic respiration will increase strongly with temperature, eventually overwhelming the CO_2-fertilisation of plant primary production and leading to a loss of soil carbon to the atmosphere (Jenkinson et al., 1991).

The climate-carbon cycle models differ in the timing and sharpness of this threshold as a result of different climate sensitivities to CO_2, different sensitivities of heterotrophic respiration to temperature, and different rates at which CO_2-enhancement of photosynthesis saturates with CO_2 concentration (Friedlingstein et al., 2003). The first generation climate-carbon cycle models each produce the change in land carbon storage as a result of the competition between CO_2-fertilisation and increasing decay rates at high temperatures, but in reality a myriad of other processes can also contribute to land sinks (e.g., nitrogen deposition, forest regrowth, forest fires). The processes responsible will play a large part in determining the extent to which land carbon sink will be vulnerable to environmental and land-management changes.

In fact, one of the most vulnerable sink processes is believed to be forest regrowth in agricultural lands in North America and Europe abandoned over the last 100 years (Kauppi et al., 1992; Goldewijk, 2001). Forest regrowth is thought to be responsible for a large part of the current Northern Hemisphere net sink (Caspersen et al., 2000). The abandonment of cropland due to intense agriculture has resulted in a substantial expansion of relatively young forests with fast growth rates and, therefore, with high-carbon sink capacity. In addition, forest regrowth has increased in other regions because of decreased logging intensity and fire exclusion, which has further enhanced the current carbon sink (Houghton et al., 2000; Pacala et al., 2001).

However, the capacity of vegetation to remove CO_2 from the atmosphere reaches a maximum near canopy closure and declines by 20–60% as the stand reaches maturity (Gower et al., 1996). Net ecosystem production also declines in mature stands compared to younger stands as it has been measured in a variety of forests in temperate and boreal regions (e.g., Law et al., 2003; Bond-Lamberty et al., 2004). Consequently, to the extent the Northern Hemisphere net carbon sink is due to forest regrowth, a decreasing sink strength is expected as forests mature over the next decades.

From a regional and global perspective, persistence of the carbon sink due to regrowth can only be sustained by continuous expansion of new forests, something that is unlikely to happen for much longer in the light of increasing pressures on existing land for multiple uses (urbanization, industrialization, recreational, food production, etc.).

In addition to the loss of carbon sinks due to reduced uptake capacity of maturing forests, there are a number of existing biospheric carbon pools that are vulnerable to climate and land-use change. Destabilization of the pools could release hundreds of PgC to the atmosphere, and so further enhancing global warming. To establish alternative CO_2 emission scenarios to stabilized CO_2 concentrations at a given level, it is crucial to have an understanding of the possible future dynamics of these carbon pools. Most of these pools are not accounted for in current carbon-climate models, so any additional biospheric CO_2 emissions from these vulnerable pools will make stabilization pathways and efforts to reach specific target levels fall short.

Three carbon pools are thought to be most vulnerable: carbon locked in permanent frozen soils (permafrost), in wetlands/peatlands (boreal and tropical), and forests (largely in tropical and boreal zones). Very preliminary estimates show that up to 400 PgC could be released from these three pools over the next 100 years due to climate and land use change (Gruber et al., 2004).

PERMAFROST

Despite the uncertainty of the carbon stored in permafrost, recent analyses show that Northern Hemisphere cryosoils contain 268 Pg in the first meter (Tarnocai et al., 2003). Other estimates put the total amount of carbon locked in frozen soils at 400 PgC (Gruber et al., 2004). Permafrost is most sensitive to global warming due to the current and predicted climate change in high-latitude regions. Preliminary estimates show that permafrost area could shrink up to 25% with a mean global warming of 2 °C (Anisimov et al., 1999). Catastrophic destruction (within <50 years) of long-ago deposited frozen carbon could occur in case, once activated, bacterial decomposition generates enough heat to further melt carbon at depth (Zimov and Zimowa, 1993; Zimov et al., 2004).

Melting permafrost will increase CO_2 and CH_4 emissions, and it was estimated for the Canadian permafrost that up to 48 PgC could be sensitive to oxidation under a 4 °C warming scenario (Tarnocai, 1999). Very preliminary global estimates suggest that up to 5 PgC could be released from permafrost over the next 20 years and up to 100 PgC in the next 100 years if we were to assume that 25% of the carbon locked in frozen soils was to be oxidized (Gruber et al., 2004). Whether this carbon is released initially as CO_2 or as CH_4 depends on the local hydrological conditions.

WETLANDS/PEATLANDS

Carbon stored in wetlands and peatlands also constitute pools vulnerable to changes in climate and land use. Global warming and changes in precipitation may play a major role in destabilizing boreal wetlands and peatlands, while land conversion to cropland is the largest threat to wetlands and peatlands in the tropics. Furthermore, recent observations suggest that CO_2 increase alone could lead to a loss of peatland carbon through larger fluxes of dissolved organic carbon (Freeman et al., 2004). Managed and unmanaged systems store about 450 PgC largely locked due to anoxic conditions, either due to low temperatures or flooding. There exists a complex balance in wetlands between increased CO_2 emissions when water tables go down or temperature goes up, and CH_4 emissions when water tables go up. In cold regions, changes in precipitation and temperature will largely determine the net balance between CO_2 and CH_4 emissions.

Tropical peatlands alone are one of the largest near-surface reserves of terrestrial organic carbon, sometimes as deep as 20 m in thickness. They are highly vulnerable to drainage and forest clearing. Interactions with drier conditions brought about by ENSO in Indonesia during 1997–1998 resulted in the burning of peat and vegetation with an estimated loss of carbon between 0.81 and 2.57 Pg in 1997. That is the equivalent amount of 13 to 40% of the mean annual global carbon emissions from fossil fuels (Page et al., 2002).

A preliminary estimate suggests that up to 100 PgC of CO_2 equivalent could be released to the atmosphere from wetlands and peatlands over the next 100 years (Gruber et al., 2004).

FORESTS

The third major vulnerable pool is vegetation threatened by land-use change and changes in fire frequency as a result of forest conversion and climate change. Both land use and fire are also highly interactive and have behaved synergistically. Historical land use change alone, mostly conversion of forests into pastures and cropland, has been responsible for the release of 182–199 PgC to the atmosphere (DeFries et al., 1999). Deforestation will likely continue over the next decades, mostly in tropical and subtropical regions, and it is estimated to release between 40 and 100 Pg over the next 100 years based on past trends (Gruber et al., 2004). Furthermore, the harvesting of primary forests in the tropics or in the high latitudes will lead to net losses of carbon to the atmosphere, even if they are subsequently replaced by secondary forests or plantations.

The annual carbon flux to the atmosphere from global savanna and forest fires (excluding biomass burning for fuel and land clearing) is estimated to be in the range of 1.7 to 4.1 Pg (Mack et al., 1996). Under steady fire-frequency conditions most of the carbon will return to land by vegetation regrowth. However, increased ENSO-related droughts, land fragmentation and selective logging are making the humid tropics more sensitive to fire (Nepstad et al., 1999), and predictions indicate that higher temperatures in boreal regions will increase fire frequency and associated greenhouse gas emissions (Flannigan et al., 2000). Furthermore, a number of climate projections suggest that the Amazon basin could dry significantly under increased CO_2, threatening the world's largest tropical forest even in the absence of anthropogenic deforestation (Cox et al., 2004).

The vulnerability of forest and other ecosystems to climate change and direct anthropogenic perturbations depends also on their biodiversity make up. However, the extent to which this factor helps stabilize these ecosystems and their carbon pools is not known at present and constitutes an important direction for future research.

Carbon Sequestration and Sustainable Development

Climate mitigation needs to be placed in a broader context where principles of development, equity and sustainability are taken into account (Metz et al., 2001). The issue becomes particularly important for land-based carbon mitigation strategies which include afforestation, reforestation, biofuel cropping, improved management of production systems, and reduced carbon emissions through biomass conservation.

There is extensive literature on the biophysical (or technical) potential of human induced terrestrial biospheric sinks summarized in the IPCC-LUCCF special report (Watson et al., 2001). Globally, one could estimate such an upper "biological" boundary of carbon sequestration on land at a similar level of the carbon lost historically due to land-use change, about 200 PgC (DeFries et al., 1999). More realistic estimates which consider land availability and agroforestry needs derive a potential storage on land of between 50 and 100 PgC (Cannell, 2003). Based on a set of more complex and realistic driver scenarios, the potential of forest carbon sequestration was reduced to an achievable capacity of 10 to 50 PgC (Cannell, 2003), which is 5 to 25% of the upper boundary for carbon sequestration if only biophysical considerations are taken into account. The drivers taken in this last analysis included more aggressive policies in climate mitigation, adoption of best management practices, and consideration of the main drivers of afforestation and reforestation around the world, such as soil conservation and timber production.

In addition, there is a whole fabric of interlinked environmental and socio-economic constraints (and opportunities for that matter) which will ultimately determine the achievable capacity to sequester carbon, consistent with principles of equity and sustainable development. Some of these socio-economic constraints include: economical costs of using land for sequestration and for maintaining carbon stores, environmental requirements for other resources, environmental constraints, social factors, economical feasibility, institutional factors, and demographics (Raupach et al., 2004b).

There are many examples that illustrate the need for a fully coupled natural-socioeconomic analysis to determine the realistic sequestration capacity of a given region. For instance, the European agricultural soils in the EU-15 have been identified as possible carbon sinks. It is estimated that soils could sequester up to 16–19 $\mathrm{Mt\,C\,y^{-1}}$ during the first Kyoto commitment period (2008–2012), based on the existing policy framework and economic viability. This amount is less than 20% of the theoretical potential previously estimated and equivalent to only 2% of European anthropogenic emissions (Freibauer et al., 2004).

Large-scale reforestation and afforestation projects are being proposed to contribute to the net reduction of greenhouses gases at the regional and national levels. From an environmental point of view alone, negative impacts on biodiversity conservation and associated biophysical effects on the hydrological cycle and the climate (Betts, 2000), need to be balanced carefully against the carbon sequestration benefits from forest expansion.

Preliminary impact analyses for large-scale afforestation projects in Australia show that a 10% increase of tree cover in the headwaters of the Macquarie River watershed would result in a 17% reduction in inflows to the major dam. An additional 5% reduction would take place by 2030 due to a drying trend using a mid-range climate change scenario (Herron et al., 2002). The reduction of water supply downstream would jeopardize the viability of bird breeding in the marshes (protected by the RAMSAR convention) and irrigation farming communities. Changes in the hydrological cycle due to large-scale forest plantations can also jeopardize the soil quality and result in salinisation of the water table as shown in the pampas of Argentina (Jobbagy and Jackson, 2004).

To understand and manage the carbon-climate system requires the development of a research and policy framework which considers sequestration potential, resource trade-offs, and the socio-economic constraints consistent with sustainable development.

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