BLUEPRINT FOR AUSTRALIAN TERRESTRIAL CARBON CYCLE RESEARCH

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1. INTRODUCTION

In February 2005 the Australian Greenhouse Office (AGO) convened a workshop in Canberra on carbon cycle research. The purpose of the workshop was to bring together all of the major Australian researchers/ institutions in terrestrial atmospheric carbon cycle research work towards a more focused, intergrative programme at the national level. This document is an outcome of that workshop and feedback from various participants. It describes the current state of research and identifies priority research themes for terrestrial carbon cycle research (see Appendix 1 and 2).

The carbon cycle is central to the functioning of the Earth System and to human well being. It is inextricably coupled with climate, the water cycle, nutrient cycles and, through photosynthesis, provides the fundamental building blocks for life on the land and in the oceans (see figure 1a). Humans depend upon the carbon cycle for food and fibre, and since the Industrial Revolution have depended on fossilised carbon compounds for much of our energy supplies.

The combustion of fossil fuels and land clearing, primarily for conversion of forests to agriculture, have over the past two centuries led to a rapid increase of carbon dioxide in the atmosphere. Figure 1b shows the increase over the past 60 years. Since CO_2 is a greenhouse gas, its rapid atmospheric increase and the consequent changes in the energy balance at the Earth's surface and in the troposphere have led to concerns for the stability of the climate. The Antarctic ice core data show the strong link between atmospheric CO_2 concentration (and that of other greenhouse gases) and global mean temperature (Petit et al. 1999), and a careful analysis of the increase in global mean temperature through the 20th century shows a clear signal of anthropogenic forcing with increased greenhouse gas concentrations being a major factor (IPCC 2001).

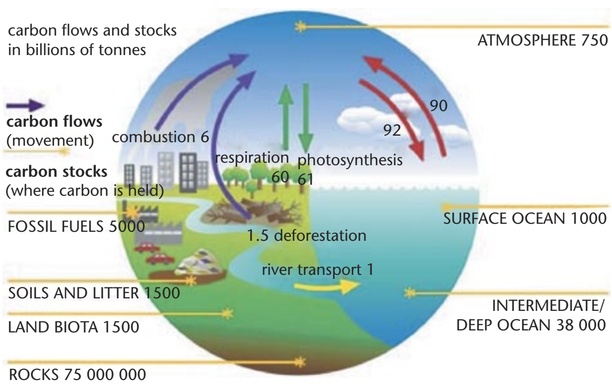


Figure 1a

A representation of the global carbon cycle, including the human perturbations due to land use and fossil fuel combustion.

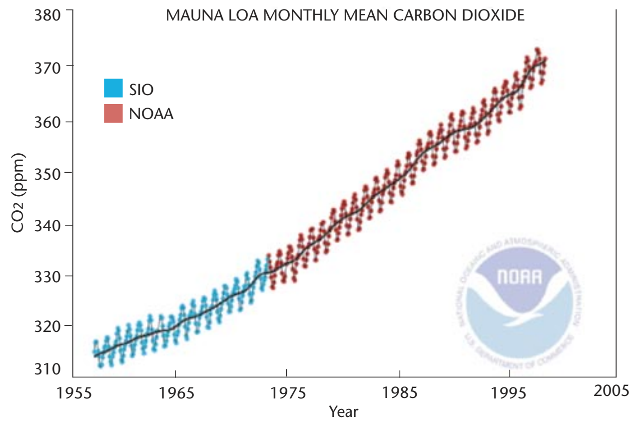


Figure 1b

Atmospheric CO_2 concentration from the instrumental record, expressed as atmospheric CO_2 monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO blue). Data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Principal investigators: Dr Pieter Tans, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678, ptans@cmdl.noaa.gov And Dr Charles D. Keeling, SIO, La Jolla, California, (616) 534-6001, cdkeeling@ucsd.edu

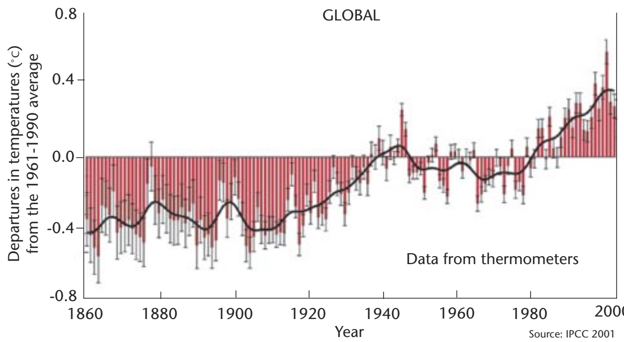


Figure 1c

Global mean surface temperature (degrees C) for the past 140 years shown as departures from the 1961-1990 average. IPCC (2001).

Although the concern about the changing global environment has focused most strongly on climate, it is through management of the carbon cycle that human societies have the most readily accessible opportunity to influence the climate. More particularly, controls on fossil fuel combustion and consequent greenhouse gas emissions and manipulation of the terrestrial component of the global carbon cycle are the two most likely points of human intervention in the carbon cycle.

To predict and assess the impacts of climate change, it is essential to consider both the marine and terrestrial contributions to the carbon cycle. The ocean is the dominant reservoir of carbon on the Earth and has absorbed roughly 40% of the carbon released to the atmosphere by human activities. Climate models suggest the rate at which the ocean takes up CO_2, and hence slows the rate of climate change, will decrease with enhanced global warming and result in a positive climate feedback. Measurements of storage and transport by the ocean also provide strong constraints on estimates of terrestrial sources and sinks of CO_2. Australia is making significant contributions to observations and models of the ocean carbon cycle and there is a need for expanded activity in several areas.

In general, terrestrial carbon research is more fragmentary and less well organised than ocean carbon research, for a number of reasons. This has been recognised in many parts of the world, where countries are developing their own coordinated carbon cycle research programmes, with a strong focus on addressing the major questions surrounding terrestrial carbon cycle dynamics. The purpose of this document is to present a strategy for a community approach to Australian research into the terrestrial carbon cycle and its interaction with the atmosphere. A fully comprehensive carbon cycle research programme must, of course, include the marine component as well.

We have only a partial understanding of how the terrestrial carbon cycle operates, especially in terms of the processes that control the biological aspects of the cycle. Well-intended interventions could easily become ineffective or even counterproductive without a much better understanding of the dynamics of the system we are trying to manage. It is paramount that our understanding of the global carbon cycle be significantly improved if we are to increase the probability that policy and management interventions will be successful and without unintended side effects.

Much research on aspects of the carbon cycle is being carried out in universities, national research facilities and other institutions around the world. At the international level, assessment of our knowledge of the carbon cycle is carried out by the Intergovernmental Panel on Climate Change (IPCC), research is being coordinated worldwide by the Global Carbon Project (GCP), and a major effort to integrate and expand observation of the carbon cycle globally has been initiated under the auspices of the Integrated Global Observation Strategy (IGOS) Partnership.

Australia's terrestrial carbon-related research spans the range from curiosity-driven work on basic carbon cycle processes to highly applied work needed to support Australia's assessment and reporting obligations in the international area. This research is supported by an equally broad range of institutions, including the universities (via the Australian Research Council), CSIRO, the AGO, the Bureau of Meteorology Research Centre, cooperative research centres and state agencies. Australian research contributes significantly to the international efforts noted above and, in addition, has been coordinated to some extent at the national level through the Australian Climate Change Science Programme and through CSIRO's Biosphere Working Group.

The Febuary 2005 workshop provided useful information to help the AGO set priorities for the components of a national carbon cycle research programme that it will directly support. The AGO's interests reflect its policy role for the Australian Government in climate change science, impacts and adaptation, greenhouse accounting, and emissions management.

Terrestrial carbon cycle research sponsored by the AGO is driven by the need to deliver policy outcomes to the Australian Government and to provide information that directly supports decision making in Government and in the private sector on climate change issues. While this remit does not mean that the AGO will fund only research at the very applied end of the research spectrum, it does mean that AGO-sponsored research, whether it be at the more fundamental or more applied ends of the spectrum, must show a current or potential linkage to the AGO's policy mandate.

The policy questions that guide the AGO's interest in carbon cycle research include:

- In the context of Australia's assessment and reporting responsibilities, what is the pattern of carbon sources and sinks in Australia, and how are these likely to behave in the future?
- How might an understanding of changing terrestrial carbon source-sink patterns through time, especially changes in the vulnerability of key sinks, affect Australia's international position on broad climate change issues, such as what constitutes 'dangerous' climate change?
- Given the need for Australian climate change policy to be supported by the best possible knowledge base, including model-based projections, what must Australia do in order to maintain a world-class climate modelling capacity?
- How can Australia contribute its share to international research on climate change, and how can Australian research and policy development benefit directly from these international linkages?
- How might changes in the coupled climate-carbon system, especially the vulnerability of terrestrial carbon sinks under a changing climate, feed through into impacts on important sectors of the Australian economy?

Although these policy-oriented questions have strong links to carbon cycle science, it is important to recognise that a broadly based national carbon cycle research programme addressing these questions directly will need to be supported by a more general effort to improve fundamental understanding of carbon cycle dynamics. Consistent with this broad scientific remit from fundamental to applied research, funding for a national carbon cycle research programme will come from an equally broad spectrum of sources.

2. CHARACTERISTICS OF A NATIONAL TERRESTRIAL CARBON CYCLE RESEARCH PROGRAMME

Several issues are important in terms of defining the nature and boundaries of a national Australian carbon cycle research programme:

2.1 A common framework for Australian carbon research

The programme should be organised around a mutually agreed framework that:

- provides a common context for terrestrial carbon cycle research carried out in many institutions around the country;
- acts as a platform for building collaborative and other synergistic activities as appropriate;
- avoids unnecessary duplication and fills critical gaps in research effort; and
- provides the means for carrying out periodic syntheses of our best understanding of the carbon cycle.

Funding for a national programme must ultimately be obtained from a distributed network of agencies and organisations, with AGO direct financial support concentrated on those components of the programme that have direct links to AGO's policy mandate.

2.2 Relationship to assessment and reporting

It is important to distinguish the complementary but distinct roles of assessment/reporting and of research, as the carbon cycle features prominently in both. The focus of this document is on research. This distinction is especially important to bear in mind when discussing the role of the National Carbon Accounting System (NCAS). We designate its current assessment/reporting role as NCAS-A (international reporting and support for Government decision-making) and its potential research mode as NCAS-R. The latter refers to the NCAS modules and data released to the public in March 2005.

It is critical that there is a 'firewall' – a clear conceptual and operational boundary - between the two modes/roles of NCAS. NCAS-A is a science-based policy tool developed within Government to serve specific Government assessment and reporting needs. The two priority goals of NCAS are to: (i) establish the overall framework for the reporting of greenhouse gas emissions from land-based activities, and (ii) provide the reporting capability to determine emissions from land use change (deforestation) from 1970 to 2000. The 'engine' of NCAS is the FullCAM model, which simulates the terrestrial cycles of carbon and nitrogen and their interactions with the atmosphere, using a mass balance approach with a hydrid of empirical and process modelling (see figure 2).

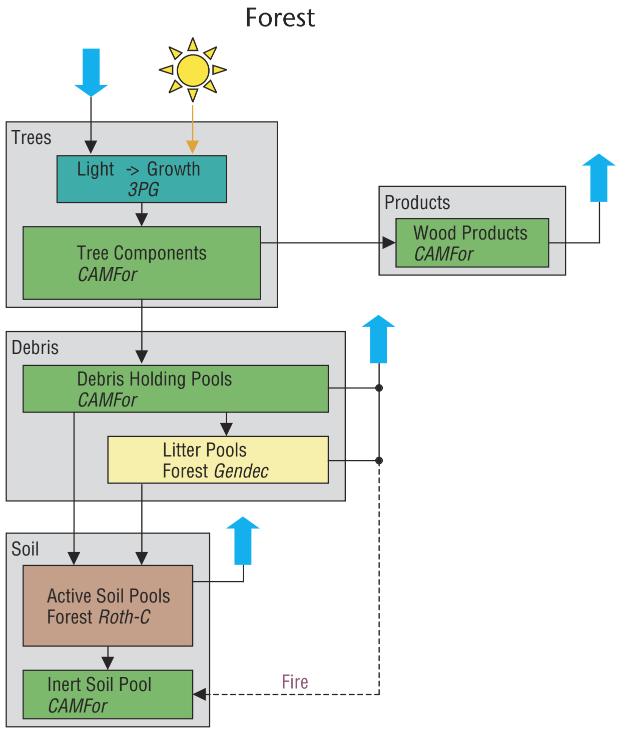


Figure 2

Overview of the FullCAM model. Department of the Environment and Heritage, Australian Greenhouse Office (2005).

Maintaining the credibility of NCAS-A as a state-of-the-science tool is critical for its acceptance and success within the policy arena. Thus, the various components of NCAS-A have been rigorously tested against the best available data to ensure the highest standards. Debate about the validity of NCAS-A, after it has gone through this process and is in the policy arena (and not the scientific research arena), is counterproductive. The scientific debate and discussion about various approaches, which is crucial for good science, should occur upstream as improvements or additions to NCAS are considered. Thus, NCAS-R is an important development on which a broader relationship between the NCAS team and the Australian research community can be built. The ultimate goal is to ensure that the best Australian carbon cycle research is used to support Australian reporting and policy development.

2.3 Thematic approach

It will be more effective to build a coherent research programme around a core set of major priorities rather than to support a large number of loosely related or unrelated small projects. It is important that a critical mass of resources and effort is achieved around each of the priorities so that significant progress can be made. Thus, three major priority themes are proposed around which to focus research; these themes were discussed and agreed at the February workshop. They are described in Section 3 of this document.

2.4 Relationship between terrestrial biosphere and carbon cycle research

It is important to differentiate between terrestrial biosphere research and carbon cycle research. They are closely related but not the same. For example, the carbon cycle module needed to couple to an atmosphere-ocean GCM (cf. Theme 3 below) must have both marine and terrestrial components. In terms of the terrestrial carbon cycle, contemporary research usually takes a whole system approach, which includes coupling of the carbon cycle to nutrient cycles, the hydrological cycle, etc.). It is important to note in this context that NCAS-A is one of the few assessment tools that, because of its model-based approach, has this broader terrestrial ecosystem perspective. Such systems-oriented work is potentially applicable to a wide range of issues, such as water resources and natural resource management, in addition to the carbon cycle. However, the research undertaken within this programme should be formulated and reported through a 'carbon eye's lens', that is, it should focus on the behaviour of the carbon cycle, even though the basic research itself is embedded in a systems approach.

From an Australian perspective, the interaction between the carbon and hydrological cycles is fundamentally important to both. This interaction is critical to understanding all three of the carbon cycle research themes described in Section 3. Thus, carbon-hydrological cycle interactions, along with interactions with other biogeochemical cycles and with carbon observations (next sub-section), are treated in Section 4 as crosscutting issues of relevance for the entire carbon cycle research programme.

2.5 Carbon observations

By its nature, experimental research generates observations. However, these are nearly always of a short-term nature (often three years or less). In addition to these research-generated data, systematic, long-term carbon cycle observations from a range of methodologies are crucial for understanding the variability of carbon sources and sinks, for giving insights into the processes that control carbon cycle dynamics, and for providing invaluable data for testing models. Funding long-term carbon observations, however, is a complex issue. Although there is well-articulated and widespread support in the international scientific community for maintaining them as a research tool (cf. the GCP science plan and the IGOS carbon cycle observation report), providing long-term funding is difficult or impossible for research funding agencies. Discussions are now underway internationally, stimulated by the Group on Earth Observations process, to secure operational agency support for high priority Earth System observations.

As noted above, carbon observations are treated as a crosscutting issue in this document (Section 4) as they are important for all aspects of carbon cycle research, assessment and reporting.

2.6 International research linkages

The interface between an Australian national carbon cycle research programme and the international global change research programmes is important. As noted above, in terms of research (as opposed to assessment (IPCC) or observation (IGOS)), the international effort is coordinated through the Global Carbon Project. There is general consensus both within Australia and globally that the GCP has developed a relevant and exciting science plan, so the challenge has shifted to implementation of the agreed research agenda. From an Australian perspective, a major issue concerns the role of the Canberra-based GCP office. The challenge is to identify 'win-win' situations where the GCP and Australian carbon research agendas coincide, suggesting focused implementation activities for the GCP, supported by the Canberra office, that benefit both the Australian and the international carbon cycle research communities.

The Global Carbon Project

The goal of the Global Carbon Project is to develop comprehensive, policy-relevant understanding of the global carbon cycle, encompassing its natural and human dimension and its interactions. This is accomplished by determining and explaining three themes:

- ***Patterns and Variability:*** What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?
- ***Processes and Interactions:*** What are the control and feedback mechanisms – both anthropogenic and non-anthropogenic – that determine the dynamics of the carbon cycle?
- ***Carbon Management:*** What are the likely dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?

THE GCP WILL IMPLEMENT THIS AGENDA BY:

- Developing a research framework for integrating the biogeochemical, biophysical and human components of the global carbon cycle.
- Providing a global platform for fostering coordination among international and national carbon programmes to improve the design of observations and research networks, data standards, information transfer, and timing of campaigns and process-based experiments, and the development of model-data fusion techniques.
- Fostering research on the carbon cycle in regions that are poorly understood but have the potential to play important roles in the global carbon cycle.
- Synthesising and communicating new understanding of the carbon-climate-human system to the broad research and policy communities.

3. RESEARCH THEMES

3.1 Patterns of sources and sinks of carbon across Australia

Understanding the nature of the carbon cycle, including the natural and modified patterns of sources and sinks on land and in the oceans, is an essential prerequisite for tackling climate change at its most fundamental level – management of the carbon cycle at the national and global levels. Carbon is naturally transferred between atmospheric, oceanic and terrestrial pools via a rich array of chemical, physical, biological and – more recently – human processes. Determining the spatial and temporal pattern of these fluxes gives valuable insights into the processes that drive the carbon cycle, and contributes strongly to the knowledge base required to manage the carbon cycle responsibly.

Knowledge of the pattern of carbon sources, both temporal and spatial, will be important for developing the future, post-Kyoto international climate change framework. To support the development of this framework, the future capacity of greenhouse gas accounting of emissions and sinks will need to be enhanced towards a full carbon budget and towards accounting for other gases, as recommended by the IPCC. Such capability will be crucial for evaluating and implementing emissions and sinks management options. The improving understanding of source-sink patterns also supports research on the other two themes of this programme: vulnerability of terrestrial carbon sinks in the future and the development of carbon cycle-climate coupled models.

The Australian terrestrial biosphere presents unique problems in terms of determining and interpreting the patterns of carbon sources and sinks. Unlike many of the northern hemisphere terrestrial ecosystems, Australia's systems are both moisture and nutrient (especially phosphorus) limited, giving rise to different patterns of carbon source-sink strength and different interactions with climate variability. From a policy perspective, Australia's large land mass coupled with its relatively small population implies that terrestrial sources and sinks play a disproportionately large role in the continental carbon balance compared to most other industrialised countries. Knowledge of the patterns of natural and modified carbon fluxes across the continent is essential background information to support Australia's policy development and international negotiating position on climate change issues.

It is important to emphasise at the outset that this theme is proposed from a scientific research perspective, and is designed to complement the assessment/reporting perspective. NCAS-A has been constructed to address the priority reporting and assessment demands arising from Australia's international obligations, but does not yet represent a tool for simulating the full carbon budget across the continent. However, such capability will be in place by 2007/2008. In the meantime, there remains the research challenge to describe and understand land-based carbon fluxes well enough to construct an internally consistent and robust Australia-wide carbon budget through time. Although there are several methodologies used or proposed for constructing continental-scale carbon budgets, they do not yet agree (see figure 3a,3b,3c,3d).

Tools/methodologies that can be applied to this theme include:

- 'Top-down' inverse studies based on atmospheric measurements of CO_2 concentration, and on satellite measurements of column CO_2 when these become available later in this decade;
- A 'bottom-up' approach based on the data and modules of NCAS-R made public in March 2005, acting as a detailed terrestrial ecosystem/land use change model but in research mode;
- Carbon-related data from a wide range of sources, both spatially comprehensive (e.g., remotely sensed data) and point data. These include data specifically designed to support research on the carbon cycle, such as flux measurements of CO_2 (and other gas) exchange from fixed tower sites and also potentially from portable towers designed to sample 'hot spots' of fluxes. The data also include measurements taken for other purposes (e.g., soil carbon measurements or forest biomass inventories) but they are relevant to carbon cycle research.
- Modelled estimates of sources and sinks of carbon across Australia.

There are several techniques for comparing the estimates of source-sink strengths and patterns from both top-down and bottom-up techniques. One is to simply analyse and compare the results on their own. Cross-methodological comparisons in a more formal sense, such as applying mass balance constraints, provide another way of testing our understanding. A more recent approach is to use data assimilation techniques or model-data fusion methods to formally optimise an inferred source-sink pattern from all of the available, relevant data streams (sometimes also called the "multiple constraints" approach). The NCAS data streams could play a useful role here. A concerted, coordinated effort using Australia as a continental-scale test-bed would significantly increase our capability to understand and simulate carbon source-sink patterns. A critical activity under this theme is thus the rigorous cross-comparison of models and methodologies and their comparison against data. Requirements for both top-down and bottom-up approaches are (i) better process understanding of the carbon cycle and (ii) suitable data from new observations (see crosscutting theme on observations) and better use of existing data.

FIGURE 3: Examples of approaches to estimating carbon concentrations and fluxes at various scales.

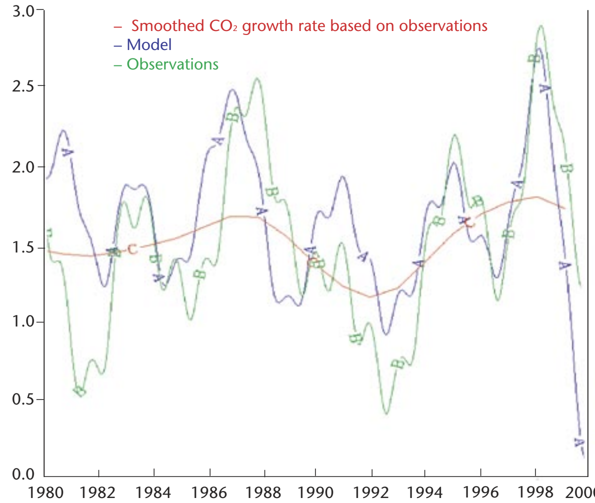


Figure 3a

Global atmospheric CO_2 growth rate in ppm/year. Kowalczyk, E. A., Law, R. M., and Wang, Y. P. (2005)

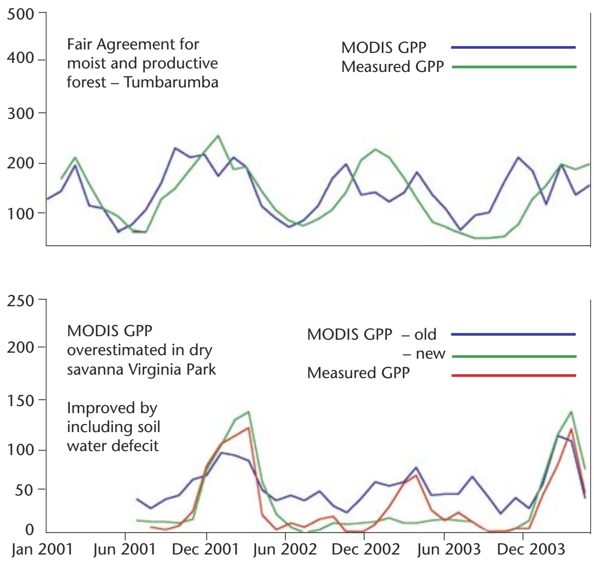


Figure 3b

Gross primary productivity (gross carbon uptake by vegetation) as measured by flux towers and estimated from remote sensing data. Leuning R.L., Cleugh H., Zegelin S.J., Hughes D. (2005)

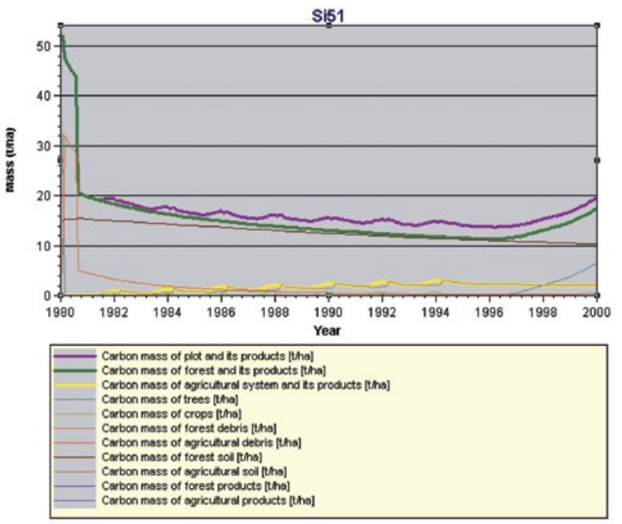


Figure 3c

The time course of change in various carbon pools simulated at the scale of a 25 metre pixel by National Carbon Accounting System. Department of the Environment and Heritage, Australian Greenhouse Office (2005)

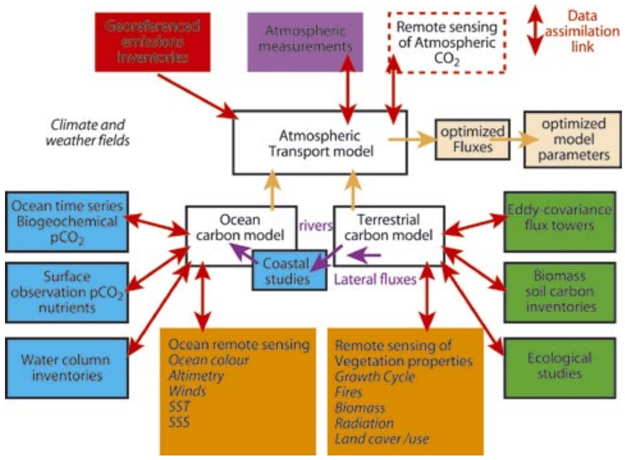


Figure 3d

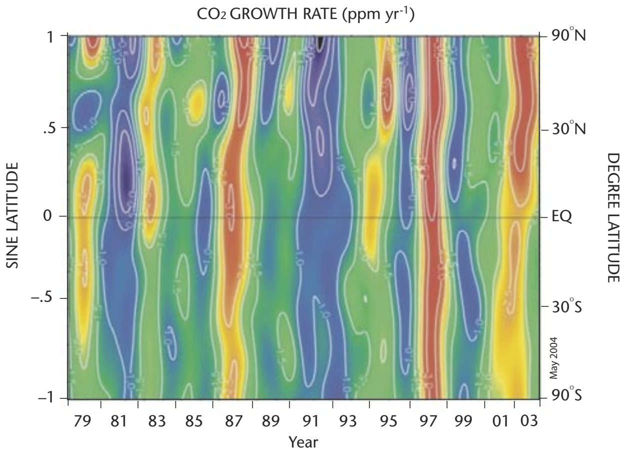
Information flow in a global carbon cycle assimilation system (Ciais et al 2004).

One outcome of this theme is the possibility to improve Australia's accounting and reporting capability through the inclusion of NCAS-R in the scientific arena and its comparison to other methodologies for estimating source-sink patterns. Thus, at the appropriate points in the development of phase 2 of NCAS-A, the NCAS team could import improvements developed through the research mode of the system (and also derived from Theme 2 work on sink vulnerabilities) to generate an NCAS-A+ system of enhanced greenhouse gas accounting capability for reporting and management purposes. In this way, the full capability of Australia's carbon cycle research community can be engaged to ensure that NCAS-A remains at the leading edge of accounting and reporting systems at the global level.

3.2 Vulnerability of terrestrial carbon sinks into the future

Improved knowledge about critical carbon cycle processes is required to understand the dynamics of the carbon cycle into the future. The behaviour of the terrestrial carbon cycle has been directly implicated in the simulated strong positive feedbacks of a coupled carbon cycle-physical climate model (see section 3.3), triggering interest in the longevity and vulnerability of terrestrial carbon sinks in the coming decades.

After strong debate in the late 1990s about the notion of 'saturation' of the terrestrial carbon sink, there is now a consensus that the currently observed carbon sink of approximately 2-3 Gt yr^{-1} will saturate, and possibly turn into a net source under some conditions. The critical questions are how vulnerable are key terrestrial sinks and how quickly might they saturate, leading to a surge in atmospheric CO_2 concentration? Indeed, the issue has recently become more urgent as the annual CO_2 growth rate has been anomalously high (over 2 ppm) for the last two years (see figure 4). The prime suspect is a change in terrestrial carbon sink strength.



Contour plot showing the temporal and spatial variations in the atmospheric increases of carbon dioxide. The cooler colours (green, blue, violet) represent periods of lower than average growth rates and the warmer colours (yellow, orange, red) represent high growth rate periods. Note the strong increase in CO_2 growth rate in 2003 in the northern hemisphere. The plot is derived from measurements of thousands of samples collected at the CMDL cooperative air sampling network sites. The variations in the growth rate of this climatically important gas are due to interannual variations in the imbalance between sources and sinks, and also to variations in atmospheric transport. Principal investigator: Thomas Conway, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado (303) 497 – 668 (thomas.j.conway@noaa.gov. http://www.emdl.noaa.gov/ccgg)

Figure 4

There is much interest globally in the longevity of terrestrial carbon sinks, but there are specific issues regarding the Australian continent that require more research. Achieving better understanding of Australia's terrestrial carbon sink dynamics will improve our overall understanding of our terrestrial carbon budget and contribute better understanding at the international level of characteristics of Australian ecosystems, such as arid and semi-arid, broadleaf evergreen forests and woodlands, and the interaction of water and nutrient limitation on productivity.

Key issues that need to be addressed in terms of the vulnerability of terrestrial carbon sinks include the nature of the biophysical system that controls the carbon flux of interest, the timescales on which the sinks normally operate, and the need to take a systems approach in analysing the security or vulnerability of the sinks. Organising the analysis of the vulnerability of sinks to changes in climate and atmospheric composition directly, the exacerbation of natural disturbance regimes by climate change, and the direct effects of management provides a useful framework. It must be emphasised, though, that often multiple factors, such as climate change and management, are involved in determining the vulnerability of particular carbon sinks (e.g., fire disturbance).

Changes in climate and atmospheric composition. Changes in temperature, precipitation/moisture availability and atmospheric CO_2 concentration can all strongly affect the fluxes of carbon between terrestrial ecosystems and the atmosphere. A better process-level understanding is required of the parameters that control ecosystem productivity and respiration, with a focus on Australian ecosystems over long timeframes that encapsulate annual variability and trends.

- *CO_2 fertilisation.* There is still debate about the magnitude of the CO_2 fertilisation effect in situ, in 'natural' ecosystems. For example, increasing atmospheric CO_2 may be a significant factor in the 'vegetation thickening' phenomenon but its role is still strongly debated. There is an urgent need for elevated CO_2 research that is aimed directly at carbon sink issues at the whole ecosystem level.
- *Heterotrophic respiration* (the mineralisation of soil carbon and subsequent emission of CO_2). This is a high priority issue in the northern mid and high latitudes, where significant amounts of carbon are stored in soils and temperature increase is expected to be the strongest. However, the issue needs to be examined carefully in Australia. How much of our terrestrial carbon pool is in the soil? This soil pool already experiences high temperatures; how sensitive is it to further increases in temperature? What is the relationship between heterotrophic respiration and soil moisture level? Does increasing heterotrophic respiration also enhance nitrogen mineralisation and thus stimulate productivity? Can we synthesise this information to make projections about the vulnerability of Australia's soil carbon pools under a changing climate?
- *Temperature, moisture and productivity.* A dramatic example of how increasing temperature can affect a terrestrial carbon sink is the sharp loss in productivity of forests and agricultural systems in Europe during the heat wave of 2003 (Ciais et al. 2005). An analysis of both data and model simulations shows a 30% reduction in gross primary productivity in European ecosystems during 2003, resulting in a strong net source of CO_2 to the atmosphere (0.5 Gt C yr^{-1}). In effect, about four years of carbon accumulation in these systems was lost in one extreme event. An increase in the frequency of such events could switch temperate forests, usually considered to be reliable carbon sinks over long timeframes, into CO_2 sources. The Ciais et al. work is supported by data from the Tumbarumba flux tower site. In this Australian example, the severe drought of 2002-03 reduced productivity from 10 t C per ha in normal rainfall years to about 4 t C per ha (see figures 5a & 5b). The drought also coincided with a severe insect attack, leading to defoliation and loss of productivity.

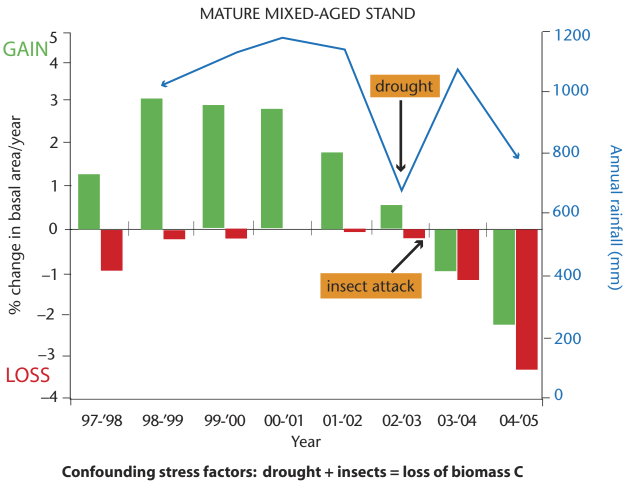


Figure 5a

Change in tree basal area, as an estimate of net carbon uptake, as a function of time. Green bars are live trees. Red bars are dead trees. Blue line is rainfall. The effects of drought and insect attacks can be clearly seen. Data from the flux tower site at the Tumbarumba temperate native forest. (Heather Keith, pers. comm.)

Figure 5b

Comparison between insect damage in Alpine Ash crowns and healthy crowns. (Photo Kris Jacobsen, CSIRO).

Figure 5c

Images of the insect attack, including damaged leaves, Psyllid insect and lerps. (Photos From Roger Farrow, 1996 Insect pests of Eucalypts on farmland and plantations in south eastern Australia, CSIRO Division of Entomology Identification Leaflet).

Natural disturbances exacerbated by climate change. Disturbance regimes that affect the carbon dynamics of Australian ecosystems include wind/storms, fire and host/parasite relationships (pests and diseases, see figure 5c). The latter two are generally thought to be important for Australian carbon sinks.

- *Fire.* There tends to be much misunderstanding about fire and the carbon cycle, particularly in the northern hemisphere. Fire is a natural part of the dynamics of many ecosystems, especially savannas and boreal forests at the global scale and, at the Australian scale, savannas and dry sclerophyll forests and woodlands. The amount of carbon emitted to the atmosphere during combustion is, when averaged over long time periods, balanced by the amount taken up in the subsequent regrowth. This relationship holds so long as the fire regime remains unchanged. However, if there is a shift to more frequent and/or more intense fire regimes, there can be a discernable effect on the carbon budget. In effect, a change in fire regime can mean a net shift in carbon stored in vegetation and soil to the atmosphere (or vice-versa, in the case of fire suppression, for example). In an Australian context, fire regimes are strongly dependent on the local or regional management practices as well as on extremes of climate and weather. Fires can deplete soil fertility under Australian conditions, an effect that over time may limit productivity and hence the strength of the carbon sink. Charcoal production may be a significant carbon sink, but this is still poorly understood.

- *Pests and Diseases.* This issue is usually associated with agriculture or human health and not with the carbon cycle. However, there is good evidence that insect infestations in the boreal forests of both Canada and Siberia have had significant effects on the carbon sinks in those regions, equivalent in magnitude to the effects of fire. There is the potential for pest and disease outbreaks of a different type in Australia, for example an enhancement of the incidence of *Phytophthera*, as climate changes. Increases of insect attacks on Australian flora are also possible as climate changes. Greater vulnerability to pests and diseases occurs in monocultures, and this poses a risk to the increasing area of plantations. Potential risk exists of increasing spread of invasive species of woody weeds under climate change. Few resources have been allocated to this area of research to date, so perhaps a scoping study would be useful to determine the seriousness of the issue for Australia.

Management. Land management practices inevitably affect the carbon cycle in a number of ways, both directly and indirectly (see figures 6a & 6b). Accounting for carbon sinks will likely become more important during the Kyoto Protocol period and in the following commitment periods. Project-level carbon accounting based on the NCAS toolkit offers the means to report changes in carbon sinks induced by management and gives insights into the processes that control sink dynamics.

- *Indirect effects of management on carbon fluxes.* A wide range of practices associated with managing land-based production systems influence carbon fluxes - tillage practices, fertiliser management, grazing intensity and forest clearing, harvesting practices and land degradation, for example. All of these potential management-induced sinks will have degrees of vulnerability, both to changes in the biophysical environment and to changes in social and economic policy.

- *Direct creation of carbon sinks.* As carbon trading schemes become more common at state, national and international levels, direct creation and management of sinks will become a growing industry. Plantation forests are already a strong candidate for such deliberate sinks, but they may be vulnerable to climate extremes and to changes in fire regimes, as noted above.

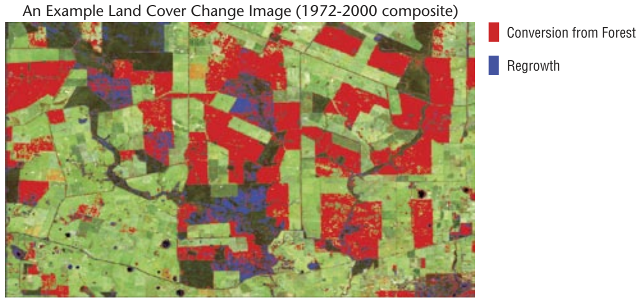


Figure 6a

An example of land cover change derived from a 1972-2000 composite image from NCAS. Department of the Environment and Heritage, Australian Greenhouse Office (2005).

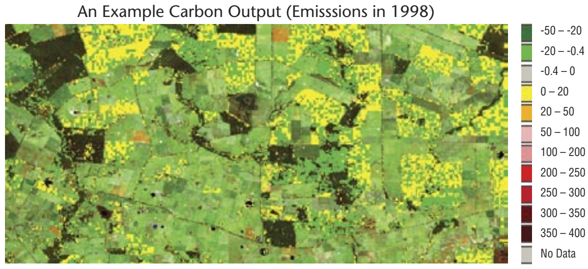


Figure 6b

An example of modelled carbon emissions in 1988 based on changes in land cover from NCAS. Department of the Environment and Heritage, Australian Greenhouse Office (2005).

3.3 Interactive coupling of the carbon cycle to the physical climate system

Global climate models support policy formulation by integrating our current knowledge base on the climate system and by providing scenarios of plausible future trajectories of climate given various forcings. Climate models also provide useful information for scientists working on climate adaptation strategies in partnership with various sectors of Australian society. Thus, it is in Australia's interests to maintain a state-of-the-art global climate modelling capability, rather than relying on climate models imported from the northern hemisphere.

Although climate models have developed strongly over the last two decades and have improved considerably in their ability to simulate current climatic patterns, there is a recognition that critical processes are still poorly represented or even missing from the models. One of the next major developments in the evolution of global climate models is the coupling of the carbon cycle, both terrestrial and marine components, with the physical climate system in an interactive way. Early attempts to do this (by Cox et al. 2000 and Friedlingstein et al. 2001) showed positive feedbacks of varying degrees. There are now seven such studies, and all show positive feedbacks (see figure 7). The Cox et al. work showed a strong positive feedback, driven primarily by the terrestrial carbon cycle, that hinted at the possibility of a 'runaway' greenhouse effect. The major factor driving this result was the increase in heterotrophic respiration with increasing temperature.

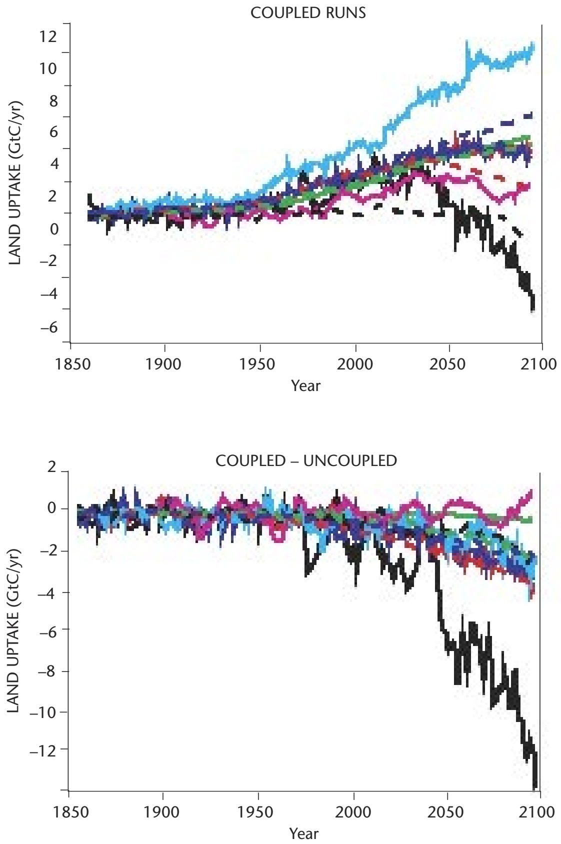


Figure 7

Climate-carbon cycle feedbacks expressed as changes in land uptake of carbon with time. The top panel shows the results of eight coupled GCM carbon cycle model simulations. The bottom panel shows the difference in land uptake between uncoupled and coupled model simulations. (Friedlingstein et al 2005)

To maintain its status as one of the top climate models in the world, the Australian global modelling capability will also need to be enhanced to include interactive carbon dynamics, atmospheric chemistry and dynamic vegetation. The suggestions below focus on the land aspects of these proposed developments and are discussed within a five year timeframe, so that an enhanced model will be ready to undertake runs for the IPCC 5th Assessment Report.

Four aspects of the terrestrial component of a coupled climate-carbon cycle model were considered important in the context of a five year development plan:

- *Interface with the global climate model.* The recent emergence of the ACCESS initiative (Australian Community Climate and Earth System Simulator, built around a CSIRO-Bureau of Meteorology-universities collaborative effort) provides the appropriate framework within which to develop an enhanced land surface component. Collaboration between the ACCESS initiative and the ARC Network for Earth System Science thus provides an institutional platform for model development but a significant infusion of new resources is required for adequate implementation.
- *Nature of the terrestrial biospheric model.* The ultimate objective is to develop a complete, integrated land surface model within the Earth System simulator; the land module should include surface and sub-surface hydrology, carbon/nutrient cycles, water/energy exchange, vegetation dynamics, aerosols, land-use change, etc. This is a significant challenge, best undertaken in a phased approach. The existing land-surface module (CBM + BIOS) is state-of-the-art and provides an excellent foundation on which to build towards the more complex land module (see figure 8). The first version of the ACCESS land surface module is under development at CSIRO Marine and Atmospheric Research and will be released to the broader community in 2005.

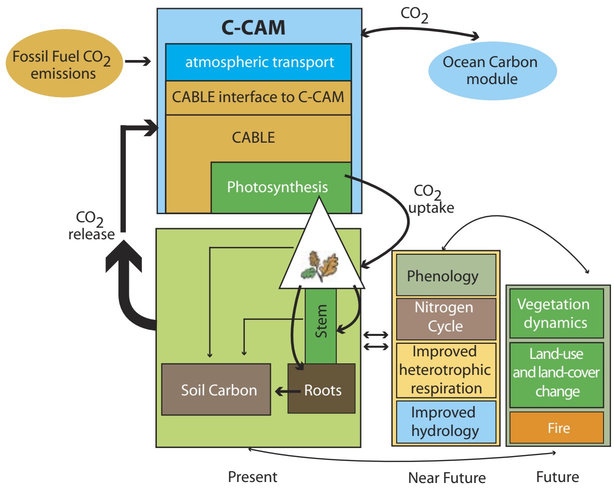


Figure 8

Representation of a coupled carbon cycle model showing present and future components (CSIRO Division of Marine and Atmospheric Research)

Phase 1: Improvements to the existing land surface module:

- Vegetation phenology
- Isotope capability (C, O, H)
- Improved hydrology (unsaturated flow, groundwater, river routing, irrigation, dams)
- Soil and vegetation respiration
- Better description of vegetation condition, including recovery after prior disturbance
- Aerosol emissions and deposition
- Planetary boundary layer dynamics

Phase 2: Inclusion of dynamic vegetation capability:

'Dynamic vegetation' refers to the ability of the model to simulate shifts in vegetation/biomes in response to a changing atmosphere and climate and to simulate changing disturbance regimes (at least fire) in response to changing climate. That is, the Australian terrestrial carbon cycle module should have the features of the Dynamic Global Vegetation Models (DGVMs; see Cramer et al. 2001) that are now being used internationally at the leading modelling centres to develop complex Earth System models. There are two strategies that could be used to develop an Australian DGVM. One option is to build a completely new DGVM using Australian expertise in ecosystem dynamics and modelling. The second is to import an existing DGVM (e.g., Lund-Potsdam-Jena [LPJ]), but modify, maintain and upgrade it with Australian expertise. The improved version (including, for example, better simulation of arid zone dynamics) could be contributed back to the international community so that Australia both benefits from and contributes to the work of international colleagues. The strategy to be adopted requires further discussion within the Australian Earth System science research community, although, for practical reasons, the second option seems more feasible. In the longer term, inclusion of land-use change is also essential, perhaps initially through collaboration with the integrated assessment modelling community.

- Participation in the international model intercomparison of coupled climate-carbon cycle models (C4MIP). The project, co-sponsored by the IGBP and the WCRP, has arisen directly out of the Cox and Friedlingstein pilot studies and supports a more systematic evaluation of coupled carbon-climate models. Protocols have already been established for the intercomparison. There is an existing commitment from Australia to be involved in this intercomparison, and the present version of the CSIRO GCM has completed the requirements for the first phase of C4MIP. Development plans for a fully dynamic land component of an Earth System model should include provision for continuing participation in C4MIP and in other international intercomparison projects.
- Integration of models and observations. A wide range of observations (e.g., atmospheric CO_2 concentrations, ground-based flux measurements, remotely sensed data) are essential for testing and improving the model. In terms of remotely sensed data, it was suggested that the land surface module should be capable of simulating radiances so that it can be directly tested against the data. In addition, observations during the last century, in which both climate and carbon cycle dynamics have changed significantly, provide a rich source of data to test the models. It is also important to have more observations from Australia and the southern hemisphere more generally; at present the database for model validation is highly skewed towards the northern hemisphere.

4. CROSS-CUTTING ISSUES

4.1 The carbon and water cycles

The interaction of the terrestrial carbon cycle with the hydrological cycle is a crosscutting issue that is especially important for Australia. Impacts/feedbacks occur in both directions and across a wide range of processes and scales. For example, continental-scale productivity, and thus the uptake of carbon from the atmosphere by terrestrial systems, is strongly limited by water availability (see figure 9). The pattern of natural sources and sinks is strongly related to moisture availability. All of the vulnerability issues outlined above also intersect strongly with the hydrological cycle. The water use efficiency effect of elevated atmospheric CO_2 is an example of a carbon cycle feedback effect on the hydrological cycle. The effect of soil moisture on rates of heterotrophic respiration is an impact operating in the opposite direction. Major disturbances to the carbon cycle, such as bushfires and insect/disease infestations, are also strongly dependent on the moisture status of ecosystems.

Feedbacks of changes in the carbon cycle to the hydrological cycle are especially important in an Australian context. For example, the expansion of plantation forests (which could be a deliberate manipulation of the carbon cycle if these are planted for carbon sequestration purposes) can lead to a decrease in runoff if they are extensive enough. Other changes in land use can simultaneously affect the carbon and hydrological cycles through changing the land surface and thus modifying the carbon source/sink pattern, the amount of evapotranspiration versus runoff and perhaps even local or regional climate and thus rainfall.

The interaction of the carbon and hydrological cycles is an issue that cuts across all three themes proposed for an Australian carbon cycle research programme. It is therefore essential that carbon cycle research be carried out in an integrated way from a whole-ecosystem approach. The results of the research, although discussed in this document in terms of improving understanding of carbon cycle dynamics, should be equally applicable to water resources and natural resource management issues. The ecosystem services concept may provide a unifying framework for synthesising this more integrative science aimed at a number of related applications.

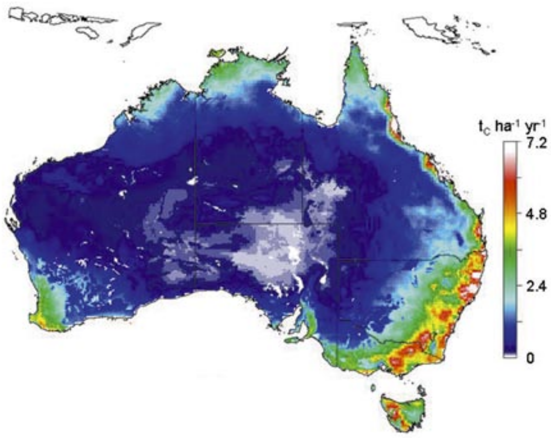


Figure 9

Net primary productivity (NPP) of Australia, modelled from remotely sensed data, for the period 1981-2000 (Damian Barratt, pers. comm.)

4.2 Carbon and other biogeochemical cycles

Although the focus of this document is on CO_2, it is important to recognise that other gases and particles in the atmosphere also affect the radiation balance at the Earth's surface. These include other carbon compounds, such as methane (CH_4) and volatile organic compounds (VOCs), as well as elemental black carbon (soot). In addition, nitrogen compounds can affect climate through changing the radiative balance of the atmosphere (e.g., N_2O) and through atmospheric chemistry (e.g., NO_x). Many of these other chemical species are coupled to CO_2 emission or uptake in various ways. For example, the nitrogen and carbon cycles are strongly coupled in terrestrial ecosystems, both through plant processes and through the dynamics of mineral soils and soil organic matter. Changes in fire frequency will affect not only CO_2 emissions, but also the emission of carbon monoxide and of a range of aerosol particles that influence climate in both direct and indirect ways. Thus, it is important that research on CO_2 ultimately be embedded in a systems framework that accounts for these various biogeochemical interactions.

4.3 Carbon observations

Observations of carbon fluxes and pools are essential for understanding the behaviour of the carbon cycle at a fundamental level, for constructing reliable accounting and reporting tools, and for testing research models of carbon cycle dynamics. NCAS development, for example, has relied strongly on databases of various types and the data assimilation techniques (model-data fusion) for improving understanding of source-sink patterns and carbon dynamics requires streams of data from a variety of observations.

While it is always easy to call for more observations, there is a corresponding need to set priorities and to match observations to science questions and to applications for accounting and policy. A capability to test the importance and sensitivity of various model inputs and parameters is critical for the strategic deployment of resources to maximise improvement in observations.

The international scientific research and observation communities have recently placed much stronger emphasis on the development and maintenance of global observation systems of critical Earth System features, including the carbon cycle, to support the global change research effort and the development of policy with regard to climate change. This new emphasis includes the enhancement of existing observing systems such as GCOS (Global Climate Observing System); development of the IGCO (Integrated Global Carbon Observation) strategy (Ciais et al. 2004) and the launch of the GEOSS (US-led Group on Earth Observations 'System of Systems'), a 'grand' Earth System observation network.

The IGCO theme has identified a core set of observations for land pools and land-atmosphere fluxes of carbon, based on both scientific research and policy/accounting needs (Ciais et al. 2004):

- Satellite observation of column integrated atmospheric CO_2 distribution to an accuracy of at least 1 ppm with synoptic global coverage.
- An optimised operational network of atmospheric in situ stations and flask sampling sites with an accuracy of at least 0.1 ppm.
- An optimised, operational network of eddy covariance (flux) towers measuring on a continuous basis the fluxes of CO_2, energy and water vapour over land ecosystems.
- Forest aboveground biomass, measured at five-year intervals by in situ inventory methodologies and more frequently by remote sensing techniques.
- Soil carbon content, measured at ten year intervals primarily by in situ inventory methodologies.

These last two observations are core activities for accounting and reporting, and have been a focus of carbon accounting activities in Australia over the last five years.

In addition, the report identified as high priority a combination of satellite observations delivering global data streams for parameters required to estimate surface-atmosphere CO_2 fluxes where direct in situ measurements are scarce. These observations include land cover status, disturbance extent and intensity, and parameters related to vegetation activity (e.g., NDVI, MODIS).

The ground-based components of the proposed carbon observation system will need to be developed on a country-by-country basis, working towards a common international framework (see figure 10). A coherent national level, systematic network of carbon observations is in our interest, for supporting the research programme described above and for supporting accounting, reporting and policy formulation according to Australian priorities. In addition, Australian participation in an international observation system is important from a global perspective, as we occupy one of Earth's six inhabited continents and we provide data on semi-arid ecosystems that are found primarily in countries at low latitudes. In addition, Australia (CSIRO) operates the second largest global atmospheric CO_2 concentration monitoring network, which has contributed significantly to the improvement of our understanding of the global carbon cycle over the last three decades. Furthermore, Australia has developed the only CO_2 concentration measurement system that is capable of measuring concentrations with an accuracy of 0.1 ppm as recommended by IGCO.

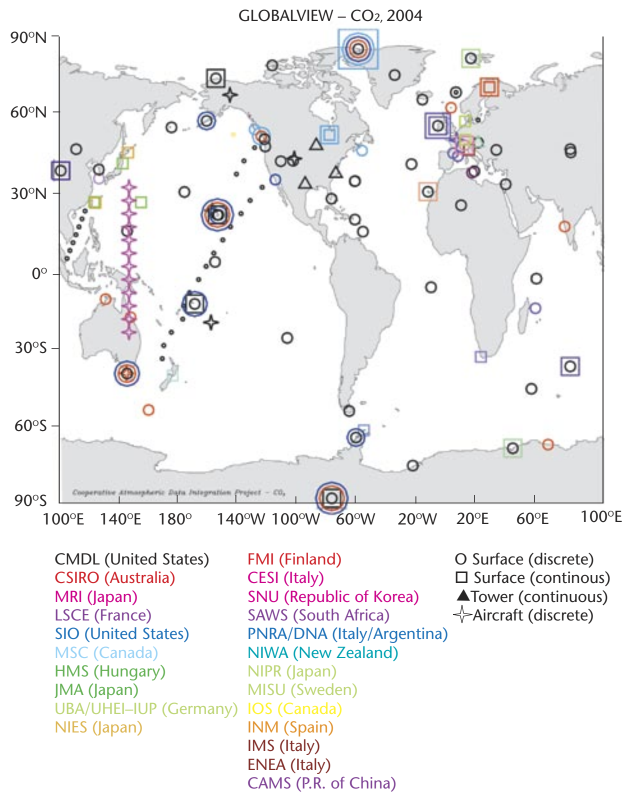


Figure 10

Global distribution of atmospheric concentration flask sites. Note the paucity of stations in the southern hemisphere. (GLOBALVIEW-CO2 2004 [http://www.cmdl.noaa.gov/ccgg/globalview/index.html]

As noted above, the international network of terrestrial flux measuring stations, FLUXNET, of which OzFlux is a member, is a core component of the global carbon observing system (see figures 11a & 11b). The inclusion of FLUXNET in the core global system recognises its value to the research and policy communities by addressing several key issues: (i) controls on the flux of carbon between the ecosystem and the atmosphere through observation of the year-to-year variation in fluxes (this is particularly important for Australian ecosystems given our highly variable climate and provides crucial data for elucidating the interaction between the carbon and the hydrological cycles); (ii) observation of the abrupt or non-linear changes in carbon dynamics (e.g., effects of droughts and insect attacks on carbon fluxes at the Tumbarumba site); (iii) monitoring carbon fluxes in and out of the ecosystem for budget purposes; (iv) provision of high quality data for testing and improving models.

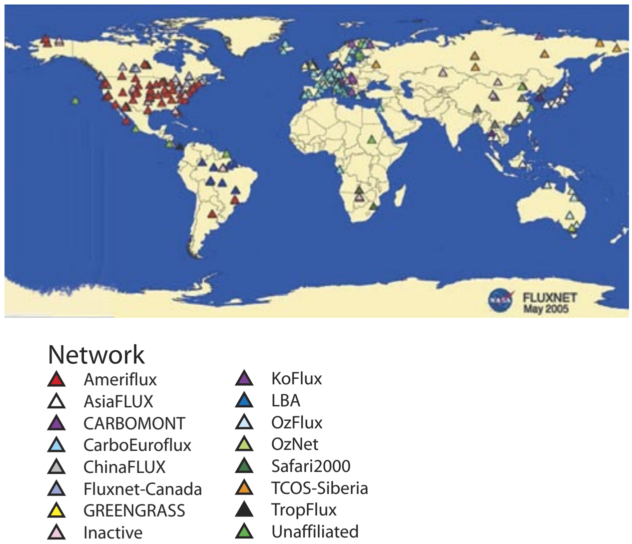


Figure 11a

Spatial distribution of FLUXNET sites and their sponsoring countries or regions. [http://www-eosdis.ornl.gov/FLUXNET/]

Figure 11b

Measurements being taken above the treeline on the flux tower at Tumbarumba, NSW (Photo Greg Heath, CSIRO).

Additional aspects of national carbon (pools and fluxes) observing activities in Australia include:

- The need to maintain the existing atmospheric CO_2 concentration measurement network and to strategically expand to a few continental (in-land Australia) locations for studying the key processes (photosynthesis, respiration and disturbance such as fires) that operate at continental scale.
- Inclusion of isotopes of carbon and water in observational systems.
- The development of one or two 'super (tower) sites' where intense research is carried out in addition to the more standard monitoring of water, energy and CO_2 fluxes. Additional research could focus on, for example, aerosol production, emissions and particle development in the boundary layer; the emission and deposition of reactive gases; and more intensive eco-physiological research on biogeochemical cycling in soils.
- The need to incorporate historical observations of carbon pools, land-cover change, etc.
- The need to identify and support an institution or a network of institutions for hosting, archiving and making available the data streams arising from these activities.

Development and maintenance of a carbon observing system presents funding challenges. Many of the observational methodologies have been in the research domain in the past, and thus have been funded through normal scientific research funding streams. This funding is normally for a few years only and is usually not suited for supporting long-term observations (note the failure of a well-formulated bid to the ARC to support OzFlux). The issue therefore is to (i) standardise observational methodologies so that they can be moved from the research to the operational domains, and (ii) secure long-term support for the observing system from operational agencies or other non-research funding streams.

5. INSTITUTIONAL ARRANGEMENTS

A national level, coordinated science programme on the carbon cycle must be based on a strategic research agenda framed around carefully defined key scientific and policy questions. In addition, an appropriate organisational framework is required to support the effective and efficient implementation of the programme. The framework should be (i) driven by and appropriate for the scientific questions being addressed; (ii) built around a common platform on which all of the major institutions and researchers can participate on an equal footing; (iii) 'minimalist' in approach and as 'light' as possible in terms of the management resources required; (iv) guided by a high-level panel that includes Australia's top carbon researchers representing all major institutions involved in the programme.

The proposal for a national level programme raises the issue of large-scale coordinated research versus the 'let many flowers bloom' approach of smaller, individual projects. There is a place for both in a national programme; the approach should match the nature of the scientific question being posed. For many of the more directly policy-oriented questions, a single, national position is required and this must be built on a consensus of the state-of-the-science. For aspects of research requiring large teams of scientists and/or large levels of funding (e.g. a continental-scale carbon observing system or the building of a coupled carbon cycle-climate model), a unified national approach is more efficient. However, where fundamental scientific questions remain unresolved, the full creativity of the scientific community is needed, and this is often best achieved via a pluralistic strategy built on many contrasting approaches. The role of a national programme is, in this case, to provide the framework for rigorous cross-comparison and eventual synthesis of the spectrum of individual approaches towards achieving a higher level understanding of the issue.

A key aspect of a national carbon cycle research programme is the need to educate and train the next generation of carbon cycle researchers. Thus, it is essential that institutions that have a strong role in teaching and research training (e.g., universities) be significant players in carbon cycle research in Australia.

Many of the key observations required to monitor changes in terrestrial carbon pools (such as soil carbon or forest biomass) reside in state agencies. It is important that these agencies are engaged in the development of a national carbon cycle research programme, and contribute especially to observational strategies closely related to accounting and reporting.

Building a national programme of carbon cycle research represents an excellent opportunity to build an enhanced level of collaboration among the Australian Climate Change Science Programme, the ARC Earth System Sciences Network, NCAS and the CSIRO Biosphere Working Group. The next step in meeting this challenge is the establishment of a planning/steering committee, perhaps under the auspices of the Australian Academy of

Science, National Committee on Earth System Science. The ultimate goal of a national carbon cycle programme is to pursue world-class research at the frontier of global change science by harnessing Australia's considerable science capacity to its fullest extent and by maximising the returns on the nation's scientific resources, both human and financial.

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APPENDIX 1

WORKSHOP AGENDA

PROGRAMME FOR CARBON CYCLE RESEARCH WORKSHOP
8-9 FEBRUARY 2005
AUSTRALIAN NATIONAL UNIVERSITY
Forestry Theatre, School of Resources, Environment & Society (Bldng 48)
CANBERRA

Objectives

- To work towards a national strategy for carbon cycle research – spanning observations, model development, international collaboration and policy linkages.
- To contribute to identifying priorities for the Australian Climate Change Science Programme

TUESDAY 8 FEBRUARY	
8.45 – 9.00	Coffee and registration
9.00 – 09.30	Workshop introduction and policy requirements • Purpose of the workshop • Policy goals and information needs **Presenters: Ian Carruthers and Jo Mummery, AGO**
9.30 – 10.00	The nexus between carbon cycle research, assessment and reporting: from 'traditional' reporting and IPCC guidelines to full carbon budgets. Presenters: Gary Richards, AGO and Werner Kurz, Canadian Forestry Service **Chair: Will Steffen**
10.00 – 11.00	Theme 2 – Patterns of Australian sources and sinks: Integrating the top-down and bottom-up approaches. Presenters: Gary Richards, AGO; and Damian Barrett, CSIRO EOC **Chair: Will Steffen**
11.00 – 11.340	**Break**
11.30 – 12.30	**Theme 1** – Vulnerability of terrestrial carbon sinks: can sinks turn into sources? What does this mean for policy? Presenter: Werner Kurz **Chair: Will Steffen**
12.30 – 1.30	**Lunch**
1.30 – 2.15	**Theme 3** – Towards Earth System models: Interactive Coupling of Climate and Carbon Cycle Models. Presenter: Peter Cox, Centre for Ecology and Hydrology, UK (To be given by Will Steffen) **Chair: Mike Manton**
2.15 – 3.30	Open discussion: Themes, Approaches, Australian Priorities **Chair: Mike Manton**
3.30 – 4.00	**Break**
4.00 – 5.30	Break out groups addressing each of the three themes **Theme 1** – Vulnerability of terrestrial carbon sinks. Chair: David Ugalde **Theme 2** – Patterns of Australian sources and sinks. Chair: Ian Carruthers **Theme 3** – Coupled climate-carbon cycle models. Chair: Will Steffen
7.00pm for 7.30pm dinner	

WEDNESDAY 9 FEBRUARY	
9.00 – 10.30	Plenary session • Chairs to report back from break out groups, followed by discussion **Chair: Ian Carruthers**
10.30 – 11.00	Break
11.00 – 12.30	Plenary session: Where is Australia at and what are the challenges? • State of Australian research • To what extent does it meet Australia's policy and information needs? • What are the gaps? Presentation: Bryson Bates, CSIRO Presentation: Mike Manton, BoM Presentation: Andy Pitman, universities research **Chair: Jo Mummery**
12.30 – 1.30	**Lunch**
1.30 – 2.30	Bringing it together – world leadership and Australian science 1 Thematic discussion: Coordinating Australian science to develop a national terrestrial modelling capacity with dynamic vegetation • Towards a community dynamic global vegetation model (DGVM) **Chair: Will Steffen**
2.30 – 3.30	Bringing it together – world leadership and Australian science 2 Thematic discussion: Engaging internationally Presentations and panel: The GCP science plan by Pep Canadell, and the policy perspective by Ian Carruthers Discussion on a coordinated approach to international engagement, including mechanisms for national coordination and the Global Carbon Project. **Chair: Jo Mummery**
3.30 – 4.00	Break
4.00 – 4.30	Synthesis & the way forward • Main themes/ areas of consensus • Key principles **Chair: Will Steffen**
4.30	**Close**

Appendix 2

WORKSHOP PARTICIPANTS	
Participant	Organisation
Ash, Andrew	CSIRO
Ayers, Greg	CSIRO
Barrett, Damian	CSIRO
Bates, Bryson	CSIRO
Beringer, Jason	Monash University
Brack, Cris	ANU
Bridle, Kerry	University of Tasmania
Canadell, Pep	CSIRO
Carruthers, Ian	Australian Greenhouse Office
Carter, John	NRM Qld
Cleugh, Helen	CSIRO
Deutscher, Nicholas	University of Wollongong
Evans, John	ANU

Farquhar, Graham	ANU
Fuller, Ashley	Australian Greenhouse Office
Gerrand, Adam	BRS
Gifford, Roger	CSIRO
Good, Roger	Consultant
Grant, Colin	BRS
Griffith, David	University of Wollongong
Hacker, Jorg	Flinders University
Higgins, John	Australian Greenhouse Office
Holper, Paul	CSIRO
Huntley, Lindsay	CDU
Isaac, Peter	Flinders University
Keith, Heather	CSIRO
Kirschbaum, Miko	CSIRO
Kowalczyk, Eva	CSIRO
Kurz, Werner	Natural Resources Canada
Leuning, Ray	CSIRO
Liddell, Michael	James Cook University
Manton, Mike	Bureau of Meteorology
McAvaney, Bryant	Bureau of Meteorology
McGregor, John	CSIRO
Mummery, Jo	Australian Greenhouse Office
Wang, Ying Ping	CSIRO
Pitman, Andy	Macquarie University
Raison, John	CSIRO
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