GLOBAL TERRESTRIAL CARBON OBSERVATION:

Requirements, present status, and next steps

Report of a Synthesis Workshop

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Executive Summary

In response to an increasing interest in terrestrial carbon and following a proposal led by the Global Terrestrial Observing System (GTOS), the Integrated Global Observing Strategy Partnership (IGOS-P) approved terrestrial carbon cycle as its second major theme in November, 1999. This report presents the results of a follow-up Terrestrial Carbon Observation (TCO) Synthesis Workshop, organised by GTOS in collaboration with the International Geosphere-Biosphere Programme (IGBP) and other IGOS-P members on February 8-11, 2000 in Ottawa, Canada. The workshop was designed to summarise existing information and observation requirements regarding terrestrial carbon, conduct initial evaluation of existing data or observations in relation to the requirements, identify major gaps or deficiencies, and propose solutions.

Existing stated requirements for terrestrial carbon information were reviewed in several areas, including international conventions, scientific understanding of the global carbon cycle and assessments of their evolution (current and into the future), and land management. Based on these, the needed observations were analysed with a view to satisfy a ‘dual constraint’ methodology for estimating terrestrial carbon fluxes, based respectively on a) local ecosystem models scaled up with satellite data, and b) atmospheric model inversions using concentration measurements of atmospheric CO_2 and other tracer gases. The workshop also discussed existing observations, gaps, and needed improvements.

To meet TCO needs, the concept of an observing system was considered. Such a system will contribute to the integrated understanding and human management of the global carbon cycle through systematic, long-term monitoring of the terrestrial exchanges of greenhouse gases, especially CO_2, and the associated changes in carbon stocks. The goal is to obtain estimates through the use of models that synthesise information from several types of measurements: atmospheric CO_2 and other gases, surface fluxes, ecological, and remote sensing. These estimates will be provided with known and decreasing uncertainty, by systematic of cross-checking independent approaches and by designed expansions of current measurement networks. The information products will be of value not only at the global and regional levels, but also for land management and assessment in support of sustainable development at the national level. Ultimately, an integrated global observing strategy should provide near-real-time diagnosis of carbon sources and sinks at high resolution in both space and time that simultaneously satisfies all the data constraints (in situ, remotely sensed, and atmospheric) at multiple scales. Such a system will be more than a set of observations; rather, it will constitute a carbon cycle data assimilation system analogous to the observing systems currently used for temperature, precipitation etc. in operational weather prediction.

Based on the presentations and discussions, the workshop reached the following conclusions :

1. Information on the global distribution of terrestrial carbon sinks and sources is essential for policy and scientific purposes in four areas: reporting for multilateral environmental agreements; understanding of the carbon cycle; assessment of global change trends and impacts; and the management of ecosystem resources at local to regional levels.
2. A dual observation and modelling approach, based respectively on the inversion of atmospheric observations and on the use of satellite data and ecosystem models, is potentially capable of achieving accurate information on the distribution of carbon sources and sinks at all scales from landscape to global.
3. Many components needed for terrestrial carbon observations are well understood. Some are in place, others need to be augmented, and all need to be placed in a consistent, functioning framework.
4. To be effective, such a framework must incorporate both international co-ordination and national implementation as essential components.

Workshop participants made the following recommendations to IGOS-P:

1. Seek endorsement for the TCO system concept.

2. If the concept is adopted, modify the proposed evolution strategy, as appropriate, and take steps to its implementation. These steps should include an integrated approach to data distribution, quality control, and archiving; arrangements for the generation of core products; and clarifications regarding the responsibilities of agencies in the planning, development, and performance assessment of these activities.

3. Ensure continuation of existing satellite observations that are important to TCO into the foreseeable future. Accelerate the development and deployment of new satellite observation technology, including lidars for vegetation biomass, canopy structure, and atmospheric CO_2 concentration.

4. Expand the system of flux networks and ensure adequate geographic coverage, continuity of observations, and co-ordination.

5. Improve the access and use of existing (non-flux) sites and national data sets for TCO purposes.

6. Review and further refine the strategy for the development of the dual constraint concept, and ensure active participation of the hydrological community in this process.

7. Give high funding priority to research and development of instruments, observation methods, and models related to carbon cycle observations.

8. In the evolution of terrestrial carbon observations, maintain close linkages with the ocean carbon cycle observation community.

9. Issues relating to scaling, gridded data sets, emissions, and others identified at this workshop should be examined by a broader scientific community in order to understand the implications for global terrestrial carbon observations.

1. Background, Introduction, and Objectives

Needs

An accurate knowledge of the terrestrial component of the global carbon cycle has become a policy imperative for this and the forthcoming decades, both globally and for individual countries. At the global level, the main reason is recognition that the increasing atmospheric CO_2 concentration is most likely affecting the variability and trend of regional and global climates. This recognition has led to important policy decisions. For example, the United Nations Framework Convention on Climate Change (UNFCCC) instituted inventories of the national greenhouse gas emissions, including terrestrial sources and sinks. More recently, the Kyoto Protocol acknowledged the role of terrestrial systems as carbon sinks and sources, and it provides a basis for developing future emission trading credits that involve C-sequestration in forests and potentially in other ecosystems. The effectiveness of the various policy instruments agreed upon by nations depends on the availability of specific observations related to the terrestrial component of the global carbon cycle. The observation needs are typically defined through a dialogue involving the policy and scientific communities, as a compromise between the desirable and the available or practically achievable information.

At the national level, in addition to the response of a country to the international or global policy agreements, the carbon cycle (expressed as vegetation productivity) has long been important to countries whose economic or social structure depend on biospheric resources. This motivation becomes stronger as an increasing portion of the global annual net primary production is employed in the economic sphere (now estimated to be ~40%) and with continuing concerns about the threats to sustainable use of terrestrial ecosystems. The national perspective and interest are very important to the implementation of global observation programs since resources for implementation will ultimately need to be made available by national governments.

The basis for understanding the global carbon cycle and the role of terrestrial ecosystems has been provided through scientific research at national, regional and global levels. During the past decade, this research greatly accelerated under the leadership of the International Geosphere-Biosphere Program (IGBP) and several of its core projects. The activities involve field research as well as modelling studies at various spatial scales. Through the Intergovernmental Panel on Climate Change (IPCC) process (IPCC, 1996), IGBP synthesis (e.g., Walker and Steffen, 1997), and other activities (e.g., IGBP Carbon Working Group, 1998), the scientific community also addressed specific questions and issues raised by the policy community. Based on these activities, it has also become evident that further progress in our understanding of the global carbon cycle and its likely future evolution depends on improved observations of the terrestrial carbon processes. Thus, commenting on the results of an intercomparison of net primary productivity (NPP) models carried out by IGBP and guidance for future research, Cramer and Field (1999, p. iv) stated "…At the heart of these are enhanced experimental and monitoring systems (flux measurements, satellite sensors, field and laboratory experiments, global data archives) which are being identified by every single paper in this collection as being important for better parameterisation of terrestrial biosphere models."

Capabilities and Response

The above policy as well as activities and interests depend on accurate, objective information about the state and changes in various parts of the terrestrial carbon cycle. Because of the many interacting factors affecting this cycle both above and below the soil surface, such information must be obtained frequently and with a high spatial resolution. Given the limitations of measurement techniques, this has simply not been possible in the past. The advent of new methods, including observing techniques and process models, makes the problem more tractable and has been a major reason for the increasing research interest in the observation and quantification of the terrestrial component of the global carbon cycle.

A substantial scientific effort has also taken place during the last decade. Since its inception in the late 1980s, IGBP has undertaken considerable research on the carbon cycle, both at the level of core projects (disciplinary aspects of the global cycle) and at the level of major sub-components of the global cycle (GAIM). As part of the IGBP synthesis/restructure project, begun in early 1998, IGBP formed a Carbon Working Group (CWG). The focus of the work of the CWG has been on the biophysical aspects of the carbon cycle, in keeping with IGBP's emphasis on biogeochemical cycling. However, there are important aspects of research on the carbon cycle which benefit from the involvement of other communities. Examples include the effects of climate variability on carbon uptake or release (joint WCRP-IGBP issue) and the institutional challenges associated with management of components of the carbon cycle (IHDP issue).

Since the early 1990s, international organisations have been working towards the establishment of systematic, long-term observations of various components of the earth system: terrestrial environment, oceans, and climate. The need for such systems was evident during the preparation of the 1992 UN Conference on Environment and Development when scientists and policy makers were hindered by a lack of key data and information upon which to base targets and performance goals. The emerging global observing systems for oceans (GOOS), terrestrial environment (GTOS), and climate (GCOS) are intended to complement the existing atmospheric observation capabilities implemented as part of the Global Atmospheric Watch (GAW) through the World Meteorological Organisation (WMO). Similarly as GAW, GTOS, GCOS and GOOS are designed to include space and in situ components. The close co-ordination of satellite and in situ observation programs is therefore essential for the successful realisation of the observing systems.

To facilitate progress in the implementation process, space agencies and international agencies (both observation and research) have recently established a new co-ordination mechanism, the Integrated Observing Strategy Partnership (IGOS-P). The IGOS-Partnership includes GCOS, GTOS, GOOS, WCRP, IGBP, ICSU, FAO,UNEP, IOC,WMO, UNESCO, IGFA and CEOS, all of whom have signed a formal letter of partnership acknowledging their commitment to work together in the context of the Integrated Global Observing Strategy. IGOS-P has chosen to proceed by themes, rather than projects, with agreed criteria being established for the selection of themes. In June 1999 IGOS-P agreed to consider a proposal for a terrestrial carbon theme by GTOS. The GTOS/GCOS Terrestrial Observation Panel for Climate (TOPC) prepared such a proposal for the November 1999 meeting of IGOS-P. At this meeting, IGOS-P made the following decisions:

* 4/5 GTOS with FAO support to lead the Terrestrial Carbon Cycle theme and to present a report to the Partners along the lines of the Oceans theme report.
* 4/6 GCOS, FAO, IGBP, ICSU, UNESCO, and CEOS to nominate representatives for the Terrestrial Carbon Cycle team by the end of November 1999.
* GOOS, GCOS, GTOS, IGBP, NASA to prepare proposals for the overarching Global Carbon Theme and to decide amongst themselves who should lead this activity.

The overall goal of the Terrestrial Carbon Observation (TCO) theme is to define observation requirements for an accurate estimation of the distribution of terrestrial carbon sources and sinks of the world with high spatial and temporal resolutions. To define the optimal system to achieve this goal requires strong scientific input, both from modelling studies and from ground-based process studies.

To initiate the process leading to the terrestrial carbon theme report, GTOS/TOPC in collaboration with IGBP and other IGOS-P members organised a workshop for February 8-11, 2000 in Ottawa, Canada. The specific objectives of the workshop were:

1. To assemble and summarise existing information on information requirements regarding the terrestrial component of the global carbon cycle.
2. To assemble and synthesise existing information on observation requirements needed to obtain the carbon cycle information, assuming that top-down (inversion modelling) and bottom-up (ecosystem modelling) strategies are employed in an integrated manner. All important data/observation requirements are to be considered (satellite, surface, atmospheric, ...).
3. To evaluate the consistency, completeness, and reliability of the information on observation requirements defined above, and refine these to the extent possible.
4. To conduct initial evaluation of existing data or observations in relation to the observation requirements, identify major gaps or deficiencies, and propose solutions to the extent possible.
5. To identify actions that need to be taken in order to: complete the definition of observation requirements; complete the analysis of deficiencies of existing observations and needed remedies; link terrestrial and ocean carbon cycle observations; and prepare a report on the terrestrial carbon observation theme for IGOS-P.
6. Based on the above, to prepare a 'straw man' framework report as an input for a joint IGBP/GTOS meeting in May, 2000. This meeting will engage the scientific community more fully to complete the design of a comprehensive approach to terrestrial carbon observations and the links between terrestrial and ocean components of the global carbon cycle.

The GTOS-led preparations for global terrestrial carbon observations are an integral part of a larger international effort to undertake collaborative research on the global carbon cycle. This international research effort, which is led by the International Geosphere-Biosphere Programme in collaboration with the World Climate Research Program (WCRP) and the International Human Dimensions Programme on Global Environmental Change (IHDP), consists of a linked suite of process level studies (e.g., experiments, field campaigns), observations, and modelling (development, evaluation, intercomparisons, etc.). The integrated international approach, which will also link strongly to national and regional carbon cycle research programmes, will contribute to an understanding of terrestrial, oceanic, and coastal process studies and modelling activities. Thus, the workshop agenda was planned to dovetail with subsequent international meetings that will take place during the year 2000, with the objective of completing the terrestrial carbon theme report to IGOS-P in October for consideration at the November meeting of IGOS-P.

This report contains information produced prior to and during the workshop. It is intended to support the further development of the IGOS carbon theme, particularly the theme report to be submitted in November, 2000, as well as the Terrestrial Carbon Observation initiative led by GTOS. Results of group or plenary discussions are provided in the main report. Appendix 10.3 contains summaries of the contributions by participants prepared prior to the workshop.

2. Information requirements for terrestrial carbon

Information on terrestrial carbon is required for many purposes:

- Understanding the global carbon cycle to: identify sources and sinks and their variation over time; predict how these may change in the future; develop succinct indicators of the status of the global climate system;
- Assessment of the actual changes in the global/regional carbon cycle and their impacts (e.g., through the IPCC process);

- Reporting to Conventions, and supporting the implementation of the Conventions;
- Assistance to national, regional and local management in making more cost-effective decisions and in evaluating their consequences;
- Providing information to assess the effectiveness of mitigation and adaptation strategies developed in response to climate change;
- Providing information to design better mitigation or adaptation strategies in the future;
- Providing information for general public, educational purposes, etc.

Specific information requirements for terrestrial carbon have previously been considered by different groups for a variety of purposes. They include policy oriented programs (e.g., the UN framework Convention on Climate Change; IPCC, 1996); international research programs (e.g., IGBP Terrestrial Carbon Working Group, 1998); global observation programs (e.g., GTOS, 1997); national programs (e.g., Appendix 10.3); and others. The workshop objective of synthesis was approached in three steps:

- Identification of the main policy and science information needs, as articulated in existing documents;
- Preparation of summaries of these needs prior to, and presentations during, the workshop;
- Synthesis of these various requirements into a coherent framework through plenary discussion.

The policy instruments reviewed include the Kyoto Protocol (Solomon, Appendix 10.3); the UNFCCC guidelines on national greenhouse inventories (Cihlar and Brown, Appendix 10.3); the Convention to Combat Desertification (Gommes, Appendix 10.3); and the Biodiversity Convention (Gommes, Appendix 10.3).

Science requirements were reviewed from the perspective of atmospheric studies (Raupach, Appendix 10.3; Gerbig et al., Appendix 10.3), ecosystem studies (Potter, Appendix 10.3; Running et al., 1999), and from the national perspective, both policy and research (Raupach, Appendix 10.3; Wickland, Appendix 10.3; Chen and Cihlar, Appendix 10.3).

There are many reasons for interest in terrestrial carbon: policy, scientific, economic, management, sustainable development, public/societal, and others. Workshop presentations have described a range of existing requirements at international or national levels. However, not all of the above requirements provide compelling reasons for the establishment and operation of global, systematic, long-term observations of the carbon cycle and the associated aspects of vegetation and soils. The discussion identified four such compelling reasons, and characterised their spatial and temporal attributes: understanding the global carbon cycle, global change assessment, multilateral environmental agreements, and environmental management. Most of the information needed for environmental management and multi-lateral agreements is also required for a focus on carbon. It is thus more cost effective to implement an observing system that integrates all above needs, with the carbon cycle leading the synthesis.

a) Understanding the global carbon cycle

Description. This requirement has both science and policy aspects. The scientific component is the need to understand the characteristics, processes, and principles governing the global carbon cycle and its evolution, in the past and in the future. The terrestrial carbon is mediated by vegetation and soils, but is intimately linked to the global cycle through land - atmosphere and land - ocean fluxes, and must therefore be encompassed in such an inquiry. From the policy perspective, understanding the carbon cycle becomes the basis for evaluating the current status, the significance of the observed trends, and the implications of these for policy development. Since future projections can only be based on models, understanding of the global carbon cycle is also essential to gaining confidence in such projections.

Information required. Fluxes between the terrestrial ecosystems and the atmosphere; changes in carbon pools (both mass and structure); and the understanding of the controlling factors for both fluxes and pools.

Spatial extent. Global.

Spatial resolution: Multiple scales, from local to global. Need to resolve the spatial heterogeneity in driving factors (including ecosystem disturbance, topography, land use, soils, etc.). Scaling strategy (local to global), translation algorithms between scales, and data that support these are a critical issue.

Temporal extent. In principle, ongoing long-term observations are required to cover cycles of various duration (from seasonal to El Nino, solar cycles, ecosystem succession, and others). In practice, this implies multi-decadal observations that cover at least one carbon residence time (length varies between biomes, ~20 to >50 years). It is also important to include recent land cover and land use history, especially regarding its effects on current and future carbon fluxes.

Temporal resolution. Different time resolutions are required, depending on the governing processes. Some of the diversity can be covered by models, some by direct observations. Also, the resolution required for present and future is usually higher than for the past.

b) Global change assessment

Description. This encompasses the assessment of climate change and of greenhouse gases in the earth system. Such assessments are periodically conducted by the Intergovernmental Panel on Climate Change for the policy community, and they rely on the results of published studies examining various aspects of the global carbon cycle. These assessments serve as the basis for developing policies at various levels, from national to global.

Information required. Fluxes between the terrestrial ecosystems and the atmosphere; changes in carbon pools (both mass and structure); and the understanding of the controlling factors for both fluxes and pools.

Spatial extent. Global.

Spatial resolution. Multiple scales, from local to global. Need to resolve the spatial heterogeneity in driving factors (including ecosystem disturbance, topography, land use, soils, etc.). Scaling strategy (local to global), translation algorithms between scales, and data that support these are a critical issue.

Temporal extent. The assessments are carried out periodically, about every 3-5 years. However, they are abased on studies conducted over various time frames, from past to future. Therefore, ongoing long-term observations are required. In practice, this implies ongoing, multi-decadal observations, from past to the future.

Temporal resolution. Similar as for ad a).

c) Multilateral environmental agreements.

Description. This requirement has been established by global or international agreements, designed to deal with specific environmental issues. Certain agreements include periodic reports on some aspect of terrestrial carbon.

Information required. Depends on the Convention (refer to Appendix 10.3 for more detail):

UNFCCC: net fluxes of CO_2 and other GHGs, resolved into UNFCC reporting categories;
CCD: information on above ground and soil carbon pools (as part of data on soils);
BDC: land cover at medium and high resolution;
Kyoto Protocol: changes in biomass stocks of 'Kyoto forest' (details remain to be negotiated);

It should be noted that land use, land use change, and land cover are an important information input to most of the Conventions. Also, while the information needs of some of the Conventions have not yet been fully defined, their objectives indicate that they would benefit from a range of terrestrial carbon information products.

Spatial extent. Depends on the Convention. In general, only parts of the global landmass are of concern. For existing Conventions, the specific areas are defined by human activities, or by natural processes affected by human activities.

UNFCCC: all land affected by land use/human activities
CCD: semiarid and sub-humid zones
BDC: all land with flora or fauna
Kyoto Protocol: Kyoto forest.

Spatial resolution. Varies with Convention; the highest resolution is of the order of 100 metres (minimum area 10^4 m^2).

Temporal extent. Defined by the Convention. Most existing Conventions are recent and do not have a pre-established termination date.

Temporal resolution. Defined by the Convention (refer to Appendix 10.3), typically one year or longer. Also varies with the type of information.

d) Environmental management at national, regional and local levels.

Information required. Of two types, strategic and tactical.

Strategic (for planning): Potential primary productivity; water supply; disturbances (fire, insects, etc.); soil carbon.

Tactical (for management and response assessment): stresses causing decrease in primary productivity (water, temperature, nutrients, soil and atmospheric contaminants); fire and other disturbances.

Spatial extent. Global, but not uniformly distributed (depends on the national/local priorities/concerns)

Spatial resolution.

Strategic: high to medium, >~10^1 to 10^2 m (>~10^2 to 10^4 m^2).
Tactical: high, >~10^1 m (>~10^2 m^2).

Temporal extent. Ongoing, but also depends on management activities and plans at the various spatial levels

Temporal resolution.

Strategic: Variable (typically seasonal or longer).
Tactical: Multiple resolutions, from minutes (e.g., biomass fires) to months.

3. Dual constraint framework

3.1 Considerations

Information requirements regarding terrestrial sources and sinks of atmospheric CO_2 include both science and policy applications (refer to section 2). While the knowledge of spatial and temporal patterns of these carbon exchanges is important, the development of scientific understanding of the processes and the prediction of future behaviour of the sources and sinks also requires the identification and quantitative analysis of the mechanisms responsible.

In the terrestrial environment, carbon is present in three main pools: atmosphere, plants and soil. The primary pathways causing changes in the terrestrial pools are photosynthesis (gain), respiration (loss), burning (loss), and other disturbances or removals (harvest, etc.; loss). The observational challenge is to determine the resulting changes in terrestrial carbon distribution, and, so far, two main approaches have been used for this purpose. One, usually called ‘bottom-up’, starts with a specific parcel of land and aims to account for the various pathways of carbon exchange between the ecosystem and the atmosphere; the large-scale pattern then emerges after combining the exchanges involving individual land parcels. The other (‘top-down’) begins with measured changes in atmospheric gas concentrations and attempts to infer the spatial distribution and magnitude of the net exchanges.

‘Bottom-up’ integration using models and spatial data

The policy community requires information on spatial and temporal patterns of CO_2 flux at high resolution over very large areas (section 2.). These requirements imply the use of models linked to satellite measurements that are available everywhere. Satellite data can also provide up-to-date information frequently, in relation to the rate of change of the variables of interest. Figure 1 gives an overview of some important variables and the data flow involved in the bottom-up approach. The process models can be developed and tested with local-scale field measurements from inventory data, eddy covariance flux towers, carbon enrichment (FACE) experiments, and long-term ecological monitoring sites. In this bottom-up strategy, local processes are thus scaled-up in space and time using satellite imagery and other spatial data.

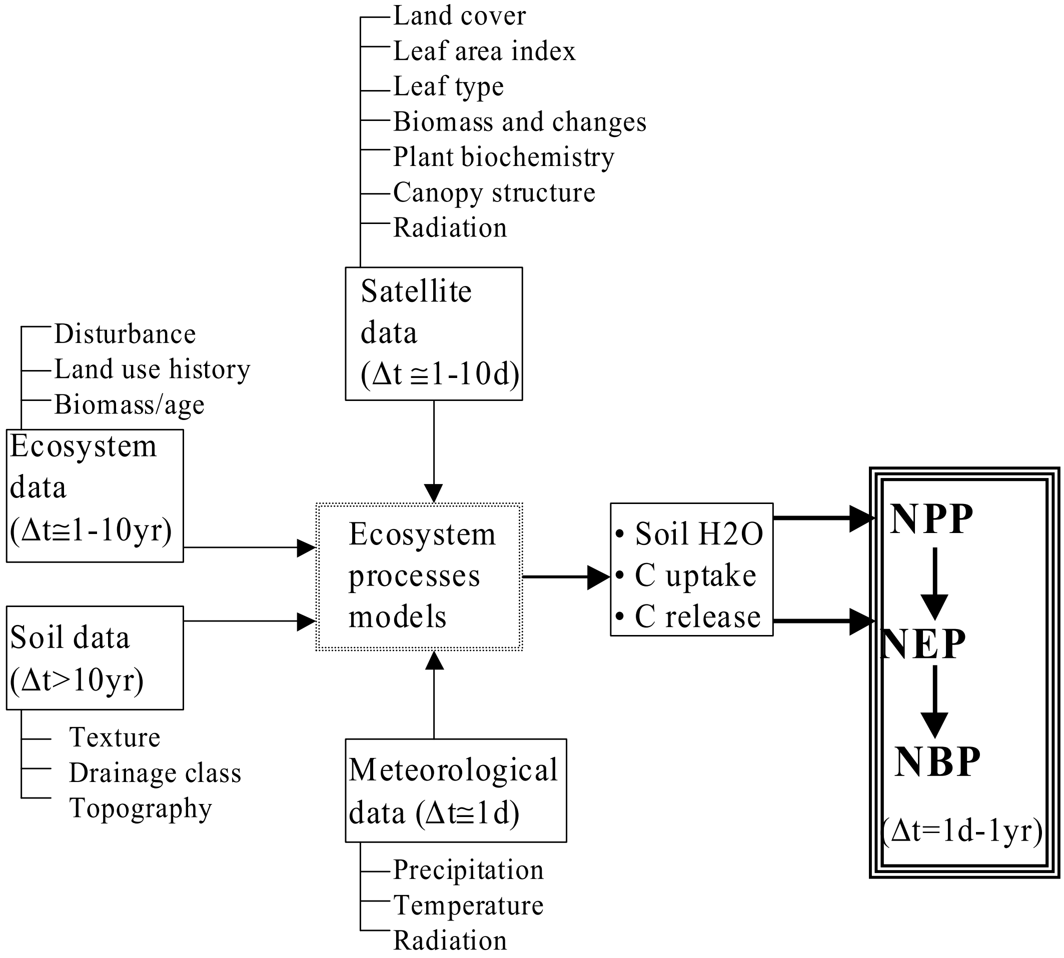

Figure 1. Typical data flow for bottom-up approach

Some advantages of such a strategy are:

- Fluxes estimated from spatial data and imagery using process models can be made available everywhere, all the time;
- The flux estimates are produced at the apparent resolution of the input data, which may be quite high;
- The estimates are based on mechanistic hypotheses about the processes that control the fluxes (e.g., climate fluctuations, land-use change, nitrogen deposition, etc.);
- Changes can be attributed to various mechanisms or compartments within the ecosystem.

The primary disadvantage of the bottom-up integration of model estimates is the difficulty of determining the accuracy and reliability of the scaled-up estimates, which is further complicated by the problem of assessing the representativeness of the sites used to calibrate and validate the process models. There is no independent way to evaluate the fluxes computed by the models, except at the small spatial scales of field experiments. The eddy covariance methods can now measure net CO_2 fluxes for areas as large as 1 km^2 under favourable meteorological conditions and homogeneous, level terrain. These data are extremely valuable for model development and evaluation, but they are very expensive to collect and are presently available for only ~100 locations globally (section 5.1.2). Furthermore, eddy covariance measurements do not adequately constrain the many components of these fluxes related to the processes represented in the extrapolation models. Some of the most important processes thought to contribute to terrestrial CO_2 sinks (e.g., recovery from past disturbance, changes in nutrient cycles due to land management, and climatic trends) are inadequately sampled by the current network of flux towers. The present eddy covariance measurement network must be expanded because of the critical function of these data for scaling up. However, the coverage and accuracy of the measurements will not likely be sufficient for obtaining confidence in the large-scale flux estimates derived through process models and satellite data.

In addition to ecosystem model deficiencies, the calculated fluxes may also be incorrect because of errors in the input data (model parameters and satellite-derived information). Model deficiencies are of at least two types, inadequate representation of the processes considered and the absence of important processes in the model. For example, a carbon source or sink which results from a mechanism that is not represented in the model will be completely undetectable by the bottom-up methods.

‘Top-down’ methods based on the inversion of atmospheric concentrations

An alternative and complementary approach is to analyse the carbon budget of the atmosphere from a mass-balance point of view. Such an analysis is predicated on the availability of atmospheric concentration data, and it can be carried out in several spatial and temporal domains. This approach has been used at the global scale for decades, since C. D. Keeling first began measuring CO_2 at Mauna Loa, and is in fact the primary line of evidence that originally suggested the existence of a terrestrial carbon sink. Today, there are nearly 100 flask sampling sites around the world from which air is analyzed for several trace gases, including CO_2 (section 5.1.1).

Inverse methods have been developed to estimate the spatial and temporal variations in CO_2 flux from atmospheric concentration data, and they are now being applied by about a dozen modelling groups world-wide (http://transcom.colostate.edu). These methods aim to deduce surface emissions or sinks responsible for the spatial and temporal variations in concentration by accounting for atmospheric transport using numerical models of winds, convection, and turbulence (Figure 2). At the coarsest spatial scales (global to hemispheric), these methods provide very robust estimates of the spatially integrated flux on time scales of seasons to years. More recent studies (Rayner et al, 1999; Bousquet et al, 2000; Peylin et al, 2000; Kaminski et al, 2000)) have estimated monthly CO_2 fluxes for as many as 25 regions (at sub-continental spatial scales), including interannual variability. At much finer spatial scales, pollutant emissions have been estimated from local time series data using mesoscale transport models and "back-trajectory" analysis (e.g. Morris *et al*, 1995; Pryor *et al*, 1995; Fast and Berkowitz, 1997), but this is only now being attempted for CO_2 (Gerbig et al., Appendix 10.3)

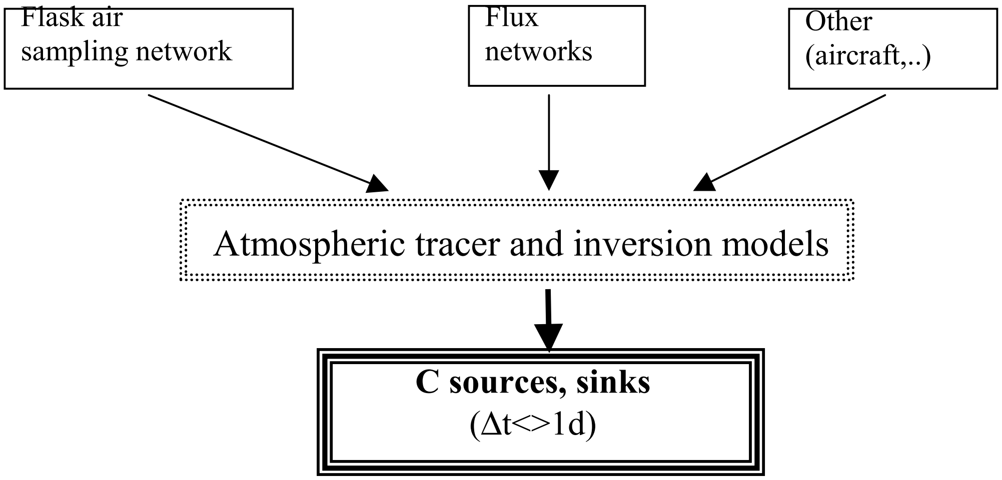

Figure 2. Typical data flow for top-down approach

Some advantages of the top-down methods are:

- A robust estimate of spatially-integrated carbon flux over very large areas is produced and is independent of process-based model estimates;
- Fluxes and their variations can be detected and quantified even if they result from unexpected or poorly understood processes;
- Some inverse methods allow concurrent estimation of both fluxes and uncertainty in the inferred fluxes;
- Spatial and temporal patterns can often be interpreted in terms of underlying mechanisms, facilitating further development and refinement of ecosystem process models.

The primary disadvantages of these methods are that (1) they provide no direct information about the mechanisms responsible for the fluxes, and thus have no predictive power; and (2) the current configuration of atmospheric observing stations is so sparse and the stations are generally so far from major landmasses that terrestrial fluxes can only be inferred at extremely coarse spatial resolutions. Although a number of attempts to recover monthly fluxes at sub-continental scales from flask data have now been published (Rayner et al, 1999; Kaminski et al, 1999; Peylin et al, 1999; Bousquet et al., 2000), they disagree dramatically about the spatial structure of the sources and sinks. Atmospheric transport is rapid in the mid-latitude westerlies, with a parcel of air requiring a few weeks to circumnavigate the globe. Inter-hemispheric transport is much slower, with a mixing time in the order of one year. The atmospheric signal is therefore relatively easy to resolve in terms of latitude zones, but the more dynamic longitudinal structure is not well determined by the current observing network. Significant uncertainty in the estimation of regional fluxes by inverse methods arises from errors in the model transport which are difficult to evaluate. Inter-comparison experiments (http://transcom.colostate.edu) have shown that the leading models can to reproduce the available surface data (mostly marine, distant from local terrestrial sources or sinks), but they disagree over the continents and aloft, where there is no data constraint (Law *et al*, 1996; Denning *et al*, 1999).

3.2 Dual-Constraint Concept

An integrated global carbon observing strategy would include elements of both the top-down and bottom-up approaches because significant synergy can be achieved by applying both types of constraints simultaneously (Figure 3). Such a strategy would seek to maximise the information extracted from the observing network in terms of both distributions of sources and sinks in space and time and the mechanisms responsible for the distributions. In addition to CO_2 fluxes, this strategy would include estimation of the uncertainty associated with the fluxes as a critical part of a credible information product. The strategy would also make possible direct testing of quantitative hypotheses about the function of the current carbon cycle, thus facilitating the development of improved process models and of predictive models.

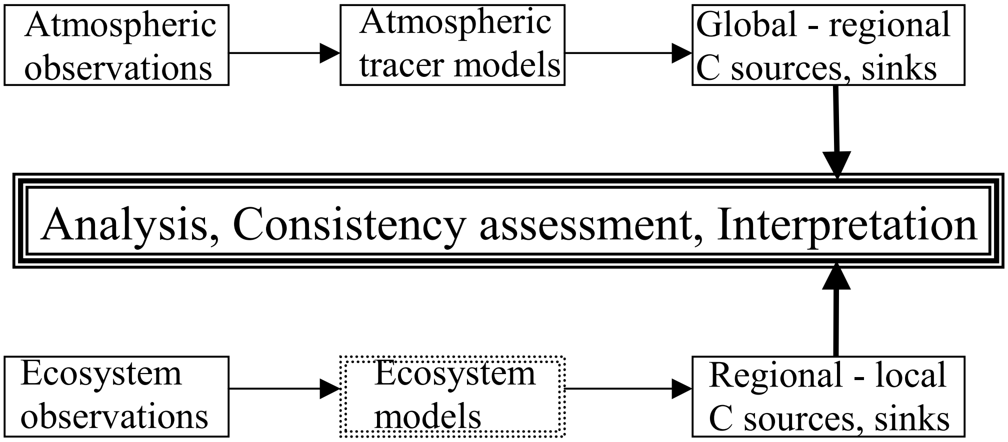

Figure 3. Data flow for dual constraint approach

A ‘nested design’ with multiple observational components is envisioned that allow meaningful comparisons of flux estimates obtained by independent methods at multiple spatial and temporal scales. Such a system should include a set of ongoing and associated research activities:

Ongoing:

- Routine regional atmospheric sampling for multiple trace gases over continental areas from in situ and airborne platforms to establish spatial and temporal patterns;
- Routine collection of spatial data and imagery needed to apply process models at large scales and to unsampled locations;

- Estimation of local to global daily carbon fluxes from gridded climate, vegetation, soils, land-use, emissions, and other spatial data using process-based models and extrapolation/scaling algorithms;
- Estimation of regional to global sources and sinks by mesoscale inverse modelling using atmospheric data to establish integral mass-balance constraints on the operational model/satellite products.

Associated research:

- Field experiments (flux towers, FACE rings, LTER sites, etc.) deployed globally across gradients in climate, vegetation, soils, nutrient deposition, disturbance, and land use history to improve our understanding of the processes of carbon exchange;
- Evaluation of spatial and temporal variability of ecosystem properties and fluxes in the field, to allow upscaling to patches (1 km^2 or less) observed by satellite sensors such as MODIS and similar instruments (Table 4);
- Atmospheric observing campaigns and associated local- to mesoscale transport modelling to allow direct estimation of area-mean carbon fluxes and flux uncertainties over field sites for an evaluation of models and scaling algorithms (e.g., using convective boundary layer budgets);
- Model development and testing associated with the field research sites, with an attempt to capture the source/sink mechanisms across a range of different conditions;
- Estimation of sub-continental scale sources and sinks by global inverse modelling using an augmented set of surface and tropospheric measurements of multiple tracers.

The goals of an integrated observing strategy should include meaningful overlaps between independent methods of flux estimation at each transition in spatial scales, from site to pixel to region to continent to globe. These overlaps can be built through a combination of ongoing/research and observation/modelling tools listed above. An important consideration in optimising such a strategy is to incorporate the scale integration through modelling efforts as well as through data collection, both in terms of ecosystem processes and atmospheric processes.

Ultimately, an integrated global strategy seeks near-real-time diagnosis of carbon sources and sinks at high resolution on both space and time that simultaneously satisfies all the data constraints (in-situ, remotely sensed, and atmospheric) at multiple scales. Such an observing system is more than a set of observations. Rather, it constitutes a carbon cycle data assimilation system, analogous to the current observing systems used for operational weather prediction.

Many of the elements of an integrated terrestrial carbon observing strategy outlined above are in place now or already under development. The challenges of this strategy are to ensure the presence of the appropriate overlaps and leverage among the disparate data sets, to ensure that important data gaps are filled and that the necessary modelling work is carried out to link the data sets of various types at different scales. The next sections discuss possibilities for a phased implementation of an integrated observing system.

This report focuses on the terrestrial system, but information about air-sea fluxes of carbon provides a valuable top-down constraint through the global atmospheric mass-balance. A fully integrated global strategy would thus also include estimation of the carbon balance of the oceans at multiple spatial scales from site studies, process modelling, ocean-colour imagery, flux surveys, gridded climate and sea-surface temperature data, tracer studies, and ocean models.

4. Observation requirements

4.1 Procedure

The dual constraint strategy (section 3.2) implies a range of observations required to provide information on the spatial and temporal distribution of carbon sources and sinks. Various groups have previously considered these requirements. Similarly to the information requirements, the workshop employed a three-step process to converge on an integrated set of requirements:

- Review of observation requirements by existing programs;
- Synthesis of bottom-up and top-down requirements;
- Identification of gaps and observation issues.

Various observation requirements for existing programs were considered (refer to Appendix 10.3): global programs and international conventions (Cihlar and Brown, Gommes, others), ecosystem modelling at national to global levels (Ahern, Chen and Cihlar, Potter, Wickland); and atmospheric modelling (Raupach, Gerbig et al.) perspectives.

4.2 Synthesis: top-down approach

In principle, atmospheric inversions require two types of observations. The first type are those needed to characterise and model the behaviour of the physical climate system. These are similar to the observations and data sets employed in numerical weather prediction or in general circulation models, and presently various national and global observing systems acquire them. The second type, observations on atmospheric concentrations of CO_2 and other gases are required to predict the spatio-temporal distribution of sources and sinks. The workshop did not consider these requirements in detail because they had been subject of special meetings (see e.g. Francey, 1997).

4.3 Synthesis: bottom-up approach

Requirements for bottom-up modelling were assembled in table format in a breakout discussion. In preparing the table, several factors were considered for each variable, with the intent to ascertain their observational implications:

- ➢ Reasons for using the variable and its role in modelling carbon fluxes:
  - as a driver (thus always required, usually as a gridded data set), or for model validation (needed for a sample of sites/conditions);
  - as an input (needed for the computations), output (final result of the computations, where the role of the observation is to validate the final results), or internal variable (intermediate product of model computations, where the role of the observation is to check internal model consistency);
- ➢ The required spatial resolution of the observation;
- ➢ Measurement method: in situ, remotely sensed, or modelled.

Table 1 contains the list of observation requirements required for the bottom-up approach. The ‘Type’ column characterises the nature of the variable as external forcing (thus observations are needed as model input), internal status (as input or for model validation), or output variable (for output validation). The ‘Spatial’ and ‘Temporal’ columns refer to the desired spatial coverage of an observation. The ‘Method’ column describes the expected approach to obtaining the result: through in situ measurement, remote sensing, inventory, or modelling.

It should be noted that the observations required in each setting need consideration not only individually, but also in relation to one another. For example, eddy flux measurements should be associated with suites of ecological measurements, and for the most part should not be done in isolation.

Table 1. Observation requirements for bottom-up approach

Variable	**Type**	**Spatial**	**Temporal**	**Method**	**Comments**
	(a)	**(b)**	**(c)**	**(d)**	
	1. DRIVING VARIABLES (for model application/upscaling, required at every grid point)				
ATMOSPHERE					
Air temperature	1	3	1,6	1,2,3	daily maximum, minimum, mean
Precipitation	1	3	1,6	1,2,3	
Photosynthetically active radiation	1	3	1,6	1,2,3	
Relative humidity	1	3	1,6	1,2,3	
Wind speed	1	3	1,6	1,2,3	
Net radiation	1	3	1,6	1,2,3	
Snow water equivalent	1	3	1,6	1,2,3	
Aerosols	1	3	1,6	1,2,3	for atmospheric corrections of optical data
Integrated atmospheric water vapour	1	1	6	1,2,3	for atmospheric corrections of optical data
ECOSYSTEM					
Vegetation cover class	2	1	4	3	physiognomic classes, dominant species (overstory, understory)
Biota biomass	2	1	4	3	may be used to drive decomposition models
Soil moisture	3	1	1	2,3	
LAI	2	1	4	3	
Foliage N	2	1	4	3	needed to drive decomposition rates
Chlorophyll	2	1	4	3	to drive canopy photosynthesis in some models
Natural disturbance history	1,2	1	4	1,4	includes biomass burning and insect-induced mortality
Management history	1,2	1	4	4	includes forest harvest, thinning, fertilisation, etc.
Topography	2	1	3	3, 4	influences radiation and surface water
	2. CALIBRATION/VALIDATION VARIABLES (required at selected sites)				
ATMOSPHERE					
Air temperature	1	2	6	1	15 to 60 minute averages (continuous)
Precipitation	1	2	6	1	15 to 60 minute averages (continuous)
Solar radiation	1	2	6	1	15 to 60 minute averages (continuous)
Relative humidity	1	2	6	1	15 to 60 minute averages (continuous)
Wind speed	1	2	6	1	15 to 60 minute averages (continuous)
Net radiation	1	2	6	1	15 to 60 minute averages (continuous)
CO_2 concentration profile	1	2	6	1	15 to 60 minute averages (continuous)
Integrated atmospheric water vapour	1	2	6	1	for atmospheric corrections of optical data
Snow water equivalent	1	2	1,6	1	15 to 60 minute averages (continuous)

Aerosols	1	2	1,6	1	15 to 60 minute averages (continuous; for atmospheric corrections)
ECOSYSTEM					
SITE					
Natural disturbance history	1,2	2	4	1,4	includes fires and insect-induced mortality
Management history	1,2	2	4	4	includes harvest, thinning, fertilisation, etc.
Topography	2	2	3	3, 4	influences radiation, and water fields
Spatial pattern	2	1,2	3	3, 4	may assist spatial scaling
VEGETATION					
Vegetation cover class	2	2	2	1	physiognomic classes, dominant species (overstory, understory)
Root carbon	2	2	2	1	coarse and fine
Aboveground biomass	2	2	2	1	stem, branch, foliage
Leaf area index	2	2	4	1	
Foliage N	2	2	4	1	used for canopy photosynthesis modelling
SOIL					
Biota C, N	2	2	4	1	may be used to drive decomposition models
Biota biomass	2	2	4	1	may be used to drive decomposition models
Temperature profile	1,2	2	4	1,2	profiles are useful as a driver and for process studies
Maximum thaw depth	1,2	2	4	1,2	critical for climate impact on permafrost-affected areas
Thermal conductance	2	2	3	1, 2	to estimate heat transfer and heterotrophic respiration
Thermal diffusivity	2	2	3	1, 2	related to thermal conductance but needs heat capacity information
Soil moisture	1,2	2	5	1, 2	affects heat transfer and decomposition
Hydraulic properties	2	2	3	1, 2	for vertical and horizontal water exchange
Ground water table depth	2	1,2	4,5	1,2	influences wetland dynamics
Carbon content (org. & inorg.)	2	2	3	1	directly affects heterotrophic respiration
Carbon age	2	2	3	1	needed to improve Rh calculation
N, P content	2	2	3	1	affects gross primary productivity
Bulk density	2	2	3	1	needed for diffusivity estimation
Sand and clay fraction (%)	2	2	3	1	
pH	2	2	3	1	important limitation to growth and soil biology
Macro & micro nutrients	2	2	3	1	these processes affect plant nutrient uptake
Microbial biomass	2	2	3	1	affects decomposition
PHYSIOLOGY					
Foliage N	2	2	2	1	needed to drive decomposition rates
Foliage lignin	2	2	2	1	needed to drive decomposition rates
Chlorophyll	2	2	2	1	needed to drive canopy photosynthesis in some models
Rubisco	2	2	2	1	needed to drive canopy photosynthesis in some models
FLUXES					
Carbon fluxes (above&near ground)	3	2	6	1	critical for model validation
Aboveground NPP	3	2	4	1	C storage flux
Belowground NPP	3	2	4	1	C storage flux
Litterfall N, P, C	2	2	2	1	C flux to soil & litterfall nutrients indicate nutrient availability

H, ET (above stand)	3	2	6	1	important for C flux estimation
CH4	3	2	6	1	important for wetlands
VOC	3	2	6	1	can be significant in total carbon budget
DOC	3	2	2	1	C exchange can affect stocks and processes
Heterotrophic respiration rate	3	2	4	1	needed to validate NPP and NEP components
DOC = dissolved organic carbon, VOC = volatile organic carbon					
a: 1 = external forcing variable; 2 = internal status variable; 3 = output variable					
b: 1 = gridded with a resolution of 1 km or better; 2 = one or more sites for each land cover class; 3 = gridded with a resolution of 0.5-1 degree or better					
c: 1, since industrialisation with desirable frequency; 2, periodical measurement once every 5-10 years; 3, one-time measurement; 4: multiple-year continuous measurement; 5, daily in calibrations years; 6, continuous					
d: 1 = site measurement (including characterisation of its spatial heterogeneity as appropriate); 2 = modelling; 3 = remote sensing; 4 = existing survey or inventory					

5. Present status of observations

5.1 Atmospheric and meteorological observations

5.1.1 Atmospheric gas concentrations

Present status:

Two major observation networks exist at present, operated by the US National Oceanic and Atmospheric Administration (NOAA) and the Australian Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Atmospheric Research. They involve high-precision, continuously operated baseline stations for measuring the concentrations of over 100 atmospheric constituents in the marine boundary-layer air, together with analyses of flask samples routinely gathered at scores of locations world-wide. The sampling interval is typically about 2 weeks. Data from these networks and other sites are compiled under the GLOBALVIEW-CO_2 project (http://www.cmdl.noaa.gov/ccgg/globalview/co2/default.html).

Gaps and proposed solutions

Significant issues in extending the gas concentration network for the purposes of terrestrial carbon observation include the following:

(a) ***Range of gases:***

While the primary emphasis is on CO_2, several other gases have significance because they may (a) participate directly in land-air carbon fluxes (CH_4, CO, NMVOCs); (b) act as tracers of anthropogenic emissions which alter CO_2 concentrations by non-terrestrial processes (CO, NMVOCs); (c) provide tracers of biomass burning, a part of the terrestrial carbon cycle requiring explicit identification (CO, NO_x, CH_4, NMVOCs); or (d) constitute significant greenhouse gases in their own right (CH_4, N_2O). Other significant constituents include the ^{13}C and ^{18}O isotopes of CO_2, because they contain information on the relative magnitude of air-sea gas exchange and terrestrial carbon exchange, ecophysiological properties such as water use efficiency, C_3/C_4 ratios in plant communities, and ratios of soil evaporation to transpiration. The priority order among these gases for measurements is situation-dependent but is likely to be (1) CO_2; (2) CH_4, CO, N_2O; and (3) NMVOCs and isotopic constituents. This order will change in response to circumstances.

(b) ***Intercalibration issues:***

Intercalibration among different measurement networks is a serious problem and is currently no better than around 0.2 ppm for CO_2. Significantly better accuracy, to 0.1 ppm or less, is required for many atmospheric inversion methods. A global inter-comparison program called GLOBALHUBS, run from CSIRO Atmospheric Research in Australia addresses this problem. Based on the current status of observation programs and inversion methods, the following accuracy targets appear realistic: 0.2 ppm for CO_2 flask and continuous data, 0.05 ppm for ^{13}C, and 0.1 ppm for ^{18}O. While less accurate data would also be useful because of the spatial and temporal dynamics of the land-atmosphere interactions, the higher accuracies will be essential to discern longer-term trends and their spatial characteristics at the regional or smaller scales.

(c) ***Site locations and sampling strategies:***

For atmospheric concentration measurements obtained for terrestrial carbon estimation, site selection criteria and sampling strategies should be different from those which apply in the present global networks and are based mainly on sampling in the marine boundary layer. There are two primary reasons. First, the terrestrial atmospheric boundary layer has strong diurnal variability because daytime CO_2 draw-down by photosynthesis is associated with strong, deep convective mixing whereas nocturnal CO_2 build-up from respiration is associated with the formation of shallow stable boundary layer. These differences lead to a highly asymmetric CO_2 signal with time through the full day-night cycle (the "rectifier effect"; Denning et al., 1995, 1996, and 1999). Second, terrestrial ecosystems exhibit high horizontal heterogeneity in trace gas exchange. These factors have several implications for the sampling strategies:

- Continuous observations, at least for CO_2, are crucial at a ‘reasonable’ number of sites. Where these are supplemented by flask sampling, mid-afternoon samples are most appropriate because boundary layer development and mixing is usually greatest at this time.
- As in the present global networks, accurate long records at fixed locations will be crucial for detecting and interpreting long-term variations and trends in terrestrial biospheric functioning.
- Aircraft profiles of CO_2 (and where possible, other trace gas) concentrations through and above the atmospheric boundary layer will be needed, at least at some sites, for two reasons. First, such data are useful for extending near-surface observations to represent the entire boundary layer. Campaign-style studies largely accommodate this aspect. Second, higher-altitude (upper-air) tropospheric profile data is needed, in addition to surface and boundary-layer data, to improve the constraints on top-down atmospheric inversions. In contrast to the campaign studies, the upper air observations need to be ongoing.
- Uncertainty analyses of present atmospheric inversions suggest that the most critical locations for additional terrestrial observations of atmospheric gas concentrations are in continental locations, especially in the tropics (Rayner *et al*, 1996; Bousquet et al. 1999; Gloor *et al*, 2000). The placement of stations is complicated by the need to obtain “regionally representative” samples with minimal local influence, which proves difficult for most continental locations. For example, the siting of observations near continental coastlines is attractive to provide access to both continental and oceanic air (depending on wind direction) from a single station, but the influences of terrain variability and associated mesoscale circulation (such as sea breezes) complicate the measurements and must be carefully addressed at such sites. Gloor *et al* (2000) estimated that adding 12 routine vertical profiling sites would reduce the mean error in regional fluxes by a factor of five, to about 0.2 GtC yr^{-1} for 17 regions.
- There is a major need for an objective, model-based analysis of both measurement locations and temporal sampling requirements. This also extends beyond atmospheric sampling to other components of the observation system.

5.1.2 Eddy correlation flux towers

Present status:
Investigators can now apply the eddy covariance technique to acquire nearly continuous measurements of carbon exchange between the atmosphere and biosphere.

Regional collections of eddy covariance flux towers were formalised into the EUROFLUX (Europe) and AmeriFlux (North and South Americas) networks in 1996 along with MEDEFLU (Mediterranean region) started in 1998 and followed by AsiaFlux and OzNet (Australia) in 2000. A variety of organisations within each country typically fund the towers; for example, the Department of Energy, Department of Agriculture, NASA, and NSF fund the towers in the USA. Although some towers have been in operation for many years, 1996 marked the start of a community effort to collect continuous measurements of ecosystem carbon and energy exchange to understand the controls on carbon fluxes. In 1997 the FLUXNET project was established to compile the long-term measurements of carbon dioxide, water vapour, and energy exchange from the regional networks into consistent, quality assured, documented data sets for a variety of ecosystems world-wide (Baldocchi et al. 1996, Running et al. 1999).

FLUXNET is a "partnership of partnerships", formed by linking existing sites and networks. As of early 2000 there are over 130 flux towers in FLUXNET. Measurements and terminology from existing but disparate sites and networks are brought together and harmonised into a common framework, thereby substantially increasing the usage and value of the flux data and information for the global change community. The core FLUXNET variables include both meteorological model-driving inputs (photosynthetic active radiation, air temperature, precipitation, relative humidity, wind speed and direction above the canopy, barometric pressure, soil temperature, and carbon dioxide concentration) and flux model checking variables (net ecosystem exchange (CO_2 flux**)**, sensible heat, and latent heat from eddy correlation; net radiation; and soil heat flux). In addition, associated site vegetation, length of growing season, stand density, stand age, leaf area index, leaf nitrogen, edaphic, and hydrologic characteristics are compiled.

Gaps and proposed solutions:

Significant issues that will challenge the use of flux data in TCO include the following.

(a) ***Intercalibration***
A fundamental goal of the networks is to establish and maintain long-term intercomparability of results between the sites. Intercomparability is achieved through consistency in measurement techniques, strict attention to calibrations (and traceability to standards), and site intercomparisons in, for example, software processing of standardised flux data files (distributed by EUROFLUX) and comparisons of flux system response to a roving standard (as implemented by AmeriFlux). At present, the flux measurement community has agreed on common measurement techniques (http://www-eosdis.ornl.gov/FLUXNET/fluxnet.html). Most flux groups use common measurement techniques (open or closed path infrared gas analyser, 3-D sonic anemometer) and data processing routines. Resources will must be devoted to verifying the overall comparability of flux measurements.

(b) ***Representative Sites***
There are gaps in the distribution of flux towers, most notably so in savannah and desert biomes, in urban areas, in all successional states, and in managed systems. Funding for new flux towers may help to fill these gaps.

(c) ***Nighttime and Complex Terrain Bias Errors***

At night, CO_2 flux measurements are subject to error and underestimation, as turbulent mixing is low. Drainage of CO_2 in sloping terrain is another compounding factor and has recently been investigated. Compensation for the expected under-estimation of nighttime net ecosystem exchange include the use of spatially extrapolated chamber measurements of leaf, soil and bole respiration, modelled values, or the u* correction (a relationship inferred from nighttime measurements during high turbulent mixing; e.g., Goulden et al., 1996). This correction remains an open research issue.

(d) ***Incomplete data***

Data from eddy covariance measurements are usually reported in half-hour increments with an objective to collect data 24 hours a day and 365 days a year. However, the average data coverage during a year is only 65 % due to system failures or data rejection. No universal method has emerged for the filling of missing or rejected data. Therefore, gap-filling procedures need to be established for providing complete data sets (Falge et al., 2000).

(e) ***Footprint and regional scaling***

Towers typically sample fluxes within a kilometre of the tower, based on changing wind conditions. The characterisation of the source area, or footprint, requires a detailed inventory of the vegetation and soils contained in the source area and the pattern of changing wind conditions. This information can be used with soil-vegetation-atmosphere transfer models as part model validation and scaling up to the region.

(f) ***Data Availability***

Flux data are slow in becoming available to the broader scientific community. Although significant flux data are becoming available, additional incentives are needed to ensure the flow of data into the regional networks and ultimately into FLUXNET for distribution and archiving. Fluxes and ancillary information are unified in FLUXNET into consistent, quality assured, documented, readily accessible datasets via the World Wide Web (http://www-eosdis.ornl.gov/FLUXNET/).

5.1.3 Meteorological variables

5.1.3.1 Present status:

Current sources for meteorological forcing variables (Table 1) are a combination of existing ground-based meteorological networks, remote (satellite, radar) observations, and assimilation/interpolation from numerical weather models in nowcasting mode (ECMWF, NOAA, etc.).

5.1.3.2 Gaps and proposed solutions:

(a) ***Precipitation:***

Precipitation data for terrestrial biospheric models are not available at the spatial resolution (< 1 km) needed to resolve topographic and other forms of landscape heterogeneity, nor with the temporal resolution (< 1 hr) needed to resolve short-term responses of water fluxes (especially canopy interception, infiltration and runoff) to intermittency in precipitation. The current global data sets have a spatial resolution of 0.5 to 1.0^{o} and temporal resolution of days to months. (http://orbit35i.nesdis.noaa.gov/arad/gpcp/). Two alternatives exist in principle: (i) increase the spatial and temporal resolution of precipitation data, and/or (ii) develop improved parameterisations in ecosystem models for the statistical treatment of subgrid-scale processes in space as well as time. Both approaches are important because the available precipitation data are currently far from sufficient in spatial and temporal resolution, and will unlikely become adequate in the foreseeable future.

Because of its importance in many fields, the study of precipitation, both observationally and statistically , rapidly evolves. Resources are becoming available through these developments which need to be harnessed in the development of a strategy for terrestrial carbon observations. These developments include the following:

- There are developments in statistical downscaling of precipitation in both space and time ("weather generator"), incorporating techniques such as correlation of statistical attributes of precipitation with orographic variables (elevation, aspect, distance to coastline, others). This work needs to ensure realism in the statistics - not only of precipitation, but also its correlation with other variables such as radiation.
- Maintenance of the present surface measurement network represents a major challenge. It must deal with the problem of station closures and continue to address the long-standing but difficult question of gauge corrections.
- The GPCP (Global Precipitation Climatology Project) is producing a global, on-line precipitation data set (5-day, 0.5°, retrospective to 1998, ongoing; http://orbit35i.nesdis.noaa.gov/arad/gpcp/).
- Regional studies under the GEWEX program have produced intensive data for the midwestern USA and other regions (http://www.ogp.noaa.gov/mpe/gcip/index.htm).
- Coverage of North America and Europe by weather radar is now complete, and will rapidly extend to other parts of the world. Archiving and distribution of these data would augment precipitation data in the context of global terrestrial carbon observations.
- At least two satellite-borne remote sensing techniques are under active development: TRMM (active radar) and DMSP (passive 2-band microwave).
- Global NWP models (ECMWF, UKMO, NOAA, etc.) overcome most temporal and spatial consistency problems through their global domain coverage and high frequency of output reporting. However, (1) all relevant variables for surface water, carbon and energy balance determination need to be archived; and (2) caution is in order because properties and assumptions in the NWP land-surface scheme influence these outputs. Temporal consistency of the global NWP outputs may also be an issue of concern.
- Mesoscale NWP models provide even higher resolution but to minimise the problems of region-to-region inconsistency, these models should be provided with boundary conditions from a global model.

(b) ***Radiation**:*

The key radiation variables are incoming solar, photosynthetically active radiation (PAR), and net radiation (or estimates of the upward and downward longwave components). Excluding the obvious diurnal cycle, the temporal and spatial variability of radiation variables is not as great as for precipitation but still remains a significant issue. There are also far fewer long-term, directly measured records for radiation than there are for most other meteorological variables. Strategies to deal with these issues include the following:

- A set of high-quality, long-term measurements of solar, net and PAR radiation needs to be established in the context of a terrestrial carbon observations, to calibrate satellite-based estimates and to improve local parameterisations of the long-wave terms. Consistency and quality of calibration is vital. These measurements can opportunistically be located at flux tower sites, although additional measurement sites are desirable.
- NWP and mesoscale models produce outputs that include radiation variables. However, the qualifiers regarding the usefulness of NWP-derived estimates (see a) above) also apply here. In addition, NWP archives are required to include all the terms in the surface radiation budget; they are usually calculated but not always archived.

(c) ***Temperature and Humidity:***
For these variables the effects of terrain heterogeneity are smaller than for either precipitation or radiation, although they are still potentially important. Orographically sensitive interpolation of data from existing meteorological networks (or NWP outputs in nowcasting mode) is a reasonable approach to obtaining data at the spatial and temporal resolutions needed for terrestrial carbon observations.

(d) ***Wind:***
Wind data are important for three reasons. First, they are necessary to specify aerodynamic transfers in models of land-atmosphere exchanges. The observation issues here are similar to those for temperature and humidity, resulting in the need to include orographic effects and to consider the role of atmospheric stability. Second, wind data are needed to determine the Green's functions in atmospheric inverse approaches (Enting, 2000). These are usually obtained from GCMs or NWP models, but there is a need to archive and interpret the sub-grid scale transports used in constructing the wind fields as these play a significant role in the forward calculation of the Green's functions. Third, wind information is needed to interpret flux tower data (flux measurements by eddy covariance, eddy accumulation, mass balance or profile methods) in any circumstances except for flat, homogeneous terrain. The acquisition and interpretation of wind data for this purpose is best undertaken in campaign mode rather than through long-term observations, though long-term measurements in the vicinity of some flux towers may be beneficial.

(e) ***Wet and dry deposition:***
Data on wet and dry deposition of nutrients and contaminants may be an important biogeochemical forcing input for terrestrial biosphere models. The main present requirement is to access existing networks. Additional measurements, for instance at flux tower sites, may require implementation as significance of this forcing becomes better understood. These requirements should be considered from a regional or biome perspective; for example, nitrogen deposition is known to be important for the boreal biome (McGuire et al., 1992).

An important overarching issue is commonality between the requirements of terrestrial carbon observations and ‘terrestrial water’ observations. While the latter is now largely carried out at national or regional scales, many of the compelling reasons for establishing a global carbon observing system (section 2.) extend to water as well. Linkages between carbon and water cycles and observations include:

- The close process links between the cycles of energy, water and carbon;
- The need in carbon cycle modelling for good specifications of water plant availability, including soil moisture and depth to groundwater table if the latter is accessible to plants;
- The improvement in modelling the water cycle through linkage to carbon cycle modelling, through the stomatal coupling between transpiration and carbon assimilation;
- The dependence of both carbon and water exchanges on similar suites of meteorological forcing variables.

5.2 Surface Fluxes and Stocks

5.2.1 Present status

Surface measurements and monitoring of carbon fluxes and stocks has a rich history. However, there are large gaps in the data in terms of (i) complete above and below ground components, (ii) spatial and temporal consistency, and (iii) completeness of an adequate spatial and temporal coverage. The surface measurements are produced by scientific research studies, inventories focused on commercial interests such as forest inventory or yield, and broader surveys or compilations, e.g. country-level statistics assembled by FAO.

5.2.2 Gaps and proposed solutions

The following describes some major gaps in information and potential ways to address these:

1. Forest stocks and productivity data at global to sub-national levels:

Gaps:

- Limited access to the original plot-level measurements;
- Exact co-ordinates of plot data are not released due to confidentiality concerns;
- Not all the biomass is measured: aboveground components only, focus on commercial tree species, focus on merchantable volumes, does not include litter production; thus the best way to use biomass data for total flux estimates is not well established;
- A variety of inventory methods are used with varying degrees of uncertainty;
- Accurate data on stock changes (due to harvest, fires, other disturbances) are not available, particularly at sub-national levels;
- Inventories usually have a good statistical design to estimate volumes and growth for large areas of forest; they do not provide information at a local level.

Solutions:

A two-prong approach is required: (i) increase access to quality forest biomass data, and (ii) develop methods for using the existing forest data and inventories to improve estimates of carbon fluxes. Some options are:

- Determine availability of the Food and Agriculture Organisation (FAO) forest and other carbon-related statistics at the sub-national scale as part of Forest Resources Assessment (FRA) 2000and other ongoing programs. Such data are often collected but are mostly not centrally available in a country, even in the form of metadata;
- Work with forest inventory data for selected countries (e.g., US, Canada) to demonstrate the potential use of inventory data for global terrestrial carbon observations;
- Explore the potential for acquiring and using long-term mensurational data for sub-national scales, including review of inconsistencies, deficiencies, etc. with various country programs;
- Explore use of the data in combination with models based on land use, remote sensing, or other approaches to downscale national level inventory data to finer resolution.

2. Below-ground coarse and fine root biomass, root turnover rates

These observations are generally made at flux tower sites, but the characteristics of the distribution over large areas are not known.

Gaps:

- Scarcity of measurements, especially in tropical deciduous and boreal deciduous needleleaf systems (e.g., larch);
- Difficulty in performing measurements with consistent methods.

Solutions:

- Refer to the status of data and procedures to estimate root biomass based on soil and climate (Jackson et al., 2000);

- Promote the development of new measurement tools.

3. High resolution forest inventories

Depending on the resolution of the Kyoto Protocol reporting requirements, there will be a need for repeated measures of biomass/carbon with high degree of accuracy for small forest parcels. Traditional forest survey methods are generally too expensive to meet this need. Vegetation Canopy Lidar from aircraft or satellite provides the potential for the survey need (see also section 5.3). This issue will require attention once the Kyoto reporting requirements are agreed to.

4. Soil carbon

In addition to point/soil profile measurements available at national or global (Soil and Terrain Database, SOTER) levels, a method for the spatial distribution of soil carbon has been developed by IGBP (Global Soils Data Task, 1999). The quality of the output is limited by the available site soil carbon information.

Gaps:

- Lack of measurements for many locations;
- Lack of soil depth data to compile an accurate soil carbon inventory;
- Inherent heterogeneity of soils at local scales.

Solutions:

- Ensure active sites measure soil carbon (at the sites and in surrounding areas, if feasible, using standardised methods);
- Promote new soil surveys specifically for soil carbon;
- Develop new soil carbon measurement techniques.

5. VOCs and other greenhouse gasses (methane, CH4, NOx, N2O)

Gaps:

- Generally, estimates of NPP do not consider VOCs but these may be significant. For example, using recent emissions data and estimates of biome-specific ecosystem properties such as foliar density and emission responses to climatic factors, Guenther et al. (1995) produced a global model of total biogenic volatile organic compounds (BVOCs) fluxes. They estimated combined emissions of isoprene, monoterpenes, and other reactive volatile organic compounds to be 0.31, 0.15, and 0.21 Mg C ha^{-1} yr^{-1} for tropical rain forests, tropical montane forests, and tropical seasonal forests, respectively (Guenther et al., 1995);
- Lack of measurements in time and space;
- Measurements are difficult and costly.

Solutions:

- MOPITT (http://terra.nasa.gov/Gallery/MOPITT/) will provide relevant measurements from satellite for CO and CH_4;
- Review of the TRAGNET model. The United States Trace Gas Network (TRAGNET) (http://www.nrel.colostate.edu/PROGRAMS/ATMOSPHERE/TRAGNET/TRAGNET.html) measures fluxes of CO_2, CH_4 and N_2O between ecosystems and the atmosphere to determine the factors controlling these fluxes. There are 25 sites representing a variety of regionally important ecosystems. Gas samples are taken from permanent chambers at prescribed intervals, typically one hour or less. Gas chromatography analyses the samples for CH_4, N_2O and CO_2;
- Development of a fast-response VOC measuring system.

6. Wetlands and coastal estuaries

With some exceptions, existing observations are inadequate to obtain accurate or representative spatial and temporal estimates of carbon fluxes in wetlands. The gaps concern both the distribution and functioning of wetlands (Sahagian and Melack, 1996).

Gaps:

- Aquatic issues have not been dealt with in terrestrial inventories.

Solutions:

- Satellite sensors (e.g., SAR) may provide information on wetland distribution and dynamics, especially concerned with water table.

There is a need to build linkages with aquatic communities to ensure that this component is included.

7. Missing biomes

Inventories of biomass are often poorly characterized for unique forests such as woodlands/savannahs, urban forests (human managed) and crops (especially in the tropics). Data for these ecosystems are often available from research studies, but are not compiled or archived systematically.

8. Comments

An overall approach to acquiring much of the desired in situ information could be to ensure that the variables will be measured at the existing sites within the networks associated with the TCO, such as the FLUXNET tower sites, EOS core test sites, the GTOS NPP sites, IGBP transects, etc. Sites that measure ecosystem fluxes are of particular importance since they provide the basis for enhancing the value of other site observations through process models tested against the flux measurements. The specific measurements are in Table 1 but should include where possible: soil C, root biomass and turnover, litter fall, phenology, decomposition (litter bags), canopy chemistry. Most of these are low cost and relatively simple measurements. In addition, the core variables of aboveground NPP, LAI, and others should be measured at all sites.

The acquisition of in situ observations around the globe is complex, regarding both the observations themselves and a strategy for their continued acquisition and availability. Some of the considerations or incentives to acquire these data include:

- Create a structure within TCO to co-ordinate the collection of common measurements and compilation of the resulting data;
- Prepare a manual, such as the BigFoot Field Guide (Campbell et al., 1999), to help standardise the measurements in different regions and biomes, and a way to compile the resulting data;
- Ensure that participating sites receive recognition for their contributions;
- Provide analytical services as needed, e.g. soil analysis;
- Provide an educational component, such as training workshops;
- Provide return-in-kind (e.g., remote sensing data) for access to in situ data;
- Use successful networks as models, e.g. the flask network, DIVERSITAS litterbag studies, etc.

Research studies have collected a large amount of information that has not been readily available. Therefore, another general approach to locating and accessing this extensive information is to collaborate with scientists in the countries of interest. A successful example of this approach is the IGBP-DIS Global Primary Production Data Initiative (Scurlock et al., 1999) which resulted in a comprehensive global database of NPP. Activities that may be useful to promote collaboration of this type include synthesis workshops and exchanges of students and researchers.

5.3 Satellite observations

Satellite data are important in both top-down and bottom-up approaches (Table 1). For top-down, NWP or GCM models presently make the most extensive uses of these data, although their value for trace gases estimation has also been shown in research mode (Reichle et al., 1994; Connors et al., 1994) and will increase in the future (e.g., MOPITT; http://terra.nasa.gov/Gallery/MOPITT/). Section 7.2 discusses additional requirements for top-down satellite observations and the needed technological developments . Sections 5.3.1 to 5.3.3 deal primarily with bottom-up observation issues.

5.3.1 Status and recent progress

Satellites provide an important measurement technology for a number of essential variables, especially those used in upscaling from sites to globe. Table 1 (section 4.3) identifies the observation requirements that may be met through satellite remote sensing, and Table 2 lists variables for which data products have been produced from satellite measurements. From Table 2, it is evident that remarkable progress has been achieved in converting raw satellite measurements into products useful for terrestrial carbon assessment. However, the quality of the products obtained so far (third column of Table 2) needs further improvements; this is discussed further below.

For terrestrial carbon observations, several kinds of sensors are required (Table 3, 4). They differ in terms of the spectral bands (from about 0.4 μm to 21 cm), the illumination source (passive or active), spatial resolution (from ~25 m to ~1000 m), and the control over which region is imaged (fixed or remotely pointable). The conceptually most important sensor types are listed in Table 3. In virtually all cases, the technology is changing, thus the characteristics of specific sensor types also evolve. The current representatives of the various types are listed in Table 4 for sensors generally available to date (fine- and coarse- spatial resolution, SAR) and in Table 5 for recent, innovative concepts (very high spatial resolution, multi-angle, lidar, hyperspectral). Future research should focus on an effective use of data from these new sensors.

Compared with the situation 5-10 years ago, substantial progress has been made in several areas related to the use of satellite data for studies of the terrestrial biosphere. They include:

- The reduction in costs associated with the Landsat-7 data policy, leading to vastly improved data availability and the possibility of obtaining accurate information on land cover and land cover change, by taking proper account of the spatial heterogeneity in carbon density and the processes governing carbon exchange ;
- Improvements in data acquisition strategy. For example, a new approach has been developed for Landsat 7 which aims to maximise the number of useful (atmospherically uncontaminated) images over land (Arvidson et al., 1999, 2000);
- Availability of large-area radar data sets. Several campaigns have been carried out by space agencies to provide continent-wide mosaics of SAR data (the Amazon Basin, boreal forest of North America, etc.; examples can be found at http://trfic.jpl.nasa.gov/GRFM/worldmap.html);
- Convergence on land cover classes. There seems to be gradual convergence to the IGBP land cover classification scheme. GOFC and FAO have agreed that the FAO Africover scheme should be included in any classification exercise. Progress has also been made in novel land cover products, e.g. fractional cover, leaf type, etc. ;
- Agreement was achieved on LAI as a product and progress was made on the LAI measurement and validation protocols (e.g., Chen et al., 1999; Campbell et al., 1999);

- New, larger datasets are being planned for a more routine production. For example, global burn scar products will be produced with SPOT-VEGETATION, MODIS and ATSR data;
- New sensors are being developed that will provide critical information for TCO (e.g., VCL; Table 5).

In spite of the above progress, gaps still remain in several areas. Much more needs to be done for satellite data to fulfil their potential in determining the distribution of carbon sources and sinks around the globe. Some of these gaps are discussed below.

5.3.2 Gaps and solutions:

Gaps:

The most serious gaps or problems regarding satellite observations for terrestrial carbon include:

- Lack of commitment to long-term data continuity for fine resolution sensors (Landsat – type) and SAR (JERS-type) sensors. This problem is well understood and is related to program planning and priorities of individual space agencies. IGOS-P is intended to assist in resolving this problem.
- Lack of commitment to long-term data continuity for critical observations begun with MODIS (in particular, into the NPOESS series). Building on the long (1983-) AVHRR series, EOS/MODIS will greatly improve the quality and quantity of products needed for terrestrial carbon studies (Table 2,4). However, there is presently no assurance for data continuity beyond approximately 2005 (the nominal lifetime of the Terra satellite).
- Lack of consistency in, and access to, existing long-term archives. This problem exists in most archives, although its severity varies with agency and sensor. The access to older data is especially difficult. The problem includes not only storage media, but also access to metadata such as calibration information. Nevertheless, solutions are possible if enough attention is given to this challenge.
- Lack of commitment to providing information products, as opposed to data only, and to ensuring that in situ observations are used effectively in preparing the satellite-derived information products. The provision of information products that also incorporate in situ observations is fairly common for meteorological and oceanographic applications (e.g., Reynolds and Smith, 1994; http://www.nodc.noaa.gov/dsdt/oisst/index.html; http://ibis.grdl.noaa.gov/SAT/). However, such products are not yet available for the terrestrial environment over large areas. Current plans of some programs include the generation of experimental data sets (e.g., EOS Terra; http://terra.nasa.gov/) but in situ data are intended to be incorporated in a limited way and as a research activity only. The incorporation of surface observations is exacerbated by the difficulty of accessing timely in situ data from various parts of the globe.
- Lack of globally applicable, robust algorithms and other infrastructure needed for low-cost, large volume production of information products. Numerous algorithms have been developed based on existing satellite data and applied to partial (in spatial and/or temporal coverage) data sets. Their limitations are due to the input data (calibration, resolution, spectral or angular coverage) or adequate validation in a broad range of terrestrial environments. Progress is being made in both areas, with the recent or planned satellite launches and more systematic international co-ordination of validation activities under CEOS and individual programs (e.g., http://modarch.gsfc.nasa.gov/MODIS/LAND/VAL/; http://www.ceos.org/). - Previous limitations due to large data volumes and processing requirements melt away as the computing power and communication bandwidths increase. However, reliable product availability requires agency commitment and support, and this has been lacking so far for terrestrial products.

- Poor inter-agency co-ordination of observations. To date, the co-ordination of terrestrial data acquisition among space agencies has been minimal. This leads to sub-optimum use of the existing space assets, and to data and products with built-in limitations. It is especially important where data from various sensors could be used in a complementary fashion, e.g. tradeoffs between spatial coverage and timeliness of acquisition (Ahern et al., 1998). IGOS-P should be an effective mechanism for making rapid progress in this area.
- The unavailability of satellite data for important terrestrial variables. The current and near future satellite programs cannot provide data for several ecosystem variables that are important for upscaling. They include aboveground biomass, soil moisture, leaf nitrogen, water table depth (especially for wetlands), and precipitation (at high spatial resolution). These areas require focused investigations regarding options for sensing technologies, to lead to the design of suitable satellite missions. In addition, some clearly promising techniques (e.g., lidar for biomass and canopy structure) require further technological development to improve the information content of the data (increase of coverage, resolution, etc.).

Solutions

- Ensure commitments to long term continuity of data from fine resolution and SAR sensors.
- Review NPOESS specifications from the TCO perspective to ensure that critical observational needs are met;
- Insist on the provision of information products, not just data;
- Invest in reprocessing archived satellite image series such as AVHRR;
- Identify a small set of C-related products which satellites can deliver (based on Table 2);
- Establish a process that will lead to consensus algorithms for specific products. In many cases, combinations of data from multiple satellites are necessary or highly desirable;
- Ensure provision of data in common formats to facilitate their integrated use. A suitable starting point would be co-registered fields of radiances and then reflectances. These will require reliable radiometric calibration and geometric correction (ortho-rectification to a common geometric base);
- Desirable early information products include LAI and land cover (fractional cover, other parameters) from each satellite.

Specific steps regarding most of the above proposed (and other potential) solutions need further discussion before devising plans for implementation.

As noted above, sound global validation strategy is an essential component of the use of satellite data for terrestrial carbon observations. The approach should focus on network sites where in situ measurements and process studies are combined with the available satellite data for algorithm development and comparison of products with independent estimates. As part of the algorithm intercomparison and validation strategy, action is also needed to set up a community process to define and implement priority locations for acquisition of high and very high resolution data. Such data could be purchased from commercial operators, obtained by co-ordinated targeted observation from multiple sensors with a restricted duty cycle, or assembled by separating out relevant data from unwieldy data streams into a separate archive.

Table 2. Products derived from satellite observations

Product	**Maturity**[1]	**Quality in production mode**[2]	**Sensors Needed**[3]	**Comments**
Land cover and land cover change				
Land cover classification	1	B	Fine-F Fine-P Coarse SAR	Class definitions can be contentious; community is gravitating toward IGBP classes
Disturbance/land cover change	1	B	Fine-F Fine-P Coarse SAR	Eventually will want to detect and estimate significant changes in any observed variable
Phenology products				
Length of growing season	1	B	Coarse	Requires NDVI composite products as input
Evergreen/deciduous ratio	1	B	Coarse Fine-F	Can usually be derived from single-date summer
Vegetation structure products				
LAI	1	C	Coarse Fine-F Fine-P	Saturation and other complications in using optical data
Fractional cover of vegetation	1	B	Coarse Fine-F Hi-Res	Currently inferred from data which has resolution better than opening sizes; requires high contrast between canopy and background or canopy and shadow
Horizontal structure[4]	1-2	B	Hi-Res Fine-F	Need very high resolution data and a clean parameter; spectral unmixing may provide partial information with lower resolution data
Vertical structure[4]	2		SAR lidar	Multi-angle optical is a potential source of additional information
Biomass density	3		SAR lidar	Need long wavelength SAR or imaging lidar
Leaf dispersion parameter (e.g., clumping index)	2	C	Multi-angle optical	Need multi-angle optical data; further discussion within the community is desirable
Biomass burning products				
Active fire	1	B	Coarse	Produced from thermal data; algorithms need to be tuned and validated regionally
Burn scars and age	1-2	B	Coarse Fine-F Fine-P	Products under development for MODIS, VEGETATION, and ATSR. Expected to be straightforward to develop

Fire emissions	2	C	Coarse	Need further definition through dialogue within the community
Meteorological products				
Radiometric surface temperature	1	C	Coarse	Atmospheric corrections need improving
Air temperature	3	TBD	Coarse	Need further advice on approach
Methane-related products				
Wetland location	2	B	Coarse Fine-F SAR	L-band SAR is essential; addition of C-band SAR and optical data provides additional information
Wetland water status	2	B	SAR	L-band SAR is essential; addition of C-band SAR and optical data provides additional information
Atmospheric methane concentration	1	B	MOPITT	MOPITT on Terra
Additional products[5]				
Foliage N content	3		Hyperspectral	Need hyperspectral approach
Chlorophyll content	3		Hyperspectral	Need hyperspectral approach
Soil moisture/wetness	3			Need dual active/passive L-band approach, near-surface
Soil organic carbon content	3			Now feasible only for bare surface soil
Precipitation	3			Need higher spatial and temporal resolution than currently available

1: Maturity: 1 = can be produced now, ; 2 = within 5 years, ; 3 = after >5 years.
2: Quality in production mode: A = excellent; B = satisfactory; C = fair.
3: Sensor type needed: Fine = pixel spacing ~25 m; Coarse = pixel spacing ~ 250-1000 m; F= fixed pointing (nadir); P = programmable pointing. Fusion of data from two or more sensors often required to generate a product.
4: The precise definition of the suite of vertical and horizontal structure products will needs further more discussion and negotiation within the community; clumping index is a possible additional product.
5: These products would be very valuable, but may be difficult to achieve with current and foreseeable technology.

Table 3. Generic sensor types

Sensor Type	Resolution (m)	Swath (km)	Repeat (days)	Fixed/pointable targeting	Blue	Green	Red	Near-Infrared	1.5-1.7µm	3-5µm	8-10µm	L-band	C-band
Fine-Fixed	~25	~200	~14	Fixed		*	*	*	*				
Fine-Pointable	~25	~75	~4	Pointable		*	*	*	*				
Coarse	~1000	~2000	1	Fixed	*	*	*	*	*	*	*		
SAR	~25*	100-200	~4	Pointable								*	*
HiRes	1-4	25-100	~30	Pointable	*	*	*	*					
Multi-angle	240->1000	400-2400	~2	Pointable	*	*	*	*					
Lidar	~25		>30	Pointable (single wavelength)		*	*	*					
Hyperspectral	~25		>~14		several	many	many	many	many				

* with 4 or more independent looks

Table 4. Current specific sensors

Fine - Fixed	Fine - Pointable	Coarse	SAR
Name(Agency)	**Name(Agency)**	**Name(Agency)**	**Name(Agency)**
TM (NASA)	HRV (CNES)	AVHRR (NOAA)	JERS (NASDA)
ETM+ (NASA)	HRVIR (CNES)	VEGETATION (CNES)	Radarsat (CSA)
LISS III (ISRO)		MODIS (NASA)	ERS (ESA)
CCD (INPE)		MERIS (ESA)	ASAR (ESA)
		GLI (NASDA)	PALSAR (NASDA)
		ATSR (ESA)	
		AATSR (ESA)	
		WiFS (ISRO)	
		WFS (INPE)	

Table 5. Specific sensors – new or anticipated capabilities

HiRes	Multi-angle	Lidar	Hyperspectral
Name (Agency)	**Name (Agency)**	**Name (Agency)**	**Name (Agency)**
Ikonos (Space Imaging)	POLDER (CNES/NASDA)	VCL (NASA)	Hyperion (NASA)
OrbView (Orbital Sciences)	MISR (NASA)	CO_2 (NASA?)	Warfighter (US Air Force) Nemo (US Navy)

6. Issues

The workshop has raised several scientifically important issues but could not give them sufficient attention.

6.1 Scaling from point to globe/region

Conceptually, the estimation of terrestrial carbon sources and sinks through the bottom-up approach requires:

a) flux tower site measurements that serve in the development and validation of models mimicking ecosystem interactions with the atmosphere;
b) measurements at additional sites to ensure that the models represent fluxes and processes in a larger region;
c) gridded data sets that permit application of the models across the terrestrial landmass, from landscape to globe; these are obtained from satellite measurements where possible.

The detailed observation requirements are given in Tables 2 and 4.

Landscape heterogeneity, caused by natural (topography, disturbances) and human (land use) agents, introduces considerable complexity into the sampling design that is necessary to ensure the adequacy of the coverage for items a) and b) above.

For a), global terrestrial monitoring/validation sites should encompass the complete range of climate and biome type combinations (Running et al., 1999). When the current flux towers are mapped over the annual temperature/precipitation climate space of current global vegetation, some important biomes are underrepresented (Churkina and Running, 1998; Terrestrial Observation Panel for Climate, 1998). Also, the correspondence between flux tower locations and permanent ecological field sites is low, illustrating the need for more combined flux and ecological measurements in order to more rigorously test the models that estimate fluxes across the terrestrial ecosystems. Thus, the design of a comprehensive flux tower network requires further analysis, taking into consideration various axes of the 'ecological space' such as climate, vegetation functional type, disturbance, succession, land use, and possibly others. While a flux tower network for TCO must take advantage of existing sites to the maximum extent possible, future sites should be established to fill gaps in coverage that are identified through the above process.

For b), the greatest potential is offered by ecological measurements of variables such as biomass and NPP (section 5.2). In addition, the potential of roving flux towers should be explored. Each such tower is associated with a nearby fixed tower and is placed at a site for a limited time period (days to weeks). One tower thus permits a more detailed sampling of the 'ecological space', providing a richer data set for model validation and scaling than would be possible with fixed towers. Measurement and characterisation methodologies have been developed in the context of satellite product validation (Campbell et al., 1999; Chen et al., 1999). They rely on in situ observations in conjunction higher resolution satellite data, as an intermediate scale at which an entire pixel can be characterised on the ground.

A similar site selection issue concerns the top-down approach. The existing trace gas sampling sites are mostly at remote marine locations (section 5.1), and thus are insufficient for a detailed atmospheric inversion. The selection of additional sites should be guided by the requirement to maximally reduce uncertainties in the estimated distribution of sources and sinks. While the locations are not obvious, objective analysis and modelling methods can be used to identify these, as further discussed in section 7.2.

A systematic examination and application of the above concepts in the context of TCO remains. This should be done for both top-down and bottom-up approaches, in a co-ordinated manner. It should result in the establishment of objective criteria for the selection of sites for the different observation methods. From these criteria and given the present distributions, the conceptual and practical feasibility of enhancing current networks to fill the gaps can be established.

6.2 Further analysis of baseline gridded data sets

The application of the dual constraint method requires the knowledge of certain variables at all points where carbon fluxes are to be estimated (Table 1). Some of these may be obtained from satellite measurements, presently or in the near future. Others cannot be obtained now, but the evolution of satellite technologies offers a realistic prospect that their measurement will be possible in the foreseeable future (e.g., canopy chemistry). Yet others cannot be expected from satellite observations, for different reasons. They include climate, hydrological data, and others. For terrestrial carbon observations, especially critical are soil physical and chemical properties, and land use (including disturbances) history. Although data sets for soils and land use have been compiled (e.g., Global Soils Data Task, 1999; Imam et al., 1999), they have been limited by the accessibility of data to the international scientific community. More detailed data sets exist, but often at sub-national levels and their compilation would thus entail significant effort. Before undertaking additional activities in this respect, it would be important to know which areas/aspects are in greatest need for improvement from the viewpoint of estimating terrestrial carbon fluxes.

6.3 Emissions

Data on carbon emissions caused by human activities are essential for the use of the dual constraint approach to estimating carbon sources and sinks. Such data are available at the national level due to the

UNFCCC reporting requirements (IPCC, 1996) but their timely availability at the regional to local levels is virtually non-existent. In a longer term, satellite sensors may provide three-dimensional, temporal distribution of CO_2 in the atmosphere (section 7.2). The issue of near-term observation requirements for such emissions and potential solutions needs to be discussed. Further attention also needs to be given to observations that would be required to complement satellite CO_2 measurements and the accuracy/resolution of the latter.

6.4 Transfer between pools

The transfer of carbon between pools becomes important in characterising the global carbon budget when it takes place between pools that differ widely in their present or future turnover rates. At the workshop, discussion has focused mostly on carbon fluxes between the ecosystem and the atmosphere. The most important transfers involve terrestrial dissolved organic (DOC) and inorganic (DIC) carbon. Carbon moves from soils undergoing relatively rapid carbon turnover (tens of years) through groundwater to fresh water (lakes, rivers, reservoirs), or directly from soils to fresh water. There, the dissolved carbon is captured in slow-turnover lakes (thousands of years) or carried to the sea for eventual incorporation into very-slow turnover sediments (millions of years). Schlesinger's (1997) analysis of extant data concluded that globally, over 0.8 Gt C yr^{-1} enters rivers and groundwater, with DIC slightly exceeding DOC. Both quantities are likely to increase when plants are immersed in higher atmospheric CO_2 concentrations, as carbon transfer between above and below-ground terrestrial pools increases.

While these transfers do not affect the fluxes between the ecosystems and the atmosphere, they are important for understanding the global carbon cycle and thus its predictability. It should also be noted that it is not the magnitude of the different fluxes but changes in these that are of key importance. Observations that can provide reliable estimates of the DOC/DIC include separate measures of carbon in soils, groundwater, streams and lakes. The data are generally not amenable to remote sensing but rather must be gathered in situ. Measurements in soils and groundwater will be most useful if they include recurring measurements of the age of the carbon in each of these pools. This issue also required further attention, and its implications for TCO need to be examined.

6.5 CH_4 and other gases

Discussions at the workshop focused on the CO_2 as the most important greenhouse gas. However, other carbon gases are also involved in the fluxes between the biosphere and the atmosphere. While NMVOC gases play a significant role under some circumstances, CH_4 is arguably the most important, especially in wetlands where it is produced under anaerobic conditions. Globally, the increase in atmospheric CH_4 concentration has stabilised in recent years, but the understanding of the CH_4 status and trend is important for the knowledge of the global carbon cycle (and thus its predictability). Satellite sensing technology will also play an important role at the regional to global scales in the near future, with the successful launch of MOPITT on Terra in December, 1999. The need for satellite and in situ observations of these gases, and the implications for TCO, require further discussion.

7. From vision to reality

The vision for TCO is to contribute to the integrated understanding and human management of the global carbon cycle, through systematic, long-term monitoring of the terrestrial exchanges of greenhouse gases, especially CO_2, and the associated changes in carbon stocks. To achieve this vision, a monitoring system is required which synthesises information from several types of measurements: monitoring of atmospheric

CO_2 and other gases, observations of surface fluxes, ecological in situ measurements, and remote sensing. For brevity, such a system is referred to as 'TCOs' below, without pre-judging the form TCO implementation may take. The combined monitoring system will provide estimates of terrestrial CO_2 sources and sinks at spatial and temporal scales from global to those relevant to land use policy and land management. These estimates should be provided with greatly reduced uncertainty relative to current practice, by systematic cross-checking of independent approaches and by designed expansions of current measurement networks.

Many of the elements of an integrated terrestrial carbon observing strategy are in place now or under development. The challenges are to ensure that important existing observations continue and key new observations are initiated; to build in appropriate overlaps and leverage among the disparate data sets, thus filling important data gaps; to identify activities and agencies willing to contribute to establishing TCOs; to design and implement linkages among components, activities and contributions; and to carry out the necessary research and modelling work that links observations of various types at different scales.

In this section, implementation and way forward issues are discussed. First, the progression to a functioning TCOs is briefly sketched out, with a preliminary list of important tasks listed. Specific issues are then discussed in two areas, a) further development of the dual constraint concept and b) data and information handling needs and capabilities for TCOs.

7.1 Implementation tasks

TCOs makes measurements and generates products in order to determine and monitor the terrestrial sources and sinks of carbon dioxide and their relationship to land use and land cover. It involves:

- Networks of sites making co-ordinated surface measurements on an ongoing basis of atmospheric, vegetation, and soil variables, particularly networks for concentrations of atmospheric carbon dioxide (and other trace gases) and networks of towers for ecosystem flux measurements. Atmospheric sampling from aircraft in selected areas, ongoing or periodical.
- A sustained program of satellite-based remote sensing of a variety of vegetation and land surface parameters at a hierarchy of spatial and temporal resolutions. These include the long-term continuation of the key observations that can be made currently (Table 2, 4) and their ongoing improvements as the evolving technology permits. Importantly, observations for which no appropriate satellite sensing technology exists at the moment but are essential to TCO (Table 1,3), should be added as soon as feasible. There are also experimental programs employing reduced-performance sensors which produce data critical for TCO, e.g. VCL (Table 2,5). Such activities need to be extended and enhanced so that the observations are improved and their long-term continuity is assured.
- Products derived from remotely sensed measurements, using algorithms that are validated with data from selected sites and regions. Specific plans for satellite-based products for several variables in Table 2 have been formulated by the Global Observation of Forest Cover (GOFC; Ahern et al., 1999) project and these need to be implemented. These activities will not only produce important global data sets urgently needed by the various communities but will also provide valuable experience regarding the procedures and mechanisms for future ongoing operations.
- Higher level products that compare and synthesise information from the above (and other) subsystems.

TCOs also depends upon products from the existing observing and analysis systems for weather prediction and hydrology; on national records of land use, forests and agricultural productivity; and on other types and sources of data. In particular, there is the need to ensure availability of forest and vegetation inventory data and other in situ observations of carbon stocks and fluxes that have been obtained for various purposes by national inventory agencies, regional networks, or research programs. Continuing access to these data types and the appropriate institutional mechanisms will represent a significant challenge for TCOs.

In common with other observing systems designed according to the Integrated Global Observing Strategy, TCOs should be:

- global and long-term in scope, nationally sponsored, and internationally co-ordinated;
- multi-user, needs driven; and focused, but accommodating to complementary uses (e.g., global hydrological cycle)
- based on quality controlled observations and data products, and on full and open exchange of data and information
- adaptable to changing needs and capabilities; and evolving with improving observation instruments, platforms, techniques, and uses (see below)
- helping to build capacity on a global basis.

TCOs should be implemented within the concept of a rolling review. This concept was originally developed for the observing system used for weather prediction, but is more generally applicable for other long term environmental measurements as it entails:

a) A periodic cycle of:
  - assessments of user needs;
  - assessment of existing system performance;
  - expert analysis of possible changes in design and operations to improve cost effectiveness and meet new needs;
  - policy level decisions on changes to be made
  - implementation of changes, followed after an interval by another iteration of the cycle.

b) Supported by ongoing programs to:
  - measure system performance;
  - enhance the quality and reliability of existing operations;
  - ensure calibration and validation of instruments and products;
  - develop techniques for new or improved measurements and analysis algorithms.

Such rolling review will facilitate making the best use of current assets (observing facilities, new research findings, technological developments, plans and programs under development) to meet the near- and mid-term future needs.

The participating networks are initially comprised of volunteer organisations with dedicated communications and a co-ordination/data assembly centre. To assure continuity of the data records over many decades, these need to transition from volunteer status to ongoing commitment as their track record and national funding permit. Wherever possible, network sites should be utilised in research campaigns to assist understanding of site environmental characteristics and its regional – global significance.

A potential scenario for TCOs evolution is as follows:

Planning phase (2000-2001): Towards implementation
a) Identify and consult with existing potential components

- GLOBALVIEW-CO2 and the participating networks
- Fluxnet
- LTER sites
- Pilot projects
- Research projects
- National forestry records
- National land use records
- Other

b) Consult with potential users of anticipated products to define more precisely their needs and benefits. Review existing statements of requirements in the light of this information:

- FCCC-COP
- IPCC
- Forest managers
- Local observing site managers
- Research scientists improving understanding of the carbon cycle and its forcing functions
- …

c) Review existing globally relevant products

- Operational status
- Data dependencies
- Status of algorithms
- Product quality/deficiencies

d) Identify most serious gaps/deficiencies

- in *available* measurements
- in products

f) Design the initial observing system as an integrated whole

g) Identify and secure the participation of components of the Initial TCOs

- International Co-ordinating Office
- Communications, metadata
- Satellite programs and primary analysis centres
- In situ networks and primary analysis centres
- Communications networks and archive centres
- Synthesis centres
- Calibration and data validation activities
- Rolling review and supporting programs
- …

h) Needed developments for the next phase

- MODIS analysis and algorithm validation
- Demonstration of Vegetation Canopy Lidar
- Improved algorithms for selected variables
- Critical improvements in infrastructure
- …

i) Strategic actions needed for sustainability

- Obtain commitments to ongoing satellite programs
- Secure institutional mandates where required for long term commitment to in situ activities
- Clarification of data policies
- …

Pilot Phase (2002-2006): Initial Operations

- Operations
- Rolling review
- Needed developments
- Strategic actions; etc.

7.2 Dual constraint methodology research and development

While top-down methods for the estimation of area-averaged fluxes from atmospheric data will always be limited by the spatial density of sampling, it is possible to consider different observation strategies to achieve denser sampling. Particularly useful is a distinction between (i) campaign-style measurements that are part of integrated field programs intended to develop and evaluate bottom-up scaling methods, and (ii) augmentation of the global atmospheric observing network intended to improve global carbon flux inversions. Early implementation should focus on the development of methods for estimating spatially-integrated fluxes at moderate scales and should include model development and observing system simulations, targeted measurement campaigns, and enhancement of existing observational networks. These experiments can be used to guide the further development and later deployment of observing system components. Such evolution can be considered over three periods: between now and 2005, between 2005 and 2010, and after 2010.

7.2.1 Near-term priorities (2000-2005)

Spatial scaling from point measurements to area-average fluxes is already the focus of a number of initiatives being carried out in several areas of the world (e.g. CarboEurope, Australian carbon cycle program, LBA-Ecology; see also Appendix 10.3); these and similar studies should be encouraged and augmented. Intensive field studies addressing spatial heterogeneity and scaling of flux estimates are underway as part of EOS and other satellite programs. Tower flux measurements are accompanied by ancillary data on carbon pools and fluxes in the surrounding region, using spatial statistics to obtain estimates of representative conditions (section 5.2). Fluxes measured from multiple heights on very tall transmission towers (Bakwin et al., 1998) can also be used to directly evaluate scaling algorithms across heterogeneous landscapes. Such measurements need to be accompanied by careful analyses of the flux footprint at each height under various meteorological conditions (see also Appendix 10.3). The above studies are essential to the development and evaluation of the satellite and model based "gridded" global carbon flux estimates.

Flux towers have now been deployed across a large range of climatic and ecosystem conditions, though there are still some conspicuously undersampled parts of climate space (section 6.1). These data are crucial for the development and evaluation of models of the "fast" ecosystem fluxes, but carbon sources and sinks on time scales of ≥1 year are likely driven more by slow processes such as changes in nutrient loading, disturbance/recovery dynamics, and land-use history. Assuming that the number of eddy covariance studies will likely continue to grow over the next five years, a rational design for the flux network should also include sampling across gradients in these "slow" processes controlling the carbon balance of terrestrial ecosystems (section 6.1).

Scaling studies using bottom-up methods can be directly evaluated using atmospheric trace gas measurements collected in "campaign" mode (as opposed to ongoing sampling) by several approaches. Such campaigns (e.g., Gerbig et al., Appendix 10.3) are expensive and so can only be mounted selectively, but can be very valuable if paired with other ground-based data collected by integrated field programs:

- Spatial heterogeneity in surface fluxes can be estimated by eddy covariance measurements made from low-flying aircraft (Desjardins *et al*, 1995; Dobosy *et al*, 1997). These measurements typically have "footprints" only slightly larger than tower-based data, but can be made repeatedly across large distances;
- Area-average fluxes can be estimated directly by mass balance of the convective boundary layer, taking CBL-top entrainment and horizontal advection into account (Raupach *et al*, 1992; Denmead *et al*, 1996; Desjardins *et al*, 1997; Chou, 1999);
- Direct inversion of atmospheric concentration data collected by airborne platforms using tracer transport models and methods similar to those used in global inversions (Stephens *et al*, 2000).

Regional aircraft campaigns may not be cost-effective by themselves in terms of added information about regional fluxes and processes. However, they can add powerful constraints to existing experiments that include tower flux measurements, characterisation of landscape-scale variability in carbon fluxes and pools in vegetation and soils, imagery collected at multiple spatial scales, and models. Such nested experiments can become incubators for credible methodologies to be applied at high resolution at larger scales. As methods are developed for quantitative estimation of area-averaged fluxes from atmospheric data, they can be tested against archived data from major field experiments such as FIFE, BOREAS, HAPEX, and EuroSiberia. The retrospective analyses can be accompanied by "pseudodata" experiments in which simulation models are used to construct realistic tracer fields consistent with known surface flux patterns. Sampling strategies can then be quantitatively evaluated and errors can be analyzed.

Global-to-regional downscaling

The current atmospheric observation (flask sampling) network used in global inversion studies is insufficient to resolve regional fluxes at scales smaller than a continent or an ocean basin. Sampling sites are nearly all located in the remote marine boundary layer to obtain representative "background" data with a minimum of local influences. Sampling over continental locations would provide a more powerful constraint on model inversions, but the interpretation of continental data is fraught with problems involving strong spatial and temporal heterogeneity. Samples collected from airborne platforms during convective conditions in the mixed layer or in the free troposphere would alleviate many of these problems. The goal should be to sample air under conditions that can reasonably be represented in a global transport model used for the inversions. This precludes the terrestrial surface layer in most areas, necessitating sampling from very tall towers, balloons, or aircraft.

Before an airborne sampling network to support better inverse modelling can be deployed, thorough network optimisation analyses will need to be carried out. Such observing system simulation studies have been carried out already with respect to point sampling at the surface (Rayner et al, 1996) and with limited extension to free tropospheric sampling (Gloor et al, 2000). Further analyses will include existing atmospheric data such as those collected by regional aircraft sampling studies in Europe, Australia, Siberia, and Brazil and from tall transmission towers in the US and Europe (see also Gerbig et al., Appendix 10.3). Network optimisation studies must include careful analysis of the uncertainty of the measurements themselves. They should quantify the trade-offs between uncertainty in the estimated fluxes and network density, measurement error, and cost. Multiple tracers should be measured (e.g., CO_2, CO, CH_4, $\delta^{13}C$, $\delta^{18}O$, and O_2/N_2) to improve the accuracy of the inversion process. Observing system simulations will need to evaluate the errors in the estimated fluxes given errors in each of the tracers. The optimisation analyses should help answer questions such as: what to measure, to what precision, where to measure, how high to fly, how often to fly, and how the uncertainty depends on errors in the model transport. These simulations will be a major goal of the integrated observing strategy in the next five years.

A modest enhancement of the existing tropospheric observing network over the next several years would pay off substantially in terms of more robust inversions of regional fluxes at higher spatial resolution than is possible given the current data. Current transport models agree on tracer distributions in the remote marine boundary layer, but diverge strongly over the continents and aloft (Law et al, 1996; Denning et al, 1999). A handful of vertical profiles over the continents could remedy this situation at moderate cost. Inexpensive rental aircraft (at perhaps US$100/hour) could sample as many as 20 shallow vertical profiles distributed around the continents weekly for about US$100K per year in direct aircraft costs (equipment, analytical, and personnel costs would also be incurred). The atmospheric constraint on tropical fluxes is particularly weak because of rapid convective and meridional mixing with respect to the current stations. Such an augmentation of the existing network, especially combined with an intensive campaign-style sampling in some areas as mentioned above, would certainly lead to significantly reduced uncertainty and improved spatial resolution in flux estimates from global inverse modelling.

Another potential source of significant new information about atmospheric CO_2 concentrations over the continents that could be obtained at modest cost in the near future is direct measurements at eddy flux towers. These sites already measure CO_2 (typically every 0.1 seconds) for flux determinations. Since only the variations of the concentration through time is needed, the current measurements are not calibrated with standards traceable to the WMO (and thereby to the rest of the flask network), nor is the typical instrumentation installed at the towers adequate for highly precise CO_2 determinations. At an upgrade cost of less than US$50K per tower and about US$10K per year per tower in operating expenses, existing flux towers could be instrumented for CO_2 determination with accuracy comparable to the global flask measurements. For use in global inverse calculations, regionally representative values would have to be extrapolated from these data, treating ordinary flux towers as "virtual tall towers." Surface layer similarity theory can be used to extrapolate mid-CBL concentrations to high precision from accurate surface values, given simultaneous measurements of heat and momentum flux as are commonly made at flux towers. Alternatively, background concentrations can be estimated from surface time series after correction for local effects using other tracers and momentum flux (Potosnak *et al*, 1999). These measurements would likely have a major impact on global CO_2 inversions, but are beyond the current scope of work proposed or funded at most flux towers. Access to these observations will therefore require institutional support beyond that already committed to funding the flux measurements themselves.

Two orbital sensors (NASA AIRS and ESA IASI) will be flying by 2002 and will allow direct retrieval of atmospheric CO_2 from space. The accuracy of these estimates is unknown at this time, but even rough measurements of CO_2 at thousands of locations every day are potentially very powerful for estimating fluxes by atmospheric inversion. The most important question involves the weighting function of these measurements. The majority of the information about surface fluxes is contained in the spatial variability in CO_2 in the lowest couple of kilometres of the atmosphere where boundary-layer turbulence mixes the signal. Above 500 mb, the spatial gradients are so weak as to be beyond detection with an instrument that can only resolve concentration to 2 ppm. Thus, both accuracy and the ability to penetrate to CBL will determine the utility of spaceborne CO_2 sensors . Observing system simulations will be essential to make the most of these new data.

A final priority in the near term will be to invest in the development of new technologies for inexpensive and accurate determination of CO_2 concentrations and fluxes over continental regions. Promising technologies for which moderate investment might yield major improvements in the next five years include:

- Inexpensive and lightweight solid-state sensors for measuring CO_2 that might be used for continuous monitoring near flux towers, on aircraft, or on operational radiosondes;
- Ground based and/or satellite lidar and tunable diode lasers with the potential to allow remote determination of CO_2 and $\delta^{13}C$ with high accuracy;

- Sampling from pilotless aircraft, which could sample long transects inexpensively.

7.2.2 Mid-term priorities (2006-2010)

Following a thorough analysis of observing system simulations and network optimisation, a sampling network for tropospheric CO_2 above the continents should be deployed operationally. Tans et al. (1996) envisioned such a network over North America, but global inversions would benefit from global observations. Of course, higher data density in heavily sampled regions of upscaling campaigns will enhance the performance of the network. Sampling should include multiple tracers for additional constraint on the locations and mechanisms responsible for the terrestrial sources and sinks. Platforms might include tethered balloons, light aircraft, commercial aircraft, and virtual tall towers. Further development of new technologies such as solid-state and lidar remote sensing of CO_2 and other tracers is also expected to lead to a major expansion in the sampling of the atmosphere in the mid- term.

With an increasing data density, the limiting factor for accuracy and resolution of the fluxes by inversion of concentrations will become the transport models used. Model development will be required to correctly account for realistic transport of trace gases globally and at high spatial resolution. Many of the current generation of models used for inversions have unrealistic wind fields, unresolved subgrid-scale transport by convection, or both (http://dendrus.atmos.colostate.edu/transcom/). High resolution inverse models will require consistent data on trace gas concentrations, winds, and the convective mass flux. This can be accomplished by identifying the inversion of CO_2 fluxes as an important objective of the global weather assimilation system. Operational centres have the most accurate description of the four-dimensional variations of transport available, yet much of the subgrid-scale mass flux is not archived. The future higher data density of trace gas concentrations will require archival of full four-dimensional transport by operational assimilation and forecasting centres, through direct assimilation of trace gas concentrations in the operational models, or both. It is unlikely that the full range of data could be assimilated in real time because of the delay required to analyse some species in the laboratory, so there will probably always be a role for archival analyses in CO_2 inversions. The reality is that the data volume is much larger when one includes the subgrid-scale parameterised transports. So, provisions will have to be made for these to be saved.

As data and models improve, a meaningful “dual constraint” will be formalised for consistent, global-scale top-down and bottom-up estimates of the spatial and temporal variability of terrestrial carbon sources and sinks. This constraint will include quantifying the uncertainties associated with the satellite and model based estimates, and will lead in this period to direct evaluation of EOS and other carbon products at regional scales in some parts of the world. Such effort will require the involvement of the operational meteorological infrastructure (WMO and its members), and will be a step toward true Earth system data assimilation.

7.2.3 Long-term priorities (after 2010)

By 2010, technological developments will likely lead to lightweight and inexpensive CO_2 sensors that can be flown operationally from radiosondes, producing concentration profiles at hundreds of locations several times daily along with winds, temperature, and humidity. These data, along with in situ measurements, remote sensing of trace gases, and measurements from aircraft, will be assimilated using 4-dimensional variational data analysis or other operational methods to produce high-resolution gridded fields of trace gases consistent with other meteorological information. Such operational methods will integrate the top-down and bottom-up approaches in a coherent analysis and prediction scheme, constrained by the satellite and in situ observations.

By this time, it is possible to envision the development of a dedicated spaceborne instrument capable of measuring CO_2 in the lower troposphere to an accuracy approaching 1 ppmv. This would be extremely valuable, as it would allow the use of high-time frequency variations as well as spatial patterns in inverse calculations. Preliminary studies using idealised scenarios suggest that such measurements would allow regional fluxes to be estimated to within 0.1 GtC/yr.

Given high resolution atmospheric data and improved transport models and the continued development of eddy correlation flux as well as other in-situ data, we will be able to produce near-real-time descriptions of the terrestrial components of the global carbon cycle that are simultaneously consistent with all of these constraints.

7.3 Data and information system considerations

Achieving the TCO goals described above will require a data and information system (DIS) that both builds on the internationally distributed data resources and develops the capacity to generate new products. Given the limited resources initially available, such DIS will depend on existing components. Its design and implementation will evolve along with TCO plans; however, some of the important components and potential approaches are described below:

- Web page
- Web-based metadata and data exchange system
- Centralised database(s) of selected data
- Network of analysis and modelling centres

7.3.1 TCO Web page

Similar to most international projects, a Web page will be the cornerstone of communicating information within TCO and to outside interests. TCOs can take advantage of existing systems to provide the capability to catalogue existing datasets and the links to retrieve the data. Two such systems exist that are relevant to TCO: the Terrestrial Ecosystem Monitoring Sites (TEMS) Database (http://www.fao.org/gtos/PAGES/TEMS.HTM), and Mercury (http://mercury.ornl.gov/).

TEMS is an international directory of metadata about monitoring stations and their activities; it is not a compilation of raw data. The objective of the database is to document existing long-term monitoring sites which may be suitable for inclusion in the GTOS network once this is established. In addition, the database will provide information on who is doing what and where in ecosystem monitoring.

Another example is Mercury, a Web-based system that allows the searching of distributed metadata files to identify data sets of interest and deliver those data sets directly to the user. Mercury is designed to support the data and information needs of projects where the critical aspects are: 1) quick exchange of data between researchers; 2) complete control of data visibility in the system maintained by researchers; 3) rapid and economic deployment; and 4) high automation and easy scalability. Data providers need not run any database software locally, and their data can reside in any convenient format. At selected intervals, Mercury automatically builds a metadata index (used to provide the search capabilities) at the central data facility. Mercury is now operational at the Oak Ridge National Laboratory DAAC and harvesting environmental data from over 1,000 data sources in twelve countries. It is also being used by IGBP-DIS.

7.3.2 Database

To perform the integration and synthesis of carbon data, there is a need for one or more facilities that compile selected data from a variety of sources in a multitude of formats. This task will deal with issues of heterogeneity of spatial and temporal scales, different units of measure, data documentation, and general data consistency. Such problems were addressed in the development of FLUXNET (http://www-eosdis.ornl.gov/FLUXNET/) and CLIMDB.

FLUXNET provides researchers access to consistent and integrated measurements of carbon dioxide, water vapour, and energy fluxes and associated site vegetation, edaphic, hydrologic, and meteorological characteristics. Fluxes and ancillary information are unified into consistent, quality assured, documented, readily accessible datasets via the World Wide Web (http://www- eosdis.ornl.gov/FLUXNET/). FLUXNET is a "partnership of partnerships", formed by linking existing sites and networks. Measurements and terminology from existing but disparate sites and networks are brought together into a common framework and harmonised, thereby increasing substantially the usage and value of the flux data and information for the global change research community.

CLIMDB is links LTER Network climate data together from individual site information systems into a centralised system. In the LTER Network, individual sites routinely collect daily climate data and maintain the data in local computer systems using a variety of formats. Each site provides access to standardised daily climate files via an Internet address that points to the location of static files or of dynamic scripts. A central site automatically harvests daily climate data into a centralised database and applications programs produce two monthly distribution reports or formats from the daily climate database.

7.3.3 Analysis and modelling centres

Many of the analysis and modelling tasks associated with TCOs will be performed by various groups, and brought together as needed to provide synthesis products. One of the challenges will be to co-ordinate such a network of activities. An information system model for multi-site projects was developed by LTER (Olson et al., 1999). The core component of DIS was regarded as a set of cross-site working groups (e.g., for NPP, soils, remote sensing, atmospheric sciences, etc.). Each working group would co-ordinate the development of data and models associated with their particular scientific theme. The overall data and information system consists of nodes for each scientific working group plus a central node. The system is envisioned as Web-based and accessible through one or more of the popular browsers using an html- type interface to the data and information. The group leader for each scientific-domain working group provides scientific and technical leadership, and he/she would play a critical role in the development of datasets and data products for the working group. In addition, one or more technically-oriented partners for each leader will be required. The project-level data activities would be performed by a project data staff comprised of the technical partners for the groups and a leader for the project data and information system. DIS then provides access to the complete, combined, consistent data at each node (some nodes may be located physically together). There may be links to other data archives that would provide access to related projects or data. Access may be limited to data originators during the active phases of data compilation and analysis; however, as datasets become more mature, they become publicly accessible through the project's DIS. Finally, they will be moved to a long-term archive and distribution centre.

8. Conclusions and recommendations

After examining information requirements for terrestrial carbon and the present status and capabilities in providing this information, the workshop participants reached the following conclusions:

1. Information on the global distribution of terrestrial carbon sinks and sources is essential for policy and scientific purposes in four areas: reporting for multilateral environmental agreements; understanding of the carbon cycle; assessment of the trends and impact of global change; and the management of ecosystem resources at local to regional levels.
2. The proposed dual constraint strategy, based on a) ecosystem modelling employing satellite and in situ measurements and b) atmospheric inversion modelling based on in situ gas concentration measurements, offers the best potential for accurate and consistent information on terrestrial carbon at local to global scales.
3. A co-ordinated approach is necessary to implement global terrestrial carbon observations. The concept of a TCO system, co-ordinated internationally and implemented through national means, fulfils this need.
4. Many components needed for such a system are well understood. Some are in place, others need to be augmented, and all need to be placed in a consistent, functioning framework.

The following recommendations are made to IGOS-P:

1) Seek endorsement for the TCO system concept.

2) If adopted, modify the proposed evolution strategy as appropriate and take steps to its implementation. These should include an integrated approach to data distribution, quality control, archiving; arrangements for the generation of core products; and clarifications regarding the responsibilities of agencies in the planning, development, and performance assessment of these activities.

3) Ensure continuation of existing satellite observations important to TCO into the foreseeable future. Accelerate the development and deployment of new satellite observation technology, including lidars for vegetation biomass, canopy structure, and atmospheric CO_2 concentration.

4) Expand the system of flux networks and ensure adequate geographic coverage, continuity of observations, and co-ordination.

5) Improve the access and use of existing (non-flux) sites and national data sets for TCO purposes.

6) Review and further refine the strategy for dual constraint development, and ensure active participation of the hydrological community in this process.

7) Give high funding priority to research and development of instruments, observation methods, and models related to carbon cycle observations.

8) In the evolution of the global terrestrial carbon observations, maintain close linkages with the ocean carbon cycle observation community.

9) Issues relating to scaling, gridded data sets, emissions, and others identified at this workshop should be examined by a broader scientific community in order to understand the implications for global terrestrial carbon observations.

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Appendix 2. Workshop agenda

TERRESTRIAL CARBON OBSERVATION SYNTHESIS WORKSHOP
Ottawa, Canada

Sponsored by:	Global Terrestrial Observing System (GTOS)
Hosted by:	Canada Centre for Remote Sensing (CCRS)

OBJECTIVES:

7. Assemble and summarise existing information on information requirements regarding terrestrial carbon cycle
8. Assemble and synthesise existing information on observation requirements needed to obtain the carbon cycle information, assuming that top down (inversion modeling) and bottom up (ecosystem modelling) strategies are employed in an integrated manner. All important data/observation requirements are to be considered (satellite, surface, atmospheric, ...)
9. Evaluate the consistency, completeness, and reliability of the information on observation requirements defined above, and refine these to the extent possible
10. Conduct initial evaluation of existing data or observations in relation to the observation requirements, identify major gaps or deficiencies, and propose solutions to the extent possible
11. Identify actions that need to be taken to: complete the definition of observation requirements; complete the analysis of deficiencies of existing observations and needed remedies; link terrestrial and ocean carbon cycle observations; and prepare a report on the terrestrial carbon observation theme for IGOS-P.
12. Based on the above, prepare a 'straw man' framework report as an input for a joint IGBP/GTOS meeting in May, 2000. This meeting will engage the scientific community more fully to complete the design of a comprehensive approach to terrestrial carbon observations and the links between terrestrial and ocean components of the global carbon cycle.

AGENDA:

DAY 1: am

Chair: Gosz

0800 Registration

A.	Setting the stage	
0830	Introduction, background, workshop objectives	Gosz
0900	IGBP Carbon cycle research program	Hibbard

B. Current and anticipated information needs regarding global terrestrial carbon distribution – presentations

Questions to be addressed in each presentation:

a) what specific information on terrestrial carbon is required, and why?

b) to provide that information, what specific observations are required, and at which spatial and temporal resolutions?

The above is to be based on existing/published information and presented in a structured way, to the extent possible

0930	Kyoto Protocol	Solomon
0955	IPCC (1996 guidelines):	Cihlar and Brown
1020	Refreshment break	
1040	Atmospheric inversion modelling	Denning
1105	Understanding terrestrial carbon cycle	Potter
1125	Conventions (CCD and CBD)	Gommes
1150	Global Observation of Forest Cover	Ahern

1215 Lunch (on premises)

1300	GTOS/GTOS requirements	Cihlar
1325	US Carbon cycle research and observation	Wickland
1350	Canadian terrestrial carbon research and requirements	Chen

C. Observation requirements for selected regional studies

Question to be addressed: What are the observational requirements of a 'dual constraint' approach to terrestrial carbon distribution? The review is to be based on existing/published studies/information, to the extent possible

1415	Introduction	Denning
1445	Multiple-constraint approach to carbon cycle observations in the Australasian region	Raupach

1510 Refreshment break

1530	COBRA	Saleska
1555	TRANSCOM	Denning
1620	Oceanic carbon cycle observation	Bretherton
1645	Discussion	

DAY 2 am:

0800 Continental breakfast

Chair: Cihlar

0830	Satellite and surface data us	Running

0850-1500 Breakout 1

Charge: synthesise existing information on a) information and b) observation requirements. For each variable, be specific in terms of observations required/missing, what, where, how made, how many needed. Consider specifically data needs for initial conditions, boundary conditions; for model development/testing, and validation of products. If feasible, suggest how the information gaps might be filled, using expertise available at the workshop. Summarise the findings using a consistent format.

a) top down:	Denning (leader)
b) bottom up (fluxes, stocks):	Gower

1500 Plenary presentations and discussion

1540-1700 Writing session

Evening social event

DAY 3

0800 Continental breakfast

Chair: Denning

D. Status of observations and networks - presentations

Question:

a) What data collection systems/observation networks are available related to terrestrial carbon, and what is their present status?
b) What data are available for terrestrial carbon, and what are their characteristics (completeness, quality, availability), both current and past?
c) How good are our capabilities of extracting quantitative biophysical parameters from raw measurements?

0830	Atmospheric observations	Raupach (speaker)
0910	Surface observations: fluxes	Olson
0850	Surface observations: stocks	Olson
0910	Satellite observations	Townshend

0930 Breakout 2 (lunch on premises):
Charge:
a) Review and document adequacy and completeness of existing observation networks/capabilities: satellite, fluxes, stocks, atmospheric
b) Review and document existing data sets: satellite, fluxes, stocks, atmospheric

Atmospheric and meteorological networks and data sets:	Denning (leader)
Surface stocks and fluxes:	Gower & Olson
Satellite:	Townshend

1520 Plenary presentations and discussion

1620-1730 Writing session

DAY 4

0800 Continental breakfast

Chair: Gosz

0830 Breakout 3:
Charge:
Identify unresolved issues (compare requirements with current situation, as follow-up based on results of the first breakout); potential solutions, steps to be taken,..

Surface fluxes, pools and associated observations	Gower and Olson
Atmospheric observations	Denning and Raupach
Satellite observations	Ahern and Wickland

1120 Plenary presentation and discussion

1200 Lunch (on premises)

1300 Conclusion and next steps

1400-1600 Final writing session

OUTPUTS:
A strawman report with:
- synthesised information requirements
- existing observation networks and data sets
- observation gaps and potential solutions
- further actions required

Appendix 3. Summaries of presentations

The IGBP Carbon Cycle Research Programme

IGBP Carbon Working Group: Kathy Hibbard, Will Steffen, Pep Canadell, Berrien Moore III

Abstract

International carbon activities are partitioned into policy, research, observation, and observation platforms. The policy arena is largely delegated through the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (KP). Global environmental change programs key to carbon research include the International Geosphere/Biosphere Programme (IGBP), World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), as well as national and regional programmes (USGCRP, CarboEurope, etc.). International assessments of global carbon and climate change issues is relegated to the Intergovernmental Panel on Climate Change (IPCC).

Carbon has been adopted as a theme by the Integrated Global Observing Strategy (IGOS), an initiative of CEOS (Committee on Earth Observing Satellites, representing the major space agencies around the world) as well as the three major global observational programmes, GCOS (Global Climate Observing System), GTOS (Global Terrestrial Observing System) and GOOS (Global Ocean Observing System). In addition, other groups, such as WCRP and IGBP, have joined the IGOS group as partners (the IGOS-P consortium – the 'P' standing for Partnership).

Through their joint sponsorship of the Terrestrial Observation Panel for Climate (TOPC), GTOS and GCOS have been assigned the lead role in developing the carbon observation theme within IGOS-P. In the realm of the international global environmental change research programmes, IGBP has the lead role in work on the global carbon cycle. Thus, GTOS/GCOS and IGBP have developed a partnership to develop an integrated system for terrestrial carbon monitoring and observation.

The overall goal of the Terrestrial Carbon Observation (TCO) theme is to define observation requirements for an accurate estimation of the distribution of terrestrial carbon sources and sinks of the world with high spatial and temporal resolution. To define the optimal system to achieve this goal requires strong scientific input, both from modelling studies and from ground-based process studies. The GTOS/GCOS-IGBP partnership is designed to build the scientific research-observation community linkages in the most effective and efficient way possible. The workplan outlined for 2000 aims to make use of planned GTOS/GCOS and IGBP meetings in a collaborative way to achieve both observation design (GTOS/GCOS) as well as contributing to an internationally coherent carbon framework focused on research planning and synthesis (IGBP) objectives.

As part of the IGBP synthesis/restructure project, begun in early 1998, it was recognized that IGBP needed to more proactively coordinate the various aspects of carbon research being undertaken in the programme, and the IGBP Carbon Working Group (CWG) was formed. The overall objectives for the IGBP CWG are:

- To develop an International Framework for Carbon Cycle Research;
- To facilitate and coordinate research, as appropriate, under this Framework, and
- To synthesize, at periodic intervals, our latest understanding of the global carbon cycle.

The focus of the work of the CWG has been on the biophysical aspects of the carbon cycle, in keeping with IGBP's emphasis on biogeochemical cycling. However, there are important aspects of research on the carbon cycle which go beyond IGBP's remit. Examples include the effects of climate variability on carbon uptake or release (joint WCRP-IGBP issue) and the institutional challenges associated with management of components of the carbon cycle

(IHDP issue). Thus, the Chair of the SC-IGBP presented on 13 March 2000 to the Joint Scientific Committee of the World Climate Research Program (JSC-WCRP) the concept of working together to define an International Framework on Carbon Cycle Research. The JSC-WCRP agreed to this co-operation. In late March 2000, the Chair of the SC-IGBP also presented to the Scientific Committee of the International Human Dimensions Programme (SC-IHDP) an invitation to join with the IGBP and the WCRP in this common activity. It is, thus, that the CWG of the IGBP will become part of a larger consortium based on interaction with WCRP and IHDP, and research on the global carbon cycle will become an inter-programme crosscutting activity. In addition, the IGBP and IPCC have collaborated on schedules and planned activities. The IGBP is aiming to establish a similar relationship with TOPC (Terrestrial Observing Panel on Climate). A summary of the past and current activities and products of the IGBP Carbon Working Group is given below.

Activities of the IGBP Carbon Working Group undertaken in 1998 and 1999

Activity	**Time**	**Venue**	**Product**
Terrestrial C Cycle and Kyoto Protocol: Workshop – IGBP Terrestrial C Working Group	Apr 1998	Stockhom, SE	Science paper (Science 280: 1393-1394 (1998))
Scoping Meeting: IGBP Carbon Working Group	Mar 1999	Isle sur la Sorge, France	Overview paper on the global carbon cycle
IGBP Congress: Synthesis Working Session	May 1999	Shonan Village, Japan	Refinement of Overview
Focused workshop: nutrient constraints on carbon cycle	Oct 1999	Stockholm, SE	Science paper (submitted Dec 99)

The IGBP carbon workplan for 2000 is aimed strongly towards completing the synthesis project on the global carbon cycle and on further developing the framework for an international collaborative research on carbon. A number of key activities, which will be carried out in collaboration with the IPCC and the TCO initiative, amongst others, are set out in the table below. The most important of these activities are two major meetings, in May and October. The first is aimed at producing an integrated, DRAFT International Framework for Terrestrial Carbon Cycle research and observation for the next decade as well as an initial draft of the state of terrestrial carbon research. The second meeting is focused on vetting a series of linked articles on the carbon cycle (possibly submitted to Nature) and completing a DRAFT International Framework on the Global Carbon Cycle research. The IGBP, in collaboration with WCRP and IGOS-P have developed the following key activities planned for 2000:

Key Activities of the IGBP Carbon Working Group planned for 2000

Activity	Time	Venue	Product
TCO Preliminary Planning Meeting (GTOS/GCOS lead)	8-10 Feb	Ottawa, Canada	'Straw man' framework for terrestrial C observations
Workshop on Terrestrial C Research and Observations (joint GTOS/GCOS-IGBP)	22-26 May	Portugal	DRAFT Framework for int'l, integrated approach to terrestrial C research and observations
Global C Cycle Synthesis Workshop (IGBP)	16-20 Oct	University of New Hampshire, USA	A series of linked articles on the carbon cycle and a DRAFT International Framework for Global Carbon Cycle Research

The objectives for the TCO Planning meeting are to:

- Review and synthesize existing plans and specifications for terrestrial carbon observation schemes,
- Prepare a 'straw-man' framework based on the above, and

- Recommend strategies for flexibility in future terrestrial observing systems with respect to technologies and *in situ* observations

The primary objectives for the May terrestrial meeting where paraticipants will include members from the global modelling community, process studies, and observing systems are:

- To develop an **INTEGRATED** international framework for terrestrial carbon cycle research and observations through to the next decade (and beyond),

- To produce a detailed plan for an integrated approach to terrestrial carbon observations: special emphasis on the spatial and temporal distribution of carbon sources and sinks (GTOS objective), and

- Produce a detailed framework for international terrestrial carbon cycle research including: process studies, modelling, and observation strategies (IGBP objective)

The October meeting will largely be aimed at completing a DRAFT International Framework for Global Carboy Cycle Research and will be built around a number of key scientific questions about the global carbon cycle that are best addressed through international collaboration. The Framework will place a strong emphasis on integration across a number of dimensions and themes:

1. Across oceanic, atmospheric, and terrestrial components of the carbon cycle;

2. Between process studies, experiments, observations, modelling and palaeo studies, and

3. Amongst national, regional, and international contributing projects and programmes.

Finally, as mentioned a second objective of the Durham Workshop is to review and finalize a set of linked articles on the carbon cycle establishing clearly our understanding of the current state of global carbon cycle research and the clear next steps. These articles will establish a firm foundation for the DRAFT International Framework for Global Carbon Cycle Research.

Summary of IPCC 1996 reporting guidelines for national greenhouse gas inventories

J. Cihlar and S. Brown

1. GENERAL

The purpose of the IPCC guidelines is to support the implementationof the UN Framework Convention on Climate Change (UNFCCC). As part of the Convention, countreis agreed to report on the emissions of greenhouse gases, and the Intergovernmnetal Panel for Climate Change (IPCC) subsequently prepared a set of guidelines (??ref) for such re[prting. The purpose of the guidelines is to faciliate estimation and reporting on national inventories of anthropogenic GHG emissions and removals, in a consistent format. The Guidelines are concered with emssions and removals that are a direct result of human activities or of natural processes that have been affected by human activities; within national territories (there are four exceptions, such as the decay of all wood products which assumed to take place in producing country within one year of harvest). Any emissions or removals fitting the above description may be included if they can be clearly documented and quantified. The emissions reported annually but the temporal resolution is to be compatible with data quality or availability. For example, a 3-year average is preferred for agriculture, and the resolution could be 5 or more years in forestry because of typical inventory cycles. In addition to annual reports, a complete inventory is also requested for 1990.

Two important methodological assumptions have been made for land use change and forestry:
a) flux is assumed to be equal to change in stocks stocks, and emission factors for non-CO2 gases; and b) changes can be established from the rates of land use change, and simple assumptions on the impact of these on carbon stocks and the biological response to a given land use. The guidelines allow for the use of a range of methods at different levels of detail. 'Default' methods and assumptions are provided in most cases. These are intended to provide a starting point or to be used where no better information is available since, as repeatedly pointed out in the Guidelines, national assumptions and data are always preferred. If feasible, uncertainty estimates are also to be reported if available; guidelines are provided for this purpose.

The Guidelines also emphasize that past land-use activities and their effect on current CO2 fluxes must be considered because 'inherited' emissions/removals can occur over extended periods.

The Guidelines provide a consistent format and a procedure for calculating the GHG emissions and removals, using a series of tables and an accounting approach; the format is intended to permit toll-ups and comparisons. The documentation supplied with the reports should be sufficient to allow a third party to reconstruct the report from national data and assumptions; this is a working definition of 'transparency'. Documentation should also be sufficient to justify methodology and data used.

INFORMATION REQUIREMENTS

Two main sections are of interest from the terrestrial carbon perspecitve; agriculture, and land-use change and forestry. The Guidelines also identify additional specific categories that could be considered for reporting by countries.

2. INFORMATION REQUIREMENTS

2.1 Agriculture:

This includes all anthropogenic emissions, except fuel combustion and sewage emissions (covered in Energy and Waste, respectively):

> agricultural soils emissions and removals (CH4 and N2O); emissions of CH4, CO, N2O, NOx from burning of savannahs (noted for information, not included in inventory); field burning of residues (emission of non-CO2 GHGs). CO2 from biomass burning noted but not included in the inventory). Note that soil C changes due to soil management are included in Land-use change and forestry section.

2.2 Land-use change and forestry:

This section includes total emissions and removals from forest and land use change activities (above ground biomass; below ground biomass if available):

1) emissions and removals of CO2 from changes in biomass stocks due to management, logging, fuelwood collection,..;
2) conversion of existing forests and natural grasslands to other land uses (mainly cropland or pasture, mostly in the tropics: CO2, CH4, CO, N2O, NOx, NMVOCs);
3) on-site burning of forests (CO2 and non-CO2 GHGs);
4) abandonment of managed lands (removal of CO2 from the abandonment of formerly managed lands, i.e. cultivated land or pasture; divided into 2 groups – those that re-accumulate C naturally, and those that do not or even continue to degrade; time horizons 0-20yrs., 20-100 yrs. if data available);
5) CO2 emissions or uptake by soil from land use change and management (for 20yrs. ago and present, 30 cm topsoil only plus litter mat if present). Above ground grassland biomass: assume net=0 unless data available that show otherwise

Forest harvest: includes consideration of slash,etc..Above ground biomass left after harvest assumed to decay over 10 years (default value).

3. OBSERVATION REQUIREMENTS

3.1 CHANGE IN FOREST AND OTHER WOODY BIOMASS STOCKS

[Total C uptake increment = Area of each biomass stock X Annual growth rate X C fraction of dry matter;
Total biomass consumption from stocks = (Reported commercial harvest X Biomass conversion ratio) + Traditional fuelwood used = FAO.. + other wood use – (Area converted annually X (Biomass before conversion – Biomass after conversion)) X fraction of biomass burned off-site;
Net annual C uptake/release emission = 44/12 X (Total C uptake increment - Total biomass consumption from stocks X C fraction=0.5)]

Area of each biomass stock
Annual growth rate of each stock
C fraction of dry matter=0.5
Reported commercial harvest
Biomass conversion ratio
Traditional fuelwood used
Other wood use
Area converted annually to other land use
Biomass before conversion
Biomass after conversion
Fraction of biomass burned off-site

{Categories: for changes in C stocks: by land-use/management system: defaults Cold temperate, dry, ...}

3.2 FOREST AND GRASSLAND CONVERSION

[Annual loss of biomass = area converted annually X (Biomass before conversion - Biomass after conversion)]

Area converted annually
Biomass before conversion
Biomass after conversion
Fraction of biomass burned on-site
Fraction of biomass oxidised on-site
Fraction of biomass burned off-site
Fraction of biomass oxidised off-site
Carbon fraction of above ground biomass
Area converted (=10-yr.average)
Fraction left to decay=10-yr.average

3.3 ABANDONMENT OF MANAGED LANDS

[Annual C uptake in aboveground biomass first 20yrs. =
= 20-yr.total area abandoned_and_regrowing X Annual aboveground growth rate X C fraction of aboveground biomass (0.5)]

20-yr.total area abandoned_and_regrowing
Annual aboveground growth rate
Carbon fraction of aboveground biomass
Total area abandoned>20yrs._and_regrowing
Annual aboveground growth rate
{Categories: by ecosystem type (e.g., 3 in boreal)}

3.4 EMISSIONS AND REMOVALS FROM SOIL

[Soil C managed = Soil C native X Base factor X Tillage factor X Input factors
Change in soil C for mineral soils = Soil C X (Land area_inventory_yr. - Land area_-20yrs.)
Annual net C loss from organic soils = Land area X Annual loss rate
Annual C loss from liming = total annual amount of lime X C conversion factor]

Soil Carbon native vegetation
Base factor (changes due to conversion from native to agric.)
Tillage factor (management)
Input factors (management)
Soil Carbon in mineral soils
Land area_mineral soils_inventory_current_yr.
Land area_mineral soils_-20yrs._earlier
Land area_organic soils
Annual loss rate from organic soils
Total annual amount of lime
Carbon conversion factor (or assume all is CaCO3)
{Categories: by land use management system (e.g., for cold temperate moist: forest, small grain agriculture, grain/.., permanent pasture, forest/grassland set-aside) and - for mineral soils - by soil type (6 major types, FAO)}

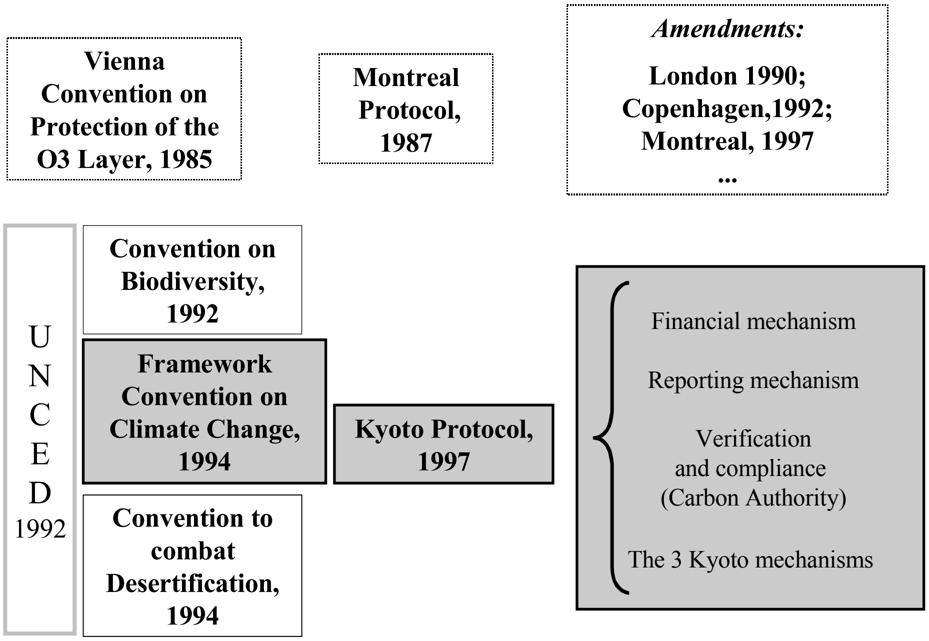
Terrestrial Carbon Observations in the context of the three Rio Conventions

René Gommes

1. Introduction

This note aims at highlighting the links existing between the Convention on Biological Diversity (CBD[1]), Convention to Combat Desertification (CCD) and the Framework Convention on Climate Change (FCCC and KP, the Kyoto protocol), collectively known as the "Rio Conventions" (figure 1). It attempts to identify their common denominator(s) in terms of their data requirements under the Terrestrial Carbon Observations Initiative.

Figure 1: overview of the three "Rio Conventions", together with the Montreal Protocol to reduce the substances that deplete the ozone layer. The Rio Conventions derive from the United Nations Conference on Environment and Development (UNCED) held at Rio, Brazil, in 1992



The Rio Conventions share a number of objectives, institutional aspects and technical issues. Among others, next to the common goal of improving sustainable use of natural resources, as well as the will to co-operate with other conventions[2], legislation and reporting to the Members through the Secretariats of the Conventions, we can also list the exchange of information and technical data, research and data collection, as exemplified in the section below.

2. References to Observations and Data in the basic texts

The issue of data collection and exchange is specifically referred to in the basic texts. This includes, for CCD, articles 16 and 18 (respectively), for CBD articles 7 and 18, and essentially articles 4 and 5 of the FCCC.

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[1] Note that CBD, more than CCD and CCC, is a member of a family of international agreements including CITES (on the trade of endangered species), Ramsar Convention on wetlands, etc.

[2] Refer, for instance, to a CCD document prepared for the 3rd session of the Conference of the Parties held in Recife from 15-26 November 1999 on the "Review of activities for the promotion and strengthening of Relationships with other relevant conventions and relevant International organizations, institutions and agencies"

2.1 Framework Convention on Climate Change and Kyoto Protocol

FCCC is particularly explicit in articles 5 (Research and systematic observations) and 4 (Commitments) where the document states that "*all Parties shall promote and co-operate in scientific, technological, technical, socio-economic and other research, systematic observation and development of data archives related to the climate system and intended to further the understanding and to reduce or eliminate the remaining uncertainties regarding the causes, effects, magnitude and timing of climate change and the economic and social consequences of various response strategies*" (4.1(g)).

In article 10(d), the Kyoto protocol provides some additional views: "*all Parties shall co-operate in scientific and technical research and promote the maintenance and the development of systematic observation systems and development of data archives to reduce uncertainties related to the climate system, the adverse impacts of climate change and the economic and social consequences of various response strategies, and promote the development and strengthening of endogenous capacities and capabilities to participate in international and intergovernmental efforts, programmes and networks on research and systematic observation, taking into account Article 5 of the Convention*".

While the points above clearly recognise the value and need of systematic observations, little is said about the parameters that are to be observed. CBD and CCD mention that indicators of biodiversity and desertification are relevant, some texts prepared for the Conference of the Parties to CCC add useful information, for instance document FCCC/SBSTA/1999/CRP.3 on Research and Systematic Observations. The document provides UNFCCC reporting guidelines and is subdivided, next to other sections, into Meteorological and Atmospheric Observations, Oceanographic Observations, Terrestrial Observations and Space-based Observations.

Countries are requested to make specific reports to the Conference of the Parties regarding the status of their national programmes for systematic observations. In particular, they are invited to examine to what extent their observations conform to GCOS, GOOS and GTOS monitoring principles and relevant best practices.

The section covering terrestrial observations is worth mention *in extenso*: "*Parties should describe their participation in GCOS and GTOS programmes for terrestrial observations including the Global Terrestrial Network-Glaciers (GTN-G), Global Terrestrial Network-Permafrost (GTN-P), and the Global Terrestrial Network-Carbon (FLUXNET), and other networks monitoring land-use, land cover, land-use change and forestry, fire distribution, CO2 flux, and snow and ice extent. Additionally, a general description of programmes for hydrological systems should be given. Parties should describe to what extent the observations correspond to the GCOS/GOOS/GTOS climate monitoring principles (...) and relevant best practices*".

The wording "*land-use, land cover, land-use change and forestry, fire distribution*" provides a direct link to the above mentioned common denominator.

2.2 Convention to Combat Desertification

CCD stresses the need to systematically collect data in Article 10 (National action programmes), the purpose of which is to identify the factors contributing to desertification and practical measures necessary to combat desertification and mitigate the effects of drought. Under point 10.4, CCD stresses the need to "*strengthening of capabilities for assessment and systematic observation, including hydrological and meteorological services*".

On subregional action programmes (Article 11), the purpose of which is to "*provide support for the harmonious implementation of*" above-mentioned "*national action programmes*", the priority areas include (11.e) "*scientific and technical co-operation, particularly in the climatological, meteorological and hydrological fields, including networking for data collection and assessment, information sharing* (…)".

Article 16 focuses on Information collection, analysis and exchange: "*the Parties agree* (…) , *to integrate and coordinate the collection, analysis and exchange of relevant short term and long term data and information to ensure systematic observation of land degradation in affected areas and to understand better and assess the processes and effects of drought and desertification. This would help accomplish, inter alia, early warning and advance planning for periods of adverse climatic variation* (…).

The article then proceeds with operational considerations such as networking institutions, facilitating the systematic observation and exchange of information, including the need for compatible standards and systems, and station geographic distribution.

16.c stresses bilateral and multilateral programmes which aim at defining, conducting, assessing and financing the collection, analysis and exchange of data and information, including, *inter alia*, integrated sets of physical, biological, social and economic indicators.

2.3 Convention on Biological Diversity

CBD is far less specific than CCC and CCD on data collection and exchange. Article 7 (Identification and Monitoring) commits Parties (7b) to "*monitor, through sampling and other techniques, the components of biological diversity*" as well as (7d) to "*maintain and organise, by any mechanism*" the data "*derived from identification and monitoring activities*".

The International Expert Meeting on Building the Clearing-House (June 1997, Bonn, Germany) recognised "*that the objectives on the Convention on Biological Diversity require more than facilitating access to existing data and information, but also needs, inter alia, the active collection of new data and information*".

Needless to say, it is mainly biological information which is referred to under CBD, together with the abiotic factors which have a determining effect on biodiversity, legislation etc. According to a World Conservation Monitoring Centre report[3] the information requirements fall into the four categories of ecosystems, species, genes and sites. The information relevant to the other Rio conventions fall mainly under the last category and include site details, ecology, land use, etc.

3. Some characteristics of data/observations required under the Rio Conventions

3.1 Some differences

It is clear from the section above that the three Conventions are bound to have different approaches in term of data collection, as this is linked with several factor such as…

- **the type of data** being considered, from purely physical (atmospheric data under CCC) to physical and biological (vegetation type, CO_2…: CCC and CCD, CBD) to purely biological (vegetation types, lists of species, etc. : CCD, CBD). In practice, the distinctions are not so clear, but there is a clear gradient from purely physical data to purely biological ones from CCC over CCD to CBD;
- **causality links**: CCC is by far the most "global" of the three Rio Conventions. The term "global" refers to the fact that (1) the atmosphere wraps the whole planet and therefore, atmospheric effects like warming or CO_2 concentration increases are global, (2) numerous inter-relations and feed-backs between land and atmosphere reach a level of complexity that is not present in the other Conventions, and because of this complexity, the implementation (verification etc) of the convention will eventually require a very comprehensive and standardised corpus of observations and finally (3) while climate change will influence desertification and biodiversity, the opposite links are much weaker (figure 2);
- **Scale of application**: as indicated above, CCC is global, while CCD focuses on dry areas. Although CBD is global, the largest land biodiversity currently occurs in equatorial areas so that, in practice, many actions focus on low latitudes. In practice, observations associated with CCD and CBD are thus more limited in space that with CCC. Not only: measures associated with CCD and CBD will be mostly ground parameters (although some can be remotely sensed), while CCC will also resort to upper air measures;
- **Level of enforcement**: the "legal" context of CCC is no doubt much less flexible than CBD or CCD. CCD, in particular, remains mostly "local" when compared with the other conventions, in the sense that it is the countries' own interest to implement anti-desertification, and neighbours or the international community at large has relatively little say on those local issues. Things are different for CBD, but even more so for CCC where actions on literally any point of the earth can have repercussions everywhere else. The result is that the legal apparatus will be much more demanding on low-level data than for other conventions;
- **Current availability of data**: the existence of the global observation systems such as the World Weather Watch (WMO), GCOS/GTOS/GOOS, FLUXNET, agricultural and forest statistics as proxies for carbon pools and, to some extent, changes as well, the FAO Forest Resources Assessments, etc constitutes a very good basis that will provide, at least initially, a good reference base and element of comparison of the more science-oriented observations under the TCO. As such, more quantitative information happens to be available for CCC than for the other Rio Conventions.

Figure 1: interlinkages between the themes of the three Rio Conventions, water availability, land-use change and forestry. The arrows indicates driving variables. Note that population pressure constitutes a dominant factor for most forms of environmental degradation, and this includes such factors as poverty. Also note that the causes of climate change (i.e. mainly industry, energy and transport) are not shown.

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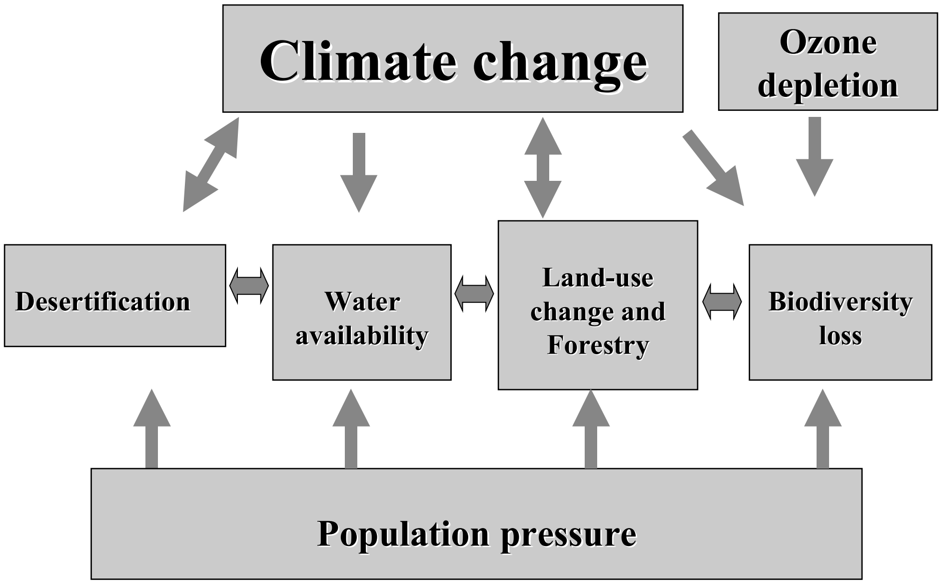
[3] T. Johnson et al., 1998 : Feasibility study for a harmonised information management infrastructure for biodiversity-related treaties, WCMC, Cambridge, UK, 70 pp.



3.2 The common denominator(s)

Listing common data and observation requirements is not easy. We can consider that, given the more encompassing nature of climate and CCC, most observations under CCC will also be relevant for the other Conventions. There is also an obvious need for the Secretariats of the Conventions to increase concertation of their efforts in data collection.

On the macro-level, we can list the observation requirements as follows:

- CBD : considering that biodiversity[4] is a direct function of the gradients/diversity of the environment, combined with the biological and pedo-climatic production potential, observation requirements include the characterisation of the biological environment at the micro-scale to meso-scales[5], the systematic observation on species composition and assemblages, the characterisation of ecosystems in terms of bio-physical diversity and functions, and as well the factors that affect the production potential. The geographic scale will be mostly very detailed, and the frequency of observations will be directly linked with the intensity of the factors affecting the environments under consideration: low (years) for areas undergoing little apparent changes, high whenever there is an ascertained or potential factor reducing biodiversity (monthly). Systematic observations will concentrate on fragile/typical environments[6] with a focus on tropical and humid areas;
- CCD being defined as land-degradation due to anthropic and climatic "changes", the relevant variables are those needed to define, to characterise and to assess land degradation, combined the anthropic and climatic factors that impact areas threatened by, or undergoing, desertification. The plural "changes" introduces an element of uncertainty and refers to both long-term changes (i.e. climate change *sensu stricto*) as well the intra- and inter-seasonal variability. The difference between change and variability is that the random component of variability is larger than in change, a wording which assumes some persistent direction of the variables, precisely as in the trend of increasing temperatures associated with "global warming". Very short sampling

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[4] Note that the term applies at different scales, from genes to organisms to ecosystems.

[5] It is to be noted that the characterisation of spatial scales as "micro", "meso" and "macro" differ widely between the biological/ecological communities and, say, the climatological practice. The "biological scale" is typically one order of magnitude smaller than the geophysical one. For instance, an ecologist may refer to the climate of a soil, a tree bark or the fur of animal as "micro-climates", while a climatologists will reserve the term for a landscape unit, for instance a valley or the sun-exposed side of a mountain.

[6] Including agricultural environments.

frequencies are usually not required, and the month (and longer) is probably appropriate for most observations under CCD. As with CBD, the observations relevant to monitor changes in biological conditions (flora/fauna, including microflora/fauna to vegetation), soil changes, land use and climate are relevant. Systematic observations will focus on the cold and warm dry areas;

- CCC has obviously the broadest observation requirements of the three conventions, in terms of the "list" of variables (from purely physical to vegetation), frequency of observation (instantaneous - at the scale of seconds, for instance some fluxes of CO2 -, to annual) and finally geographic coverage (all land, oceans, all climates, urban and "natural" areas, etc.). With the exception of the detailed biological analyses required by CBD and (to some extent, by CCD), as well as the exception of detailed soil observations needed by CCD, it is safe to assume that the observations under CCC will encompass those needed by the other Rio Conventions.

To summarise the bullets above, we can tentatively categorise the joint observation requirements of the Rio conventions as follows:

- **climate** as a factor of species richness; climate variability (including "extreme" factors) and change as a factor contributing to or driving many other changes and loss of resources;
- **ecosystem** biological composition and eco-physiology (functional aspects), including soil characteristics and land use as major indicators of biodiversity and land degradation (changes)
- **detailed maps of carbon pools and fluxes**, including such variables as vegetation, living and dead soil biomass, the atmosphere etc. Interestingly, carbon is highly relevant to all Rio conventions. When considered under CBD, it carries much information about soil biodiversity, and the fluxes are linked to the intensity of the biological processes occurring in the ecosystems. For CCD, spatial and temporal variations of soil carbon provide a major indicator of soil resilience against degradation processes, soil biological activity as well as degradation itself[7]. Finally, for CCC, carbon constitutes the yardstick against which the implementation of UNFCCC and the Kyoto protocol will be measured.

4. Conclusions

The three Rio Conventions have largely overlapping observation requirements covering the spectrum from purely biological/ecological measurements to purely geophysical ones. Unfortunately, beyond the recognition of the relevance of systematic observations there is little co-ordination between the Conventions as yet regarding operational details.

It appears that CCC is the most advanced convention in terms of (1) existing background observations and networks (e.g. forest and agricultural statistics, GTOS/GCOS/GOOS, FLUXNET), (2) comprehensiveness of the variables to be observed, (3) the practical arrangements made for the observations and (4) legal commitment of Parties to carry out systematic observations.

Most observations to be made under CCC and the Kyoto Protocol will be of immediate relevance to the other conventions; it appears that carbon constitutes one of the very "central" variable that will provide a *de facto* common denominator between the observations carried out under the three Rio Conventions.

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[7] Soil carbon is a major constituent of soil colloids which play a role in maintaining soil structure as well as adsorbing nutrients. As such, loss of soil carbon is a good indicator of soil degradation.

Terrestrial Carbon Data Needed to Implement the Kyoto Accords

Allen M. Solomon

The Kyoto Accords specify that Annex I countries (mostly, the developed countries) will use as part of their commitments to reduce greenhouse gas emissions, "the net changes in greenhouse gas emissions resulting from direct human induced land use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in stocks in each commitment period [to date, 2008-2012]. However, there are no clear data requirements at this time. The Conference of Parties (COP) will query its Subsidiary Body for Scientific and Technical Advice (SBSTA) to decide how to define carbon removals (sequestration) and emissions from land use and forestry in late fall of 2000. The information SBSTA will use is in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Land Use, Land Use Change, and Forestry, which is scheduled for delivery to SBSTA-11 on June 12. Until then, there is no way to predict what information will be needed. Instead, we can only speculate, based on the ambiguous language of the Kyoto Accords.

The IPCC and FAO definitions of forests and afforestation, reforestation and deforestation (ARD) provide a good starting point if SBSTA and COP decide to aim for the best estimates of carbon actually being sequestered and released from land use, land use change and forestry.

1. The IPCC definition of forests includes 10% canopy cover and 5 M height. Deforestation reflects a change in land use (e.g., to agriculture, urban land, etc.) as does afforestation and reforestation (e.g. from agriculture, urban land, etc.). Consequently, normal harvest and replanting cycles are considered to be "forest management" and not included as Kyoto lands which must be measured. Note then that detection of changed land cover (e.g., from forested to non-forested) requires a ground survey to determine if the change is due to forest management or to changed land use, and if not forest management, then is it natural (e.g., insect infestations, wildfire, etc.) or direct human induced change.
2. The FAO definition of forests also includes 10% canopy cover and 5 M height. However, the FAO definition (i.e., most of the several definitions used in different FAO reports) makes no distinction between cover loss to forest management or to changed land use; deforestation is loss of forest cover, reforestation is regeneration of forest cover, and afforestation is generation of forest cover where it has not previously existed. Hence, the FAO definition would be much easier to implement in a remotely-sensed observations system, as there is no need to verify on the ground whether forest management was involved in any measured change. There is still the need to verify whether forest cover loss is directly human induced or not. FAO and IPCC definitions have been applied to areas of as little as 0.01 ha, more normally 0.5 to 1.0 ha, and occasionally at 1 km^2.
3. A carbon density definition (e.g., 50 Mt/ha of woody biomass at least 5 M tall per unit area) could produce the most accurate measure of above ground carbon, but is probably not possible with current statistics, though most Annex I countries probably could generate the statistics. Introduction of remotely-sensed carbon densities must be a high priority for instrument development, however, if the Annex II countries are to be included in Kyoto land estimates which would be permitted by the Accords Article 6 (carbon trading). The need for ground survey data would still remain to establish and "verify" land uses and/or forestation change causes.
4. Finally, it must be remembered that a land administration (land use) definition could be implemented with little or no requirement for carbon observations. Here, land could simply be defined by governments as forest land use or not; if forested (whether or not forests actually existed), annual losses of forest to deforestation and gains to regeneration could be reported on a national level. Average above and below ground carbon measured at several sites could be used to calculate carbon per unit area. Indeed,FAO now has the data bases (measurements at 5 or 10-year intervals, defined as per annum values) to do so, including subdivisions of deforested land, reforested land, harvested land, etc. They also have the statistics needed to transform the areal estimates into carbon values based on volume measures.

In sum, the range of possible carbon observation requirements is very wide, although it appears to include estimates of canopy cover at 0.5-1.0 ha spatial units, annual changes in carbon densities, and identification of cause of changes as being either direct human induced or not (with the definition of "direct human induced" not yet confirmed).

Understanding the Terrestrial Carbon Cycle

Christopher Potter

The Earth's carbon cycle comprises global interactions among the solid earth, the oceans, the atmosphere, the land surface, the terrestrial biosphere, and human society. These interactions can strongly influence regional climate, food supply, and quality of the environment. At least two major factors govern the level of terrestrial carbon storage and flux. First is the anthropogenic alteration of the Earth's surface, such as through the conversion of forest to agriculture, which can result in a net release of CO2 to the atmosphere. Second, and more subtle, are the possible changes in net ecosystem production (NEP; and hence carbon storage) resulting from changes in atmospheric CO2, other global biogeochemical cycles, and/or the physical climate system.

There are several prominent but poorly understood features of the global carbon cycle that justify the effort to better observe changes on regional-to-global levels, through cooperation of the international scientific community. It appears that human-kind has emitted at least 340 Pg C (1 Pg = 10^15 g) of carbon to the atmosphere since 1850, with about 220 Pg C by fossil fuel burning and cement production, and 122 Pg C by changes in land use. The fraction of this that we can most easily measure directly is the 42% that has remained in the atmosphere. Ocean circulation models give an estimated uptake of 30% of the total, for which there is some weak observational evidence. The remaining 28% is presently unaccounted for in global budgets, although the terrestrial biosphere is thought to be the a prime candidate for this "missing" carbon sink. However, direct observational evidence is incomplete and the proposed source-sink mechanisms are highly controversial.

Owning to the scope and complexity of the problem, study of the terrestrial carbon cycle is carried out commonly using computer simulation models. Models are used to interpret field data, test theories about flux mechanisms, and make predictions of the future carbon cycle. Such ecosystem-based models must take into account global and regional energy and water budgets, sources and sinks of carbon and other biogeochemical cycles, precipitation patterns, effects of surface temperature, wind speed and direction, land cover and land use patterns, speed and direction of oceanic currents, and changes in so-called 'greenhouse gas' concentrations.

The complexity of carbon cycle models requires vast amounts of timely data assimilation from different observational sources over a relatively long periods, supported by advanced data and information systems. Many ecosystem carbon modeling procedures have strong links to field experiments, which help focus the experiments and aid in analysis of observations. Observational and experimental data assimilation and retrieval techniques are used to characterize sensitivity of model errors. Major obstacles to studies of the carbon cycle continue to be our limited ability to observe the spatial and temporal distribution of the principal global sources and sinks. Recent application of three dimensional oceanic and atmospheric general circulation models to our study of the carbon cycle offer the possibility of dramatic improvement in our ability to identify, understand, and predict the principal sources and sinks.

Atmospheric transport models, using a "top-down" approach, are constrained by CO2 observations, which may eventually make it possible to determine the specific location of the atmospheric source (or reduced uptake). From the atmospheric perspective, model simulations have suggested that the large increase in atmospheric carbon that occurs during El Niños is due to the collapse of the Southeast Asian monsoon (C-13 observations indicate that the signal is terrestrial). This type of ENSO event would reduce photosynthetic uptake by land plants, and modify the balance between uptake and decay of organic matter in soils, temporarily favoring the latter source flux.

There are now several comparable model predictions of terrestrial net biosphere production (NBP) from both the global "top-down" atmospheric inversion method and the "bottom-up" ecosystem model approach (Figure 1.). Based on preliminary comparisons, there are some interesting differences within and between the two types of predictions for NBP over time, including temporal offsets of at least six months one way or the other, and different flux magnitudes during strong ENSO events. A crucial improvement in the "bottom-up" ecosystem model approach will be the inclusion of mechanistic disturbance models, which can capture the loss of gain of carbon resulting from natural and anthropogenic alterations in terrestrial carbon pools over regional areas, generating estimates of global NBP in addition to NEP.

For detecting potential changes in terrestrial ecosystems over the past 20 years, satellite observations of vegetation greenness have been used to monitor the duration of the active growing season for terrestrial vegetation· Longer growing seasons are apparent, particularly in areas of the northern high latitudes (between 45^{o} N and 70^{o} N), where notable warming has occurred in the spring. These satellite observations also appear to be consistent with an increase in amplitude of the seasonal cycle of atmospheric CO_2 since the early 1970s.

Working further from the "bottom-up" perspective of terrestrial ecosystems, integrated climate and biophysical regulation of terrestrial plant production and interannual responses to anomalous events have been investigated, for example, using the NASA Ames model version of CASA (Carnegie-Ames-Stanford Approach) in a multi-year simulation mode. This ecosystem model has been calibrated for simulations driven by satellite vegetation index (NDVI) data from the NOAA Advanced Very High Resolution Radiometer (AVHRR). Relatively large net source fluxes of carbon are estimated from terrestrial vegetation about six months to one year following major El Nino events. Zonal discrimination of model results implies that the northern hemisphere low-latitudes could account for large decreases in global terrestrial net primary production (NPP). Model estimates further suggest the northern middle-latitude zone (between 30^{o}. and 60^{o}. N) has been the principal region driving progressive increases in NPP, mainly by an expanded growing season moving toward the zonal latitude extremes. In many cases, variability in seasonal precipitation controls the NEP of carbon on a yearly basis.

Several noteworthy enhancements in the global observing systems are of utmost importance for improving the reliability of terrestrial ecosystem carbon models:

4. Continuity and integration of satellite observations for key land surface parameters, such as leaf area and fraction absorbed of photosynthetically active radiation (FPAR), plus annual areas of forest clearing and regrowing.
5. Accurately interpolated precipitation fields for model drivers, at daily and monthly time intervals.
6. Understanding the effects of natural and anthropogenic disturbance on processes represented in ecosystem carbon models.
7. Improvement of remote and near-sensing technologies for vegetation biomass and forest stand structural attributes.
8. Integrating results from elevated CO2 experiments into scalable algorithms at the ecosystem level, including below-ground responses.
9. Understanding the effects of early spring thaw and late season freeze on processes represented in cold ecosystem carbon models.

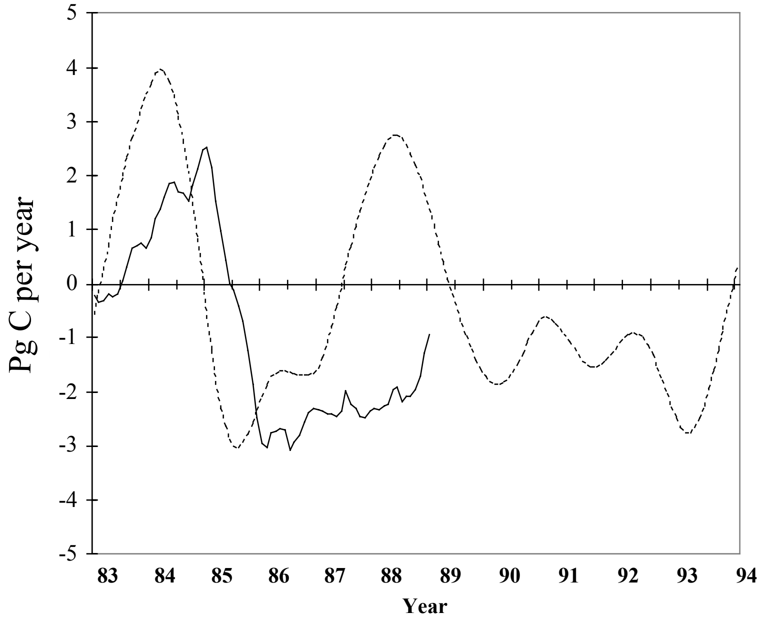

Figure 1. NASA-CASA model estimate (solid line) of global ecosystem carbon exchange with the atmosphere, compared to terrestrial biosphere flux of carbon recomputed from isotopic (δ^{13}C) deconvolution data (Keeling et al., 1995; dashed line). Running 12-month totals are plotted. Positive yearly mean values represent a net source flux from the biosphere to the atmosphere, whereas negative yearly values represent a net sink flux into the biosphere from the atmosphere.

Climate-Related Global Observation Requirements for Terrestrial Carbon: results of TOPC analysis

Josef Cihlar

The Terrestrial Observation Panel for Climate (TOPC) has been set up jointly by the Global Terrestrial Observing System (GTOS) and the Global Climate Observing System (GCOS). Its principal responsibilities are to plan, formulate and design a long-term systematic observing system for those terrestrial properties that control the physical, biological and chemical processes affecting climate, are affected by climate change, serve as indicators of climate change, or are essential to provide information concerning the impact of climate and climate change; and to contribute to the implementation of such an observing system. TOPC is composed of scientists from various continents and representing the principal domains of the terrestrial environment.

A principal task addressed by TOPC has been the design for global terrestrial observations. The revised plan (GCOS, 1997) considered the scientific and policy issues regarding the role of climate for terrestrial biosphere, hydrology, and cryosphere. Based on these, observation requirements were specified, and approximately 70 variables described in terms of observation needs, spatial and temporal resolution, observation methods, and other aspects. These requirements were to cover all the important issues, and thus are not necessarily optimised for a specific purpose such as terrestrial carbon. However, the global carbon cycle is one of the important issues considered and thus the results of TOPC analysis are relevant; in addition, the analysis provides a context for the relations between carbon and other climate change-related observation requirements. This note therefore briefly summarises some aspects of the TOPC analysis thought relevant to global terrestrial carbon observations.

The key issue considered by TOPC with respect to the terrestrial carbon was climate impact on the biosphere and feedbacks to climate. Climate affects the distribution and productivity (C uptake) of vegetation, together with the vegetation influences carbon in soils, and also affects the feedback from the two pools to climate. These interactions take place at various spatial and temporal scales. Locally, soil, topography and land use history combine to determine productivity and distribution of vegetation and the land use options. Carbon, nitrogen, phosphorus and sulphur cycles are most important because they are involved in emissions of GHGs (CO_2, CH_4, N_2O; ozone precursors such as NO, CO and NMVOC; and aerosols) and via the land surface characteristics such as biomass and leaf area which are constrained by biogeochemical considerations. Since biogeochemical cycling is strongly influenced by climate, this constitutes one of the major avenues for both impacts and feedbacks. In addition, all terrestrial water balance terms are affected by, and serve as, feedbacks to the climate system. The fluxes of CO_2 are largely controlled by photosynthesis and respiration (autotrophic and heterotrophic), and by variables constraining these processes. Because of the complexity of the various interactions, it is difficult to separate vegetation structure and processes of productivity from the atmospheric, soil, and hydrological processes produced by changes in land cover and land use.

To help define observation requirements in a manner that would facilitate the planning of satellite missions, the steps from raw measurements to final information were considered to fall into one of four categories (Figure 1): a) target (final information for an application or an important stand-alone data set for an application (e.g., net primary productivity)); b) input (variable needed as an input into an 'earth system model', a generic term referring to models which produce target variable (e.g., leaf area index)); c) ancillary (variable used to specify/correct measured variable (e.g., atmospheric optical depth)); and d) measured (variable actually measured (e.g., spectral radiance)). Given this typology and the specifications of the Committee of Earth Observation Satellites (CEOS), each observation was specified in terms of Optimised and Threshold spatial resolution, temporal resolution (revisit cycle), the timeliness of product delivery after acquisition, and accuracy (in nominal terms most often). These specifications, compiled in tabular form, were also used to update the CEOS database maintained by the World Meteorological Organisation. Table 1 shows part of the database, considered most relevant to terrestrial carbon observations.

Table 1. Terrestrial observation requirements*

		OPTIMIZED				THRESHOLD			
Type	TARGET VARIABLE	Hor Res	Cycle (d,m,y)	Timeliness	Accuracy	Hor Res	Cycle (d,m,y)	Timelines	Accuracy
Target	**Land cover**	**0.1km**	**1y**	**3m**	**50 classes**	**1 km**	**10y**	**1y**	**20**
Target	**Land use***	**0.1km**	**1y**	**6m**	**>100 classes**	**1km**	**10y**	**1y**	**5 classes**
Target	**Net ecosystem productivity (NEP)***	**1km**	**1d**	**annually**	**+10% for a**	**1 km**	**1y**	**3y**	**+20%**
Target	**Net primary productivity (NPP) sattellite**	**0.1km**	**1d**	**10d**	**+10%**	**1km**	**10d**	**1y**	**+30%**
Target	**Canopy conductance - maximum**	**1km**	**10y**	**1y**	**+ 10%**	**1km**	**20y**	**2y**	**+20%**
Target	**Biogeochemical transport from land to oceans**	**10km**	**1d**	**10d**	**+ 10%**	**100km**	**1y**	**1y**	**+30%**
Target	**Biomass - total**	**0.1km**	**1y**	**3m**	**+5%**	**1km**	**10y**	**1y**	**+20%**
Target	**Dissolved C, N, and P in water (rivers and lake**	**10km**	**1d**	**river depe**	**+ 5%**	**100km**	**1y**	**1y**	**+30%**
Target	**Dry deposition of NO3, SO4**	**1km**	**1m**	**7d**	**+10%**	**50km**	**1y**	**1y**	**+30%**
Target	**Emissions of CO2, NOx and SOx from combust**	**10km**	**1m**	**1y**	**+10%**	**country**	**4y**	**4y**	**+20%**
Target	**Fire area**	**0.1km**	**10d**	**1m**	**+10%**	**1km**	**1y**	**3m**	**+20%**
Target	**Fire intensity**	**0.1km**	**10d**	**1m**	**+20%**	**1km**	**1y**	**3m**	**+40%**
Target	**Methane flux (CH4), modelled**	**0.1km**	**1d**	**6m**	**+15%**	**10km**	**1y**	**1y**	**+30%**
Target	**Ground water storage fluxes**	**Tier 1,2,3,4**	**1y**	**Annually**	**1% of true**	**Tier 1,2,3,4**	**1y**	**Annually**	**+ 10%**
Target	**Soil moisture**	**Tier 1,2,3**	**1d**	**3d**	**+ 2%**	**Tier 1,2,3**	**5d**	**5d**	**+ 10%**
Target	**Surface water flow - discharge**	**Tier 1,2,3,4**	**0.01d**	**1d**	**+ 5%**	**Tier 1,2,3**	**30d**	**30d**	**+20%**
Target	**Surface water storage fluxes**	**50 largest lakes**	**10d**	**1m**	**+ 2%**	**30 largest lak**	**90d**	**3m**	**+ 5%**

		OPTIMIZED				THRESHOLD			
Type	INPUT VARIABLE	Hor Res	Cycle (d,m,y)	Timeliness	Accuracy	Hor Res	Cycle (d,m,y)	Timelines	Accuracy
Input	**Precipitation - accumulated (solid and liquid)**	**1km**	**0.04d**	**1d**	**<+0.1mm**	**10km**	**0.05d**	**1d**	**+0.1mm**
Input	**Radiation - fraction of photosynthetically activ**	**0.1km**	**10d**	**10d**	**+0.05**	**2km**	**30d**	**10d**	**+0.1**
Input	**Radiation - incoming short-wave satellite**	**50km**	**10d**	**10d**	**+ 2%**	**100km**	**40d**	**1m**	**+7%**
Input	**Radiation - outgoing long-wave in situ**	**Tier 1,2,3**	**0.01d**	**1d**	**+ 1%**	**Tier 1,2,3**	**10 miute mea**	**5d**	**+ 2%**
Input	**Relative humidity (atmospheric water content**	**Tier 1,2,3 & w**	**0.04d**	**1d**	**+ 1%**	**Tier 1,2,3 an**	**0.04d**	**3d**	**+ 2%**
Input	**Temperature - air**	**Tier 1,2,3 & w**	**0.02d**	**1d**	**+ 0.2C**	**Tier 1,2,3 an**	**0.5d**	**2d**	**+ 0.5C**
Input	**Volcanic sulphate aerosols**	**At source**	**continuous du**	**1d**	**+10%**	**At source**	**5d during eve**	**1m**	**+ 20%**
Input	**Wind velocity**	**Tier 1,2,3**	**continuous**	**1d**	**+ 10%**	**Tier 1,2,3**	**hourly max a**	**10d**	**+ 15%**
Input	**Snow depth**	**Tier 1,2,3 & w**	**1d**	**1d**	**+2cm up to**	**Tier 1,2,3 an**	**10d**	**5d**	**+3cm up**
Input	**Biomass - above ground**	**0.1km**	**1y**	**3m**	**+5%**	**1km**	**10y**	**1y**	**+ 20%**
Input	**Biomass - below ground**	**0.1km**	**1y**	**3m**	**+5%**	**1km**	**10y**	**1y**	**+ 20%**
Input	**Evapotranspiration**	**Tier 1, 2**	**0.5h**	**1m**	**+ 5%**	**Tier 1,2**	**1d**	**1y**	**+ 20%**
Input	**Land cover**	**0.1km**	**1y**	**3m**	**50 classes**	**1km**	**10y**	**1y**	**20 classes**
Input	**Leaf area index (LAI)**	**0.1km**	**10d**	**10d**	**+ 0.2**	**1km**	**10d**	**1y**	**+ 1**
Input	**Methane flux (CH4), in situ**	**100 sites**	**1d**	**6m**	**+5%**	**30 sites**	**1y**	**1y**	**+15%**
Input	**Necromass**	**Tier 1,2,3**	**1y**	**1m**	**+5%**	**Tier 1,2,3**	**10y**	**1y**	**+ 20%**
Input	**Net ecosystem productivity (NEP) tower**	**150 sites**	**continuous**	**10d**	**+5%**	**80 sites**	**continuous**	**1m**	**+10%**
Input	**Net primary productivity (NPP) in situ biomas**	**Tier 1,2,3**	**10d**	**3m**	**+10%**	**1km**	**1y**	**2m**	**+10%**
Input	**Peak leaf biomass of nitrogen-fixing plants**	**Tier 1,2,3**	**1y**	**3m**	**+5%**	**Tier 1,2,3**	**5y**	**1y**	**+15%**
Input	**Plant tissue nitrogen and phosphorus content**	**Tier 1,2,3**	**10d**	**3m**	**+5%**	**Tier 1,2,3**	**5y**	**1y**	**+15%**
Input	**Rooting depth - 95%**	**Tier 1,2,3,4**	**5y**	**1y**	**+5%**	**1km**	**10y**	**2y**	**+10%**
Input	**Soil available phosphorus**	**Tier 1,2,3,4**	**1y**	**6m**	**+ 5%**	**1km**	**10y**	**1y**	**+ 10%**
Input	**Soil bulk density**	**Tier 1,2,3,4**	**10y**	**2y**	**+ 5%**	**1km**	**20y**	**3y**	**+ 10%**
Input	**Soil cation exchange capacity**	**Tier 1,2,3,4**	**10y**	**2y**	**+ 5%**	**1km**	**20y**	**3y**	**+ 10%**
Input	**Soil particle size distribution**	**Tier 1,2,3,4**	**10y**	**2y**	**+ 5%**	**1km**	**20y**	**3y**	**+ 10%**
Input	**Soil pH**	**Tier 1,2,3,4**	**1y**	**6m**	**+ 5%**	**1km**	**10y**	**1y**	**+ 10%**
Input	**Soil temperature (subsurface)**	**Tier 1,2,3,weat**	**10d**	**1m**	**+ 5%**	**Tier 1,2,3,we**	**1m**	**3m**	**+ 10%**
Input	**Soil total carbon**	**Tier 1,2,3,4**	**1y**	**2y**	**+ 5%**	**1km**	**10y**	**3y**	**+ 10%**
Input	**Soil total nitrogen**	**Tier 1,2,3,4**	**1y**	**2y**	**+ 5%**	**1km**	**10y**	**3y**	**+ 10%**
Input	**Soil total phosphorus**	**Tier 1,2,3,4**	**1y**	**2y**	**+ 5%**	**1km**	**10y**	**3y**	**+ 10%**
Input	**Spectral vegetation greenness index**	**0.1km**	**1d**	**1d**	**+ 1%**	**2km**	**1d**	**10d**	**+ 3%**
Input	**Vegetation structure**	**Tier 1,2,3**	**1y**	**6m**	**+ 5%**	**Tier 1,2,3**	**10y**	**1y**	**+ 10%**
Input	**Fertilizer use (N and P)**	**Sub-national**	**1y**	**1y**	**+5%**	**National**	**2y**	**1y**	**+10%**
Input	**Dry deposition of NO3, SO4 in situ***	**200 sites**	**1d**	**1y**	**+10%**	**100 sites**	**1y**	**1y**	**+25%**
Input	**Methane flux (CH4)**	**100 sites**	**1d**	**6m**	**+ 5%**	**30 sites**	**1y**	**1y**	**+15%**
Input	**Soil surface state**	**Tier 1,2,3,4**	**1y**	**6m**	**+ 5%**	**Tier 1,2,3,4**	**10y**	**1y**	**+ 10%**
Input	**Topography**	**0.01km**	**10y**	**2y**	**+ 3%**	**1km**	**30y**	**5y**	**+ 10%**

		OPTIMIZED				THRESHOLD			
Type	ANCILLARY VARIABLE	Hor Res	Cycle (d,m,y)	Timeliness	Accuracy	Hor Res	Cycle (d,m,y)	Timelines	Accuracy
Ancillar	**Aerosols (total column)??or transmissivity mea**	**1km**	**1d**	**10d**	**TBD**	**4km**	**2d**	**1m**	**TBD**
Ancillar	**Aerosols In situ**	**Tier 1,2,3**	**continuous**	**1d**	**+5%**	**Tier 1,2,3**	**Hourly**	**5d**	**TBD**
Ancillar	Cloud cover	Tier 1,2	0.01d	1d	+10%	Tier 1,2	0.04d	5d	+ 15%
Ancillar	**Cloud cover satellite**	**1km**	**0.02d**	**1d**	**+5%**	**10km**	**0.5d**	**10d**	**+10%**
Ancillar	**Radiation - incoming short-wave in situ**	**Tier 1,2,3**	**continuous**	**1d**	**+ 1%**	**Tier 1,2,3**	**0.01d**	**30d**	**+ 1%**
Ancillar	**Radiation - reflected short-wave in situ**	**Tier 1,2,3**	**continuous**	**1d**	**+ 1%**	**Tier 1,2,3**	**0.01d**	**30d**	**+ 1%**
Ancillar	Snow surface state	10km	1d	2d	6classes	25km	3d	3d	2 classes
Ancillar	Snow water equivalent (SWE) in situ	Tier 1,2,3,surfac	1d	2d	+ 5%	Tier 1,2,3,surf	30d	3d	+ 15%
Ancillar	Vegetation hydric stress index	0.1km	0.04d	1d	+10%	4km	1d	2d	+ 20%
Ancillar	Decomposition rate	Tier 1,2,3	30d	30d	+10%	Tier 1,2,3	60d	30d	+ 15%
Ancillar	**Fire type**	**0.25km**	**1y**	**1m**	**6classes**	**1km**	**3y**	**3m**	**2classes**
Ancillar	**Ozone (total column)**	**1km**	**1d**	**10d**	**TBD**	**8km**	**2d**	**1m**	**TBD**
		OPTIMIZED				THRESHOLD			
Type	MEASURED VARIABLE	Hor Res	Cycle (d,m,y)	Timeliness	Accuracy	Hor Res	Cycle (d,m,y)	Timelines	Accuracy
Measure	**Microwave backscatter**	**0.01km**	**1d**	**1d**	**+0.2dB**	**1km**	**2d**	**10d**	**+ 0.6dB**
Measure	**Radiation - outgoing long-wave satellite (multis**	**0.01km**	**1d**	**1d**	**TBD**	**2km**	**2d**	**1m**	**TBD**
Measure	**Radiation - reflected short-wave satellite (multi**	**0.01km**	**1d**	**1d**	**TBD**	**1km**	**2d**	**1m**	**TBD**

* Refer to text for explanation of terms (TOPC, 1998).

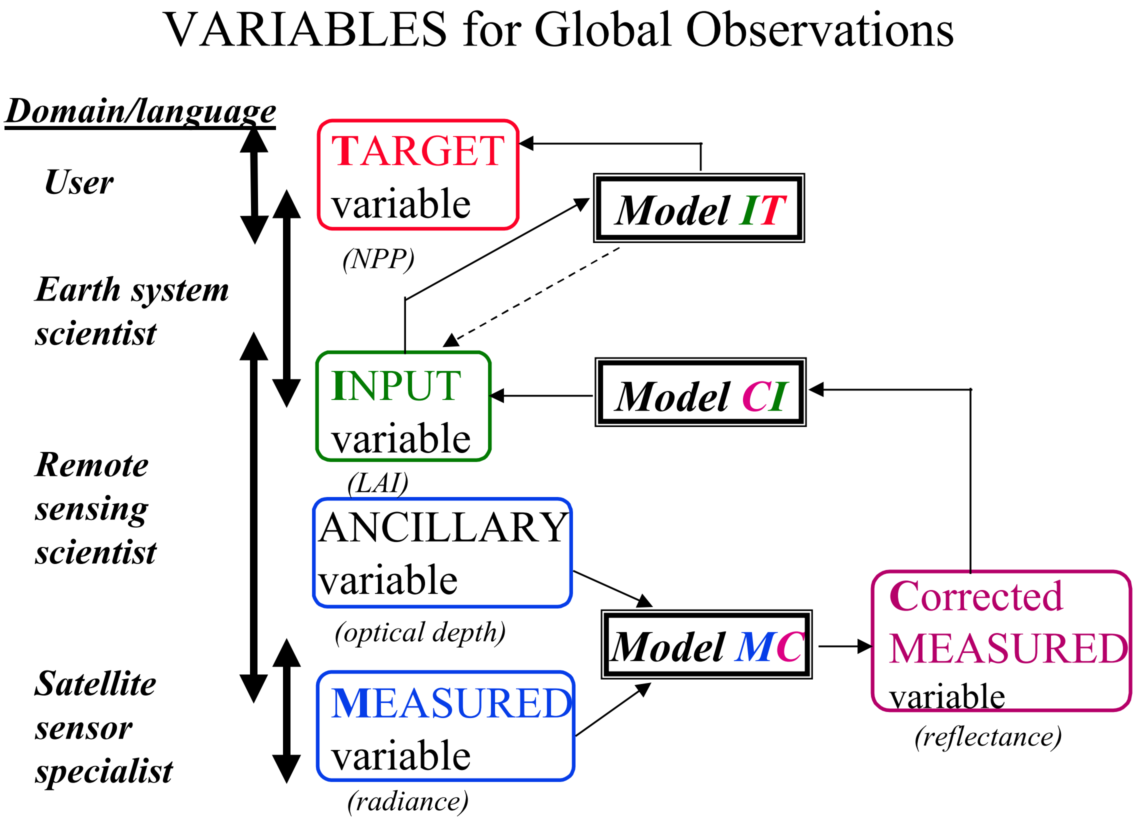

Figure 1. A scheme for defining variables for global observations. An example is given for new primary productivity (NPP), with leaf area index (LAI) as a model input variable. M, C, I and T represent measured, ancillary, input and target, respectively.

References

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TOPC. 1998. Report of the GCOS/GTOS Terrestrial Observation Panel for Climate, Fourth session, 26- 29 May 1998, Corvallis, USA, GCOS-46/GTOS – 15: http://www.fao.org/GTOS/PAGES/DOCS.HTM.

The Australian Carbon Cycle Project

Michael Raupach

Part 1: Biogeochemical Cycles on the Australian Continent: On global maps of terrestrial precipitation and runoff, Australia is clearly drier than the terrestrial average and experiences much less runoff. Climate variability is also high and strongly influenced by ENSO. Australia also has ancient, weathered, leached regoliths with characteristically low soil nutrients, especially P. These factors influence the NPP for Australia, estimated at about 1 GtC/yr by Barrett (2000) using vegetation data from 185 sites together with continental climate and soil surfaces (Figure 1). This is much lower than the NPP that would be expected on the basis of a pro-rata share by area of the global terrestrial NPP. (The global terrestrial NPP is around 55 GtC/yr; Australia is 5.0% of the terrestrial surface area of the globe; a pro-rata estimate would imply an Australian NPP of about 2.8 GtC/yr).

From the standpoints of national need and funding, Australian BGC research is motivated by multiple, overlapping agendas. These include

- the need to understand and manage the terrestrial carbon cycle and its implications for greenhouse warming and associated international obligations;
- the need to understand, manage and mitigate landscape degradation due to salinity and various forms of soil degradation, associated mainly with land clearing and the replacement of native vegetation with European-style agricultural systems;
- the links between biophysical landscape changes and human factors including economic, social and cultural viability.

Part 2: Overview of Australian Carbon Cycle Project: In the context of all the above drivers but especially the first, the project seeks to (1) increase understanding the interaction between the terrestrial biosphere and the atmosphere, particularly the role of the biosphere in the cycles of greenhouse gases (carbon dioxide, methane, nitrous oxide and others), and (2) develop new techniques for monitoring biospheric sources and sinks of greenhouse gases at local to continental scales, in support of both present inventory requirements and future requirements for full greenhouse gas budgets.

The crucial principle is the combination of measurements and models across a wide range of scales, within a synthesis framework. Key measurements include (1) stores and changes in biomass and soil carbon, determined by new methods and sampling strategies; and (2) new methods for interpreting biospheric signals in remotely sensed data; (3) land-air fluxes of greenhouse gases at local scales, using new instrumentation capable of long-term measurements; and (4) atmospheric concentrations of greenhouse gases, using new sensors with unprecedented accuracy and mobility. Models (of the terrestrial biosphere, landcover dynamics and atmospheric circulation) provide a means of spatially extrapolating small-scale measurements, within constraints imposed by large-scale measurements. A synthesis of all these techniques promises efficient, long-term, globally consistent quantification and monitoring of sources and sinks at regional and continental scales.

Part 3: Details of Observational Program:

(a) *Atmospheric Concentration Observations:* The Cape Grim Baseline Atmospheric Observation Station in Tasmania (see Figure 2 for locations) has acquired continuous records of the atmospheric concentrations of up to 100 species for two decades or more.

Important developments under way include the following: (1) Several new sites are under development for continuous observation of CO_2 and a small set of other gases, including potential sites near at Charles Point near Darwin (already active), at the Bago-Tumbarumba flux tower site, and shipboard observations. An objective analysis of site locations is also under way. (2) A low-flow CO_2 analyser based on a commercial Licor is now in prototype form. Improvements to temperature, pressure and flow control offer continuous measurements with low demands on calibration gases, repeatability of 0.01 ppm, and the prospect of deployment at much less actively maintained sites than is possible at present. The developers are Paul Steele and Grant Da Costa, CSIRO Atmospheric Research. (3) The GLOBALHUBS project for global intercalibration of long-term atmospheric concentration records is being designed by a team led (in Australia) by Roger Francey, CSIRO Atmospheric Research.

(b) *Flux Measurements:* A remote flux station for eddy covariance measurements of the land-air fluxes of CO_2, water, heat and momentum has been designed over the last two years and from October 1999 has been undergoing field tests at Wagga Wagga, NSW. This equipment is currently being deployed at a flux tower over

Eucalypt forest (50 m tall) in Bago State Forest, near the town of Tumbarumba, NSW (annual rainfall about 1000 mm). This is to be a long-term flux tower site and will be associated with many other measurements of atmospheric concentrations, biomass and soils. The leaders of the flux measurements are Ray Leuning and Helen Cleugh, CSIRO Land and Water.

Other flux measurement locations are in planning, including tropical rainforest in the Daintree region (Qld) and savannah in the Victoria River region (NT).

(c) *Vegetation and Soil Measurements:* Several groups from both CSIRO and the CRC for Greenhouse Accounting are undertaking measurements on biomass changes and soil carbon stores and fluxes. Details are available in the Strategic Plans of the CSIRO Biosphere Working Group and the CRC for Greenhouse Accounting, both soon to be released on the Web. While some of these studies are undertaken for accounting and inventory applications, the data they provide is potentially a valuable constraint in a TCOS.

(d) *Remote Sensing:* The workhorse of the program remains the multi-decadal AVHRR record. Much effort is going into calibration and validation, including the maintenance of well-instrumented remote validation ground sites at Tinga Tingana (high albedo) and Lake Argyle (low albedo). These will be important for more modern sensors also.

Uptake of new developments, especially in VCL and SAR technologies, is also anticipated. Opportunities for collaboration through ground-based validation at well-instrumented sites (such as Bago-Tumbarumba) are being sought.

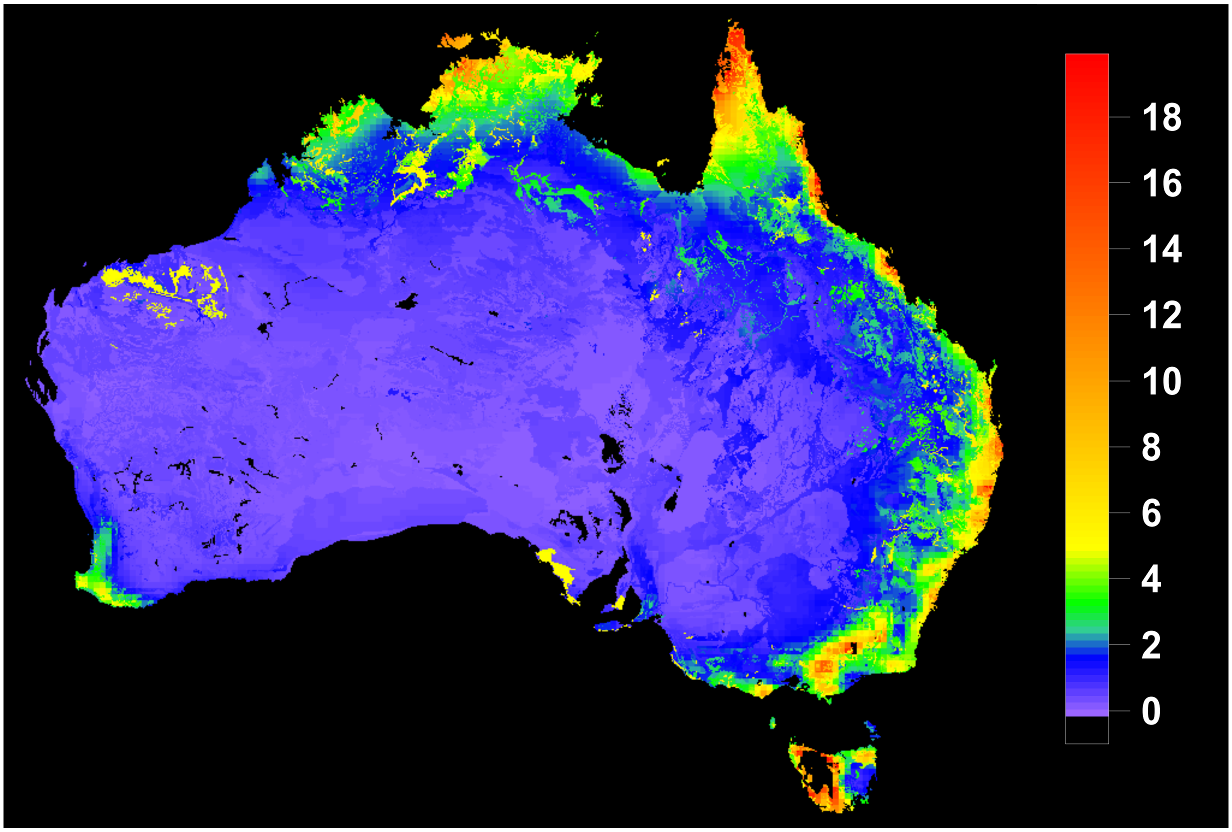


Figure 1: steady-state NPP for Australia derived from 185 measurement sites and surfaces of mean annual precipitation, mean annual temperature and soil nutrient status. [Reference: Barrett, D.J. (2000), Steady state net primary productivity, carbon stocks and mean residence time of carbon in the Australian terrestrial biosphere. *Global Biogeochemical Cycles*, submitted.]

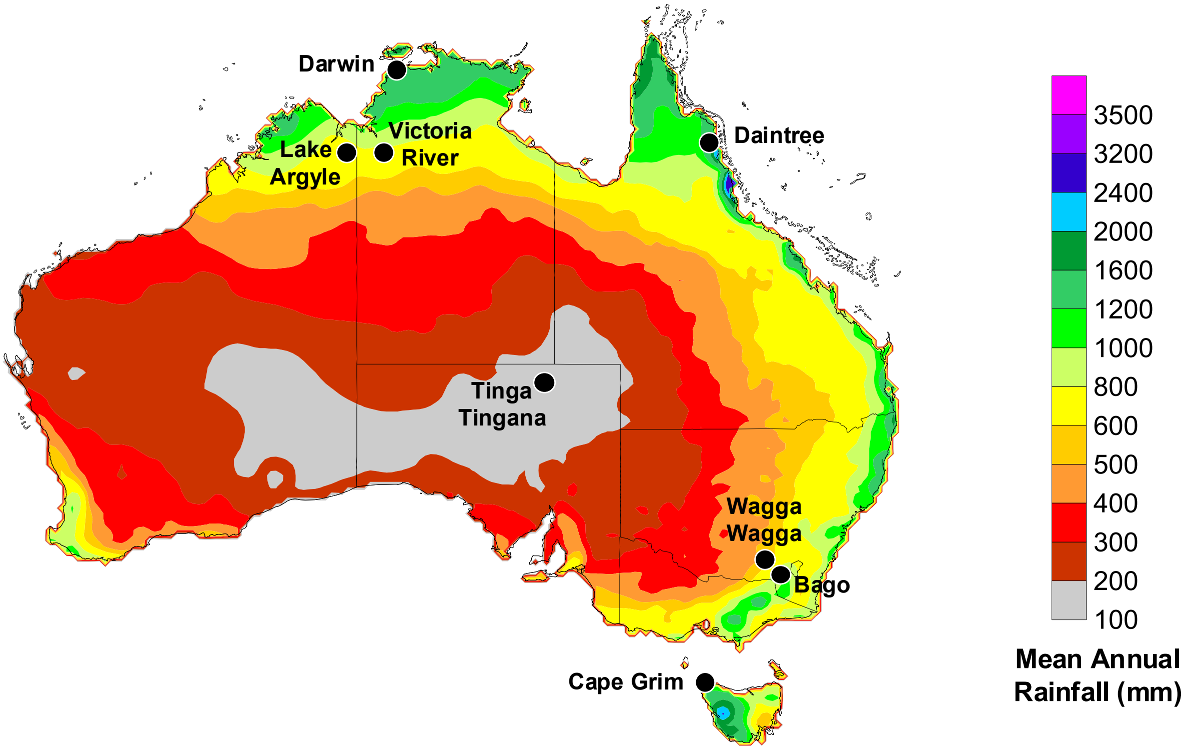


Figure 2: Location map, also showing mean annual rainfall.

Canadian Terrestrial Carbon Cycle Research and Observation Requirement: A Bottom-up Perspective

Jing Chen and Josef Cihlar

Estimation of the spatial distribution of carbon sinks and sources in Canada's forests was recently made at the Canada Centre for Remote Sensing through integrating satellite data with climate, soil and forest disturbance data. The major steps and data types used in the estimation is summarized in Figure A1. Satellite spectral measurements were first used for landcover mapping and leaf area index (LAI) retrieval. Net primary productivity (NPP) in a calibration year was calculated based on the landcover and LAI information as well as soil texture data using a process-based canopy model (BEPS) driven by daily meteorological data (Liu et al., 1999, Chen et al., 1999). The canopy model is integrated with a soil carbon and nitrogen cycle model (modified Century) to study the long-term effects on the forest carbon cycle of climate change (temperature and precipitation), atmospheric change (CO_2 concentration and nitrogen deposition), and disturbances (fire, inset, harvest) (Chen et al., 2000a). This integrated model is applied to a Canada-wide NPP map in a calibration year to estimate the spatial distribution of net ecosystem productivity (NEP) (Figure A2). In this NEP map calculation, gridded annual climate data for the last 100 years and forest age information estimated using the French satellite sensor VEGETATION were used. Major features in this NEP map are (i) large spatial variations corresponding to fire scar ages and forest types and (ii) the strong south-north gradient due to different effects of climate warming at different latitudes. On average, NEP of Canada's forests is positive, i.e., a sink. After consideration of carbon release due to disturbances, Canada's forests still remain as a moderate carbon sink of about 50 MtC/yr in recent decades (Chen et al., 2000b). The net positive effects of temperature increase, nitrogen deposition, and CO_2 concentration increase in the last century might have outweighed negative effects of the increase in disturbances in recent decades. The net effect of about 1°C temperature increase in the last century on NEP was found to be positive after considering its impacts on growing season length and nutrient mineralization and as well as on heterotrophic respiration.

According to our experience in ecosystem modelling, we suggest the following two strategies for the dual constraint between the "bottom-up" and "top-down" approaches for global carbon cycle estimation. One strategy is to use the spatial pattern of carbon source and sink distribution as a constraint. The south-north gradient in NEP shown in Figure 2A, for example, results mostly from long-term effects of climate changes, while this type of gradients can be estimated in the atmospheric inversion through considering the instantaneous horizontal and vertical diffusion processes with given atmospheric CO_2 concentration measurements. The south-north gradient derived through atmospheric inversion can perhaps provide a check on the long-term process-based ecosystem modelling. The other strategy is to use the temporal pattern as a constraint. The seasonal CO_2 flux from the vegetated surfaces generally change signs at the beginning and end of the growing season as a result of the balance between NPP and the heterotrophic respiration. This temporal pattern can be readily captured in ecosystem modelling and can be used as a constraint to the "top-down" calculation. To make such dual constraints possible, it is necessary to improve temporal and spatial resolutions in the atmospheric inversion. Daily to weekly time steps and spatial patterns smaller than 2-3° would be the basic requirements for the dual constraint.

In order to improve the "bottom-up" modelling and to reduce the uncertainty in the estimated carbon sink and source distribution, we suggested a list of key observation variables (Table A1). The reasons for the needed variables, the spatial and temporal requirements, and the suggested observation methods are included in the table.

References:

Chen, J. M., J. Liu, J. Cihlar and M. L. Guolden, 1999. Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications. Ecological Modelling, 124:99-119.

Chen, W.J., J. M. Chen, J. Liu, and J. Cihlar, 2000a. Approaches for reducing uncertainties in regional forest carbon balance', Global Biogeochemical Cycle (in press).

Chen, J. M., W. Chen, J. Liu, J. Cihlar, 2000b. Carbon budget of boreal forests estimated from the changes in disturbances, climate, nitrogen and CO_2: results for Canada in 1895-1996. Global Biogeochemical Cycle (in second review).

Liu, J., J. M. Chen, J. Cihlar, and W. Chen. 1999. Net primary productivity distribution in the BOREAS study region from a process model driven by satellite and surface data. Journal of Geophysical Research, vol. 104, No. D22, pages 27,735-27,754.

Figure A1. The major steps to use satellite spectral measurements for terrestrial carbon cycle estimation. The major ancillary data required at each step are also included.

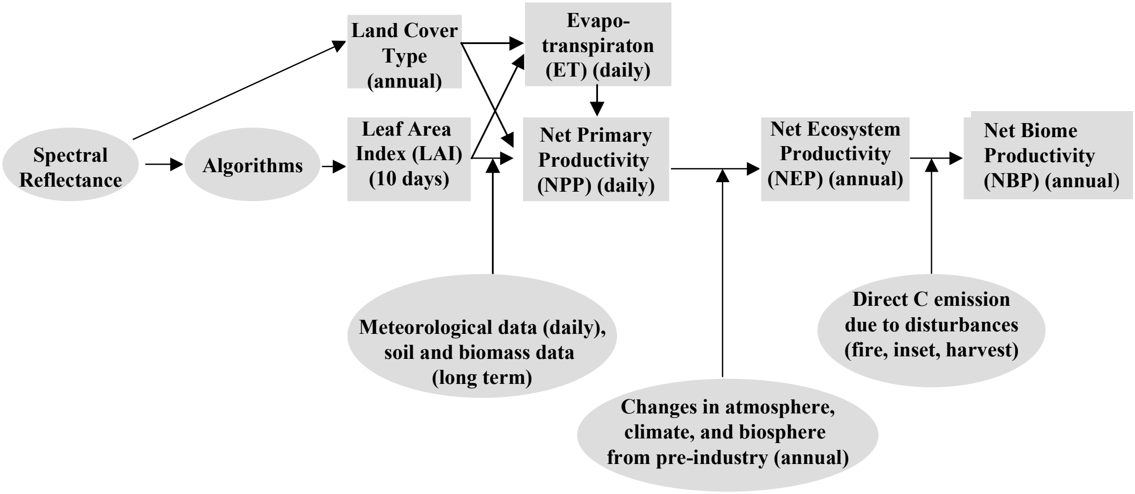
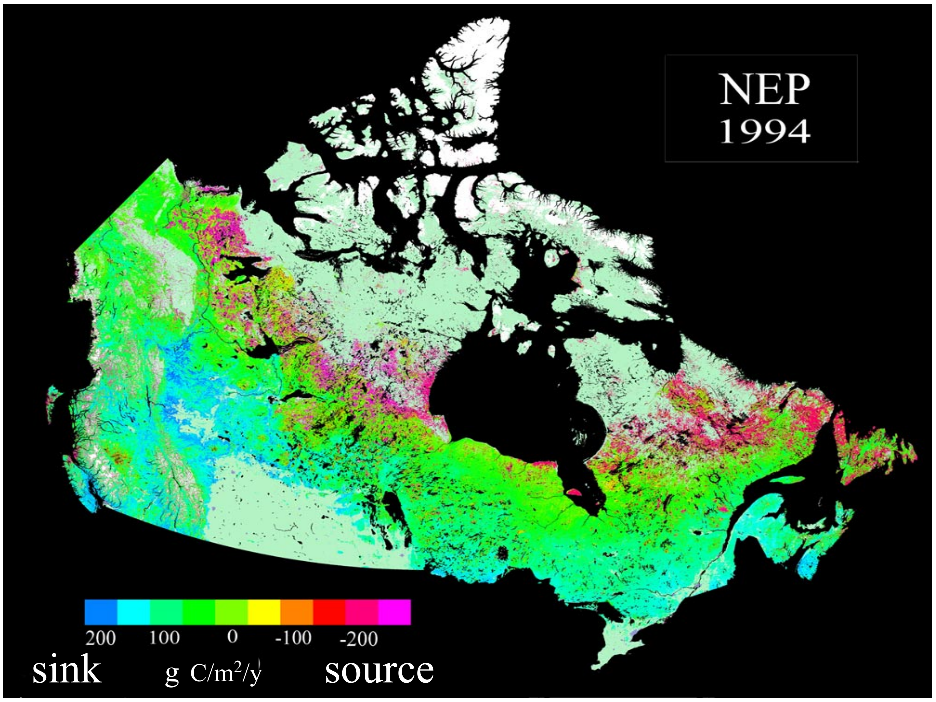


Figure A2. Preliminary net ecosystem productivity (NEP) map of Canada in 1994 produced using the satellite sensors AVHRR and VEGETATION, forest inventory, tower flux and climate data for the last 100 years.



This is a preliminary result. Much refinement is still needed.

The mean for all forested areas is +27 g C/m^2/y, i.e. sink. The total sink is about 110 Mt in 1994 (excluding direct C emission due to disturbance).

Conclusions:
- overall, the forested areas are a C sink
- large spatial variability
- considerable south-north gradient

Table 1. Data needs for bottom-up estimation of carbon sinks/sources in forests and wetlands

Components	Variable	Reason [a]	Type [b]	Spatial Requirements [c]	Temporal Requirements [d]	Method [e]
Atmosphere	Temperature	1	1	3	1, 5	1 & 2
Atmosphere	Precipitation	1	1	3	1, 5	1 & 2
Atmosphere	Solar radiation	1	1	3	1, 5	1 & 2
Atmosphere	N deposition	1	1	3	1	1 & 2
Vegetation	Forest class	1	1	1	1	3 & 4
Vegetation	Wetland class	2	2	1	2	3 & 4
Vegetation	Biomass (belowground)	2	2	2	3	1
Vegetation	Biomass (aboveground)	2	2	1	2	1 & 3
Vegetation	Leaf area index (trees, shrubs, grass)	2	2	1	2	1 & 3
Vegetation	Leaf N content	2	2	2	2	1 & 3
Vegetation	C/N ratio	2	2	2	2	1
Vegetation	Maximum stomatal conductance	2	2	2	2	1
Moss	Temperature	2	2	2	2	1
Moss	Moisture	2	2	2	2	1
Moss	Percentage of cover by type	2	2	2	2	1 & 3
Moss	Thickness	2	2	2	2	1
Soil	Temperature	2	2	2	4	1
		1	1	1	1	2
Soil	Maximum thaw depth	2	2	2	4	1
		1	1	1	1	2
Soil	Thermal conductance	2	2	2	4	1 & 2
Soil	Thermal diffusivity	2	2	2	4	1 &2
Soil	Moisture	2	2	2	4	1
		1	1	1	1	2
Soil	Water table	2	2	2	4	1
		1	1	1	1	2
Soil	C content	2	2	1	3	4
Soil	C/N ratio	2	2	2	3	4
Soil	Texture	2	2	1	3	4
Ecosystem	CO_2 flux (net and components)	2	3	2	4	1
Ecosystem	CH_4 flux	2	3	2	4	1
Ecosystem	Evapo-transpiration	2	3	2	4	1
Ecosystem	Peat carbon accumulation rate	2	3	2	3	1
Ecosystem	Topography	2	2	1	3	3 & 4
Ecosystem	Fire history	1	1	1	1	3 & 4
Ecosystem	Land use history	1	1	1	1	3 & 4

[a] 1, driver; and 2, calibration and validation.

[b] 1, external forcing variable; 2, internal status variable; and 3, output.

[c] 1, gridded with a spatial resolution of 1 Km or better; 2, each for a forest/wetland class; 3, gridded with spatial resolution of 0.5-1 degree.

[d] 1, since industrialisation with desirable frequency; 2, periodical measurement once every 5-10 years; 3, one time measurement; 4, multiple-year continuous measurement; 5, daily in calibrations years.

[e] 1, site measurement; 2, modelling; 3, remote sensing; and 4, survey or inventory.

Japanese programs in terrestrial carbon observations and research

Yoshifumi Yasuoka and Tamotsu Igarashi

Carbon cycle monitoring and modeling programs are not well structured yet in Japan, however, several programs are ongoing. They include primarily satellite observation programs and research programs. The following are a subset of examples of ongoing projects in Japan.

Satellite Observation Programs

- JERS-1: It was launched in 1993 and carried two sensors including OPS (visible and near infrared range sensor with 4 bands and 18m resolution) and SAR (L-band synthetic aperture radar with 18m resolution). It stopped operation in 1998, however, data from two sensors are valuable for carbon cycle assessment. In particular, two data set of GBFM (Global Boreal Forest Mapping) and GRFM (Global Rain Forest Mapping) from SAR covering boreal forest areas and tropical rain forest areas are now available for carbon cycle studies (see below).
- ADEOS: It was launched in 1996 and stopped after ten months operation. Although the period of operation was short global scale data set from six sensors (AVNIR, OCTS, POLDER, IMG, ILAS and NSCAT) can be usable for carbon cycle studies (Fig. yyy).
- GCOM (Global Change Observation Mission): It is a new series of earth observation mission in Japan. It includes ADEOS-II (2002), GCOM A-1 (2006), GCOM B-1 (2006), and their follow-on missions. The main mission of the GCOM program is to elucidate water and energy cycle, and carbon cycle. The details of the GCOM program are described in the section 9.3.3.

Research programs

- Estimation of Carbon Sink under Kyoto Protocol: Environment Agency started this program from 1999 to develop carbon accounting methods and to carry out carbon flux measurement and modeling.

- Global Carbon Cycle Mapping: Science and Technology Agency launched this program from 1998 to produce global scale NPP and biomass maps from satellite observation, in situ measurement and process modeling.

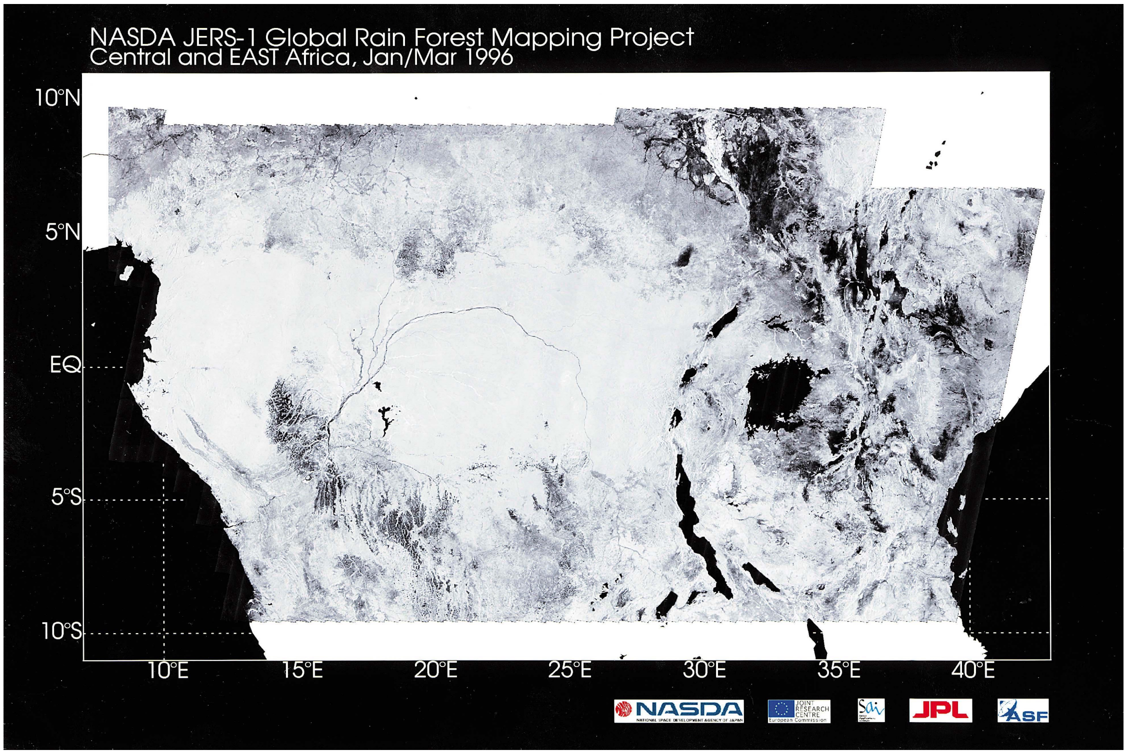
- Asian Forest Census: Ministry of Agriculture, Fishery and Forestry has a program of producing forest cover maps covering Asian region with satellite data.

- Frontier Research System for Global Change: Science and Technology Agency launched a twenty years project (FRSGC) from 1997 to tackle with global change issues. The main mission is to elucidate the environment and climate change mechanism and to produce models for them. Six research programs are already kicked off including Climate Variation Research, Hydrological Cycle Research, Global Warming Research, Atmospheric Composition Research, Ecosystem Change Research and Integrated Modeling Research. Linked with the FRSGC, Frontier Observation Research System for Global Change program (FORSGC)□is also launched in 1999 to carry out observation and to get data for modeling.

- AsiaFlux: It is a similar program as AmeriFlux and EuroFlux and is now in the design phase.

Anticipated contribution from NASDA's Earth Observation Satellite Programs to Terrestrial Carbon Observation. Japanese past and present earth observation satellite programs, JERS-1(Feb.1992-Oct.1998), ADEOS (Sep.1996-Jun. 1997), TRMM/PR (Nov.1997-) and the future satellites ADEOS-II (Nov.2001-) and ALOS (Aug.2002-) would provide science community with data sets of multispectral medium resolution data, high resolution data, L-band SAR data for the estimation of terrestrial carbon related parameters such as land cover area, vegetation environment, biomass density etc. through science programs, GRFM/GBFM and so on which will provide useful information for the estimation of CO2 stock and evaluation of the carbon sequestration by sinks quantitatively.

As the future long-term scenario for the continuous observation and the science program, NASDA and science community in Japan are proposing GCOM (Global Change Observation Mission) concept beginning from ADEOS-II (see GCOM Concept below).



An example of GRFM data set from JERS-1/SAR

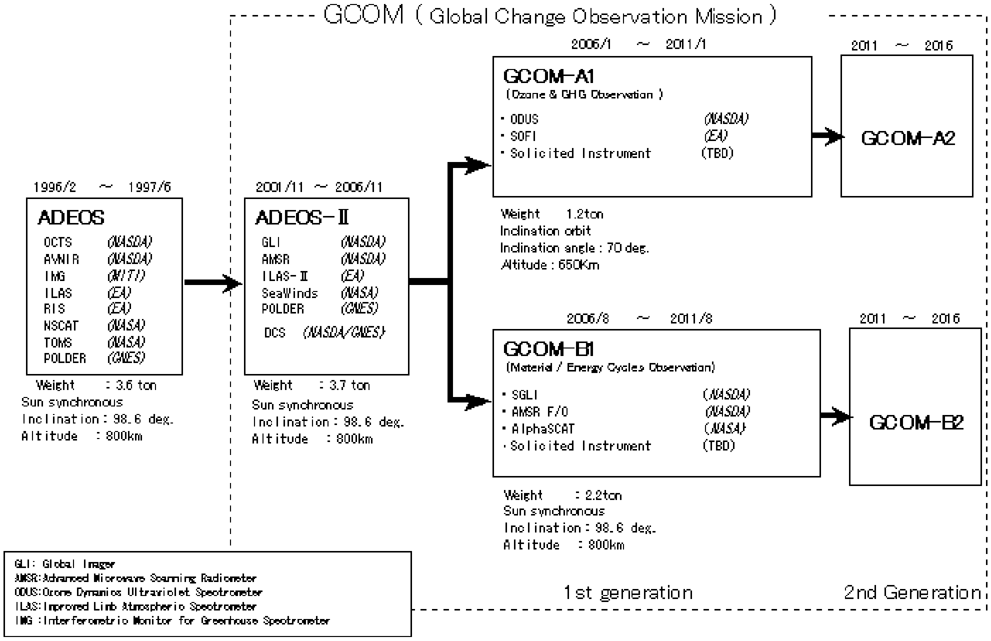


Fig GCOM Series

U.S. Carbon Cycle Research and Observation

Diane E. Wickland

The goal of the United States interagency Carbon Cycle Science Program is to provide critical scientific information on the fate of carbon in the environment and how cycling of carbon might change in the future. The following scientific questions are being used to organize the implementation plan:

- What has happened to the carbon dioxide that has already been emitted by human activities?
- What will be the future atmospheric carbon dioxide concentration resulting from past and future emissions?
- How do land management, land use, and other factors affect carbon sources and sinks over time?
- How will future environmental changes and human actions affect atmospheric concentrations of carbon-containing greenhouse gases?

The key challenges for research are viewed to be in a) locating and quantifying carbon sources and sinks regionally and globally, b) characterizing past, present, and future dynamics of the carbon cycle (i.e., identifying patterns of variability and understanding processes affecting the cycling of carbon), and c) developing understanding of the impact of human activities on carbon storage and release (including historical influences on the carbon cycle such as land use change and designed sequestration strategies). U.S. carbon cycle science will be organized into these six complementary topic areas:

1. Northern hemisphere terrestrial carbon sinks
2. Oceanic carbon sinks
3. Global distribution of carbon sources and sinks and their temporal dynamics
4. Effects of land use and land management on carbon sources and sinks
5. Predicting future atmospheric carbon dioxide concentrations (and other carbon-containing greenhouse gases)
6. Scientific underpinning for evaluating management of carbon dioxide

The U.S. Carbon Cycle Science Program's implementation plan is now under development by the Interagency Working Group on Carbon Cycle Science (under the U.S. Global Change Research Program (USGCRP)). The interagency group has reviewed and incorporated many of the recommendations of the report of an external Carbon and Climate Working Group (chaired by Sarmiento and Wofsy) entitled "A U.S. Carbon Cycle Science Plan." In parallel a Carbon Cycle Science Initiative was launched in the fiscal year 2000 budget for the USGCRP. The interagency group is also preparing to identify a science steering panel for the U.S. Carbon Cycle Science Program and is planning to coordinate its inputs to the international carbon cycle science framework through the IGBP. U.S. agencies participating in the interagency group include: the U.S. Department of Agriculture (USDA; Agricultural Research Service and U.S. Forest Service), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Interior (DOI). Additional information is available at: http://geochange.er.usgs.gov/usgcrp/ccsp/index/html

Key observational capabilities for carbon cycle science in the U.S. include NOAA's flask sampling network, the AmeriFlux network led by DOE, the USDA's forest inventory database, and NASA and NOAA's earth observing satellites. Satellite observations offer the only possibility for frequent, consistent, global observations of carbon sources and sinks. Consistent time series of global land cover, vegetation properties, and ocean color exist and are continuing into the near future. New remote sensing capabilities (lidar and radar) for estimating above ground biomass and assessing vegetation response to disturbance are being developed and tested by NASA.

Using in-situ Airborne Measurements to Infer Carbon fluxes at Regional and Continental Scales: COBRA (North America) and LARS (Brazil)

Christoph Gerbig (chg@io.harvard.edu), John Lin, Scott Saleska, Steven Wofsy

Motivation

A wide gap currently exists in carbon cycle science between the detailed information available on carbon flux at the ecosystem stand level, on the one hand, and the global-scale fluxes inferred from boundary-layer atmospheric CO_2 concentration data by latitude bands. Airborne sampling has the potential to bridge the gap by providing valuable information about carbon fluxes at regional and continental scales.

Objective

Develop framework for using aircraft observations of CO_2 and other tracers – the CO2 Budget and Rectification Airborne study (COBRA) – to quantify carbon fluxes at regional and continental scales. Obtain funding to apply this method to the Amazon basin in conjunction with the ongoing LBA study (Large-scale Biosphere-atmosphere experiment in Amazonia) in Brazil. The Amazon proposal is called the LBA Regional Source experiment (LARS).

Approach

1. Conduct preliminary measurements during several days of test flights in June 1999, followed by more intensive month-long sampling campaign in Summer 2000.

2. Conduct simple 1-D column budget calculation of surface carbon flux, according to:

$$S_{bio} + S_{foss} = \underset{\{a\}}{\frac{\partial}{\partial t}\left(\int_0^h nq\,dz\right)} + \underset{\{b\}}{W_h n_h \left(q_h - \bar{q}\right)} \qquad \text{(Eqn. 1)}$$

   where S_{bio} is the surface biospheric flux, S_{foss} is surface fossil fuel combustion flux, n is the number density of air, q is mixing ratio of CO_2, h is height of atmospheric column, W_h is vertical exchange velocity at $z = h$, and $\bar{q}$ is altitude-weighted mean mixing ratio within column. The first term on the left-hand side (a) is the rate-of-change in integrated CO_2 column amount, and the second term (b) is the flux of CO_2 across column top. S_{foss} is calculated from a similar column budget for CO, and assuming a CO_2/CO emission ratio between 0.04~0.07 ppm/ppb [Potosnak, et al. 1999].

3. Use a more detailed stochastic particle dispersion model (the HYSPLIT model, or Hybrid Single-Particle Lagrangian Integrated Trajectory [*Draxler and Hess, 1998*]) as a representation of turbulent transport to derive regions influencing measurement.

4. Overlay particle model results on land-cover data to understand the vegetation types influencing flux calculation and identify potential problems caused by spatial and temporal inhomogeneity.

Results of June 1999 Test Flights

Measurements of CO2 and other atmospheric tracers were made during test flights over North Dakota and a tall tower (the WLEF television tower) in Wisconsin in June 1999.

Vertical CO_2 concentration profiles measured over the course of a single day (8 June 1999 data is shown in Figure 1a) allow estimation of daytime surface carbon fluxes if the atmosphere is treated as a one-dimensional column (Figure 1b). This method gives estimates of surface daytime biospheric uptake in the range of 15 – 20 umol m^{-2} sec^{-1} on 8 June and 10 June (Figure 1b). The calculated negative value for fossil fuel CO_2 fluxes (S_{foss} in Figure 1b) implies transport due to horizonatal advection, and suggests that the one-dimensional column assumptions may not be appropriate.

In order to account for horizontal advection and estimate the source "footprint" for measurements, a stochastic lagrangian particle dispersion model was run backwards in time (Figure 2a). Running the model backwards gives an estimate of the footprint region from which the measured particles (air parcels) came, rather than predicting where they will go in the future. Overlying the lagranigan particle trajectories with land-cover data (Figure 2b) allows an estimate of the different vegetation classes which have influenced the aircraft measurements (Figure 2c).

Summary: Some Issues for large-scale Carbon flux estimates:

- A prerequisite for this kind of study is well-calibrated, high-accuracy [CO_2] measurements ($\leq$0.5 ppm), to fit into context of the exisiting CMDL flask network.
- A need of this kind of study is to have continuous tower-based observations serve as an "anchor" for airborne measurements. Such tower measurement can give:
    - the carbon budget for part of atmosphere below minimum aircraft height
    - continuous measurements, which provide an important long-term context into which the airborne measurements can be situated.
    - measurements under less-than-ideal flying conditions, providing an estimate of the "fair-day bias" that might arise from aircraft measurements.
- A key need is to address the issue of transport by horizontal advection which confounds the simplifying assumption of a one-dimensional column. Thus, methods need to be developed in order to:
    - account for surface inhomogeneity and transport
    - couple observations with transport model, driven by "real" winds
    - use lagrangian experimental framework (observation platform tries to sample "same" air).
- There is a high added-value of additional tracers, especially a combustion tracer (e.g. CO) to distinguish anthropogenic fluxes, and other tracers such as ^{13}C, O_2, ^{222}Rn.

Summary: "Terrestrial Carbon Observation Requirements" for
In-situ Airborne Measurements for large-scale flux estimates (COBRA/LARS)

1. Observation/Variable:	continuous measurements of atmospheric [CO_2] and [CO], plus other tracers ($^{13}CO_2$, ^{222}Rn, O_2) in flask samples
2. area involved	currently mid-latitude North America (Wofsy et al) and Siberia (Heimann et al.); possible extension to Brazilian Amazon as part of the LARS project.
3. spatial resolution	regions to continents
4. temporal resolution	~day to month (currently)
5. measurement method	airborne sampling platform with infrared gas analysis for CO_2, vacuum-UV reasonance florescence for CO
6. Remarks: requires high-accuracy [CO_2] measurements to compare to CMDL network, tower-based measurements to "anchor" airborne measurements. Issues to resolve include: accounting for horizontal advection via combination of transport modeling and experimental design (e.g. use of lagrangian experimental framework), understanding flux footprint, etc. Long-term goal: provide a foundation for the next level – satellite-based CO_2 observations to provide global coverage.	

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Figure 1a. Vertical profiles of CO_2 on June 8th, 1999, at different local times over WLEF. A marked decrease in CO_2 is observed between the morning and afternoon vertical profiles. The scatter around 1500 m at LT 1530 is due to entrainment of air from above the PBL into the PBL.

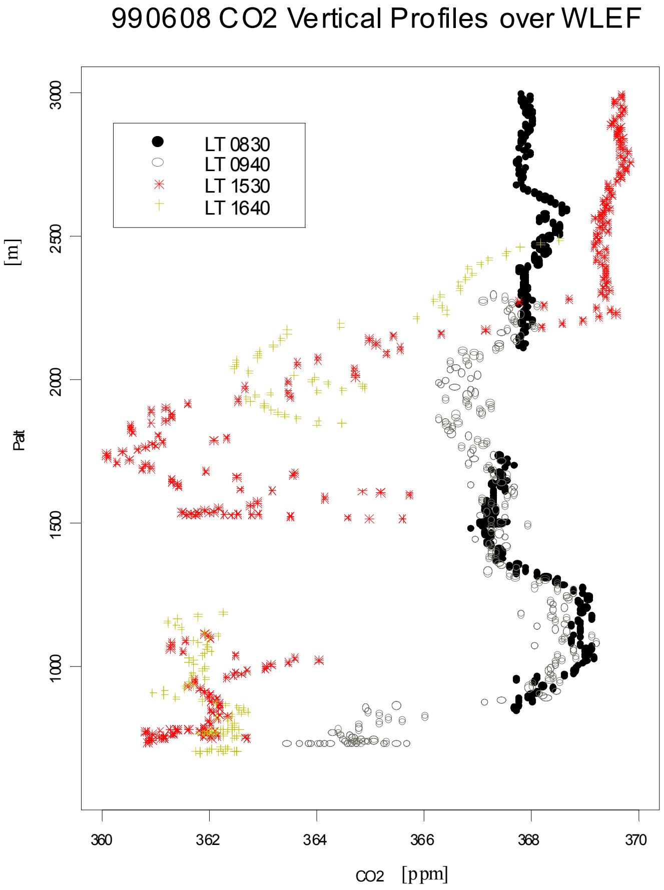
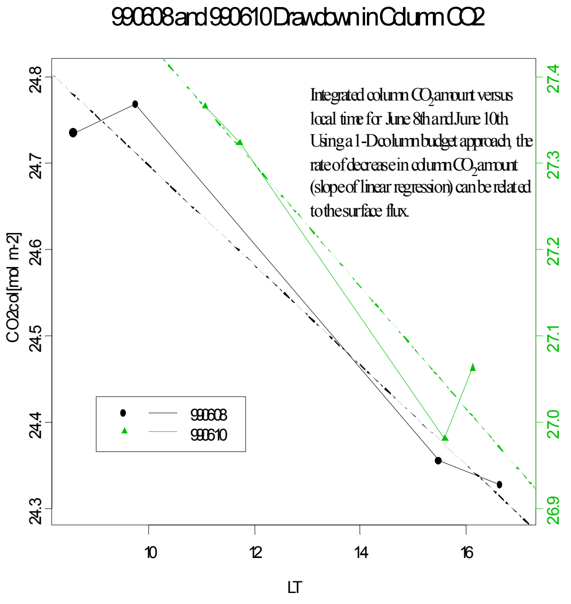


Figure 1b. 1-D vertical column-integrated concentrations during two measurement days (including June 8 vertical profile shown in Figure 1a). Fluxes derived by column budget calculation are:

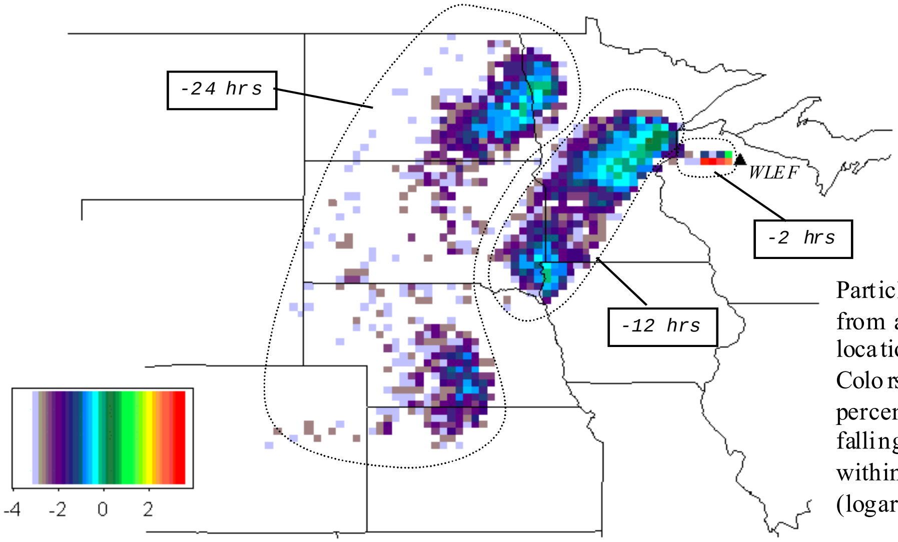
Flight Day	S_{foss} *[µmole m^{-2} s^{-1}]*	S_{bio} *[µmole m^{-2} s^{-1}]*
June 8th	–0.8 ~ –1.4	–15.3~ –15.9
June 10th	–0.4 ~ –0.6	–19.9~ –19.6



Integrated column CO_2 amount versus local time for June 8th and June 10th Using a 1-D column budget approach, the rate of decrease in column CO_2 amount (slope of linear regression) can be related to the surface flux.

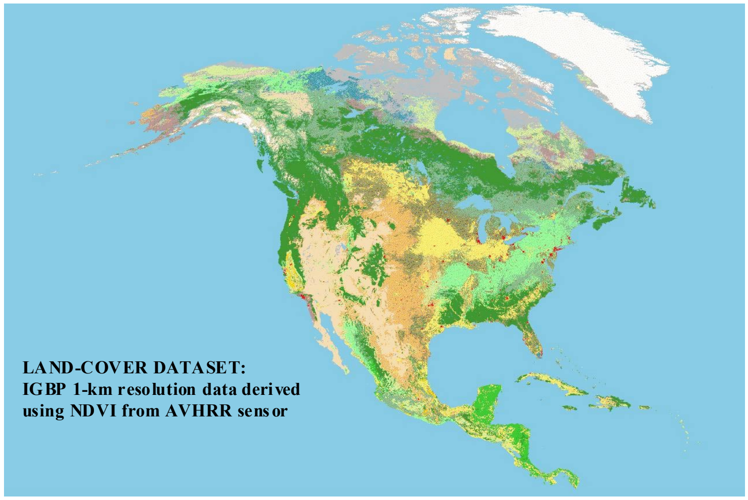
Figure 2. Combining trajectory results from backward stochastic lagrangian dispersion model (starting with the aircraft measurement location over the WLEF tower) (a), with a landcover dataset (b), allows estimation of how different landcover vegetation classes influenced observed CO2 concentrations at various measurement times (c).

(a) Backward Particle Dispersion Results: 990608 UT1300 1000 AGL

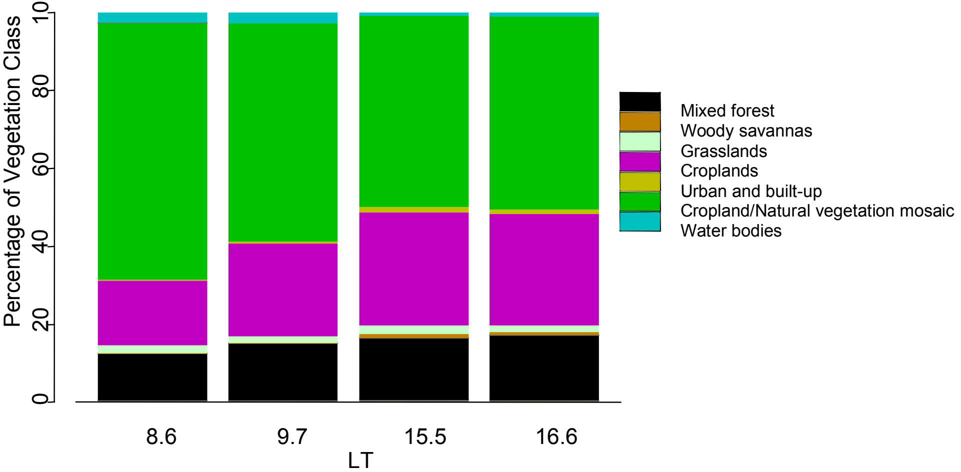


Particle model results from a single starting location over WLEF. Colors represent the percentage of all particles falling in a specific pixel within a time step (logarithmic scale).

(b) landcover dataset



(c) Influence of different vegetation classes on observed CO_2 vertical profiles, vs. time of day



The Integrated Global Observing Strategy

Roy Gibson

What is and Why an IGOS?

The Integrated Global Observing Strategy (IGOS) unites the major satellite and surface-based systems for global environmental observations of the atmosphere, oceans and land. Annex 1 gives the Terms of reference and actors.

Conceptually, IGOS is based on the simple recognition that the range of global observations needed to understand and monitor Earth processes, and to assess human impacts, exceeds the scientific, technical and financial capability of any one country. Hence strategic co-operation is necessary in defined areas so that issues can be addressed without either duplication or omitting issues. As such IGOS is not trying to replace the bottom up scientifically driven approach to individual concerns, but rather provide the overall framework for observational systems to be justified and funded.

Operational satellite missions and in situ networks require many years of planning and at a time when resources are scarce, funding agencies want to avoid all risks of duplication and wastage, and to get the maximum return for their investment. Governments and international organisations have naturally been concerned those different needs should not remain fragmented and uncoordinated where synergies are possible. Further national programmes should fit into larger international frameworks since the environment does not stop at national boundaries. Such complex activities require integration and IGOS provides both a strategic framework and a planning process to bring together remotely-sensed and in situ observations, from both research observation programmes and focuses additional efforts in areas where satisfactory international arrangements and structures do not currently exist.

IGOS is a strategic planning process, involving a number of partners, that links research, long-term monitoring and operational programmes, as well as data producers and users, in a structure that helps determine observation gaps and identify allocation by individual funding agencies, within an overarching framework that evaluates the current system capabilities and limitations – thereby helping to reduce unnecessary duplication of observations.

IGOS focuses primarily on the observing aspects of the process of providing environmental data for analysis and decision-making. It is intended to cover all forms of data collection concerning the physical, chemical, biological and human environment including the associated impacts. It also provides opportunities for capacity building and assisting countries to obtain maximum benefit from the total set of observations

IGOS and Conventions

IGOS is not a strategy for observing the global environment sitting in isolation. It is one component in a larger strategic framework of information for decision-making such as that mapped out by the international community as a major cross-cutting issue in Agenda 21. International organisations have global observation components in their institutional strategies. IGOS should therefore be situated in relation to these complementary strategies.

Chapter 40 of Agenda 21 on Information for decision-making emphasised the need to bridge the data gap through strengthening data collection activities; co-ordinating and harmonising the collection of data using continuous and accurate data collection systems. These are an essential first step in establishing a comprehensive information framework, with strong environmental assessment activities co-ordinated with an assessment of development trends. The agenda 21 also called for the use of data within geographic information systems, expert systems, models and other data assessment and analysis techniques as well as developing indicators of sustainable development and their incorporation in common, regularly updated and widely accessible reports and databases for use at the international level;

Agenda 21 also called for improved information availability through:

- Transforming existing information into forms more useful for decision-making and targeting information at different user groups;
- Achieving efficient and harmonised exchange of information at all levels, including through common data formats and communication interfaces;
- Developing documentation about information, and networking and co-ordinating mechanisms;
- Improving the sharing of information and experience involving all sectors of society, establishing and strengthening electronic networking capabilities; making use of commercial and private sector information sources; and making information available and accessible to developing countries.

Of course there are other conventions but the above serves to illustrate that an IGOS is one of the steps – and an early step in the chain of observations, analysis and decision making. There is a real need to ensure that the decisions are based upon sound analysis, which in turn is based upon good, consistent and high quality data. It is also clear that the data sets can be obtained collectively, even if the analysis and decisions are made independently at national levels. This clear distinction between the data collection/delivery, the analysis and the decision-making processes is important.

There is no single answer for each convention or protocol. Thus for example on Kyoto, the IPCC has to agree any methodologies for determining compliance and/or monitoring. These are put forward by nations and on the basis of agreed procedure the specific need for observations can be defined. These could then be fed into the IGOS partners for consideration and response. In essence this would create a specific theme. A key issue in this process is the need for dialogue between the players and a clear exposition of what is required. For our part the IGOS partners are ready and willing to participate as appropriate, but already several players are involved at national level. Again the possibility to work at a national level is important.

The components of IGOS include:

- Strengthening space-based/in situ linkages to improve the balance between satellite remote sensing and ground or ocean-based observing programmes;
- Encouraging the transition from research to operational environmental observations within appropriate institutional structures;
- Improving data policies and facilitation data access and exchange;
- Stimulating better archiving of data to build the long-term time series necessary to monitor environmental change; and
- Increasing attention to harmonisation, quality assurance and calibration/validation so that data can be used more effectively.
- Provide a framework for decisions that will result in the scientific research needed to improve understanding of Earth processes;

All the above are aimed at improving the availability and usability of the observational data.

IGOS encourages the use of a modular approach to implement specific components. Nested processes of strategic planning at different levels of integration are an important part of the IGOS process, allowing each subsidiary group to work out the specifics at its own level. IGOS partners have adopted a self-selecting thematic approach with joint planning activities to address particular domains of observations. These are selected with users and for example the first is on Oceans.

Implementation is not easy and required a careful examination of what exists and hence a deduction of what is needed. It also needs to embrace not just the observations but also the delivery of data to the point of usage. Stages in the process are:

- Establishing a consensus on the requirement for observations is a user role. There is a need to define products, which will respond to these needs and then the observations necessary to generate these products.

- Evaluating the current capabilities of observational systems against the assessment of requirements.
- Prioritising implicity or explicitly amongst the many deficiencies that analysing the current system will reveal is an important step in deciding what needs to be changed.
- Individual agencies should agree to develop, deploy and maintain new assets, either in terms of satellite based or in situ systems to meet the additional observations.
- Enhancing the product processing chain is an ongoing task. Changes in the acquisition strategy or other changes in the product processing chain, such as in Calibration and Validation, data access and networking, the assembly of data sets, improving data archiving and product generation are all ways of better meting needs.
- Determining whether or not the resultant observational systems are operating satisfactorily and meeting their objectives through continuous monitoring and analysis is a necessary step.

The IGOS Partners

Co-operation between the Partners will reflect:

- The principle of "best efforts" to maintain the commitment to the overall strategy and any specific purpose or project.
- The principle of "no additional financial obligation" or exchange of funds except with the mutual consent of relevant Partners.
- The principle of "synergy" among existing efforts, including optimal use of meetings and of resources. Two important meeting opportunities are the CEOS Plenary and meetings of the Sponsors' Group for the G3OS.
- Organisation and reporting responsibilities for IGOS Partnership meetings will rest with the hosting agency.

Terms of Reference

The IGOS Partnership will further the definition, development and implementation of an Integrated Global Observing Strategy. Towards this end, the Partners will:

Exchange information on the Partners' relevant activities;
- Promote dialogue between the space agencies and in situ observation communities;
- Identify gaps and seek to address IGOS-related user requirements;
- Identify requirements to strengthen institutional capacity to make integrated global observations;
- Carry out specific activities to develop individual components of this strategy;
- Identify and suggest projects that complement and demonstrate the value of an IGOS ; and,
- Promote all aspects of strategy implementation, among national and international agencies, as well as different user groups.

Partners

- The IGOS Partnership will initially comprise the following partners;
- Sponsors of the Global Observing Systems (ICSU, IOC, FAO, UNEP, UNESCO, WMO);
- Global Observing Systems (GCOS, GOOS, GTOS) Programme Offices;
- Committee on Earth Observation Satellites (CEOS; comprising member space agencies contributing to an IGOS);
- International Group of Funding Agencies (IGFA);
- International Geosphere – Biosphere Programme (IGBP) Programme Office;
- World Climate Research Programme (WCRP) Programme Office.

Other organisations prepared to contribute to an IGOS may be added as Partners.

NO		ACTION
3/8		UNEP contribution to the IGOS presentation to the 9th Meeting of the Commission of Sustainable Development in 2001 – Input from Mr. A. Dahl to be provided.

ACTIONS from IGOS-P 4th Meeting

No.		ACTION
4/1		Partners to send comments on Doc IGOS-P4/Doc/10, concerning in situ observations, to Mr. Landis in time for consideration of the paper at the Partners' meeting in June 2000.
4/2		CEOS/SIT to provide a report to June 2000 Partners' meeting. on space agencies' commitments in response to the Oceans Theme report recommendations.
4/3		IOC to provide a report to June 2000 Partners' meeting on in situ commitments in response to the Oceans Theme recommendations.
4/4		NOAA to consult with interested IGOS Partners to consider the optimal approach to collaboration on Disaster Application within the context of IGOS and report to a future IGOS Partners' meeting
4/5		GTOS with FAO support to lead the Terrestrial Carbon Cycle Theme and to present a report to Partners along the lines of the Oceans Theme Report.
4/6		GCOS, FAO, IGBP, ICSU, UNESCO and CEOS to nominate representatives for the Terrestrial Carbon Cycle Team by end November 1999.
4/7		NASA to lead on the Ocean Carbon element and to make an input to the Global Carbon Theme Team in time for the next partners' meeting
4/8		Partners to provide inputs on the Ocean Carbon element to the Oceans Theme Team by end November 1999.
4/9		COOS, GCOS, GTOS, IGBP, and NASA to prepare proposals for the overarching Global Carbon Theme and to decide amongst themselves who should lead this activity.
4/10		Dr. D. Williams to make reference to the IGFA Working Group on Observations and Data in the IGOS Process Document.
4/11		Volunteers requested as soon as possible from interested organisations to join Prof. J. Townshend in preparing a status report on development of Data and Information Systems paper, IGOS-P/4/04, for the June 2000 Partners meeting.
4/12		The incoming IGOS-P Chairman to develop with GCOS the interface with COP 6
4/13		UNEP, (Mr. A. Dahl) to continue to develop the interface with UN Convention Secretariats, keeping the IGOS-P Chairman and the IGOS-P Liaison Group informed.
4/14		The incoming IGOS-P Chairman and the IGOS-P Liaison Group to study the upgrading of the IGOS web site to give increased publicity.
4/15		Members of the IGOS-P Liaison Group to assume their agreed functions in support of IGOS-P Chairman and to arrange an early meeting – possibly in Geneva in January.
4/16		The incoming IGOS-P Chairman to nominate an additional member of the IGOS-P Liaison Group

Status of Observations and Networks: Surface Fluxes and Stocks

Dick Olson and Jonathan Scurlock (Oak Ridge National Laboratory)
Dennis Baldocchi, and Eva Falge (University of California, Berkley)

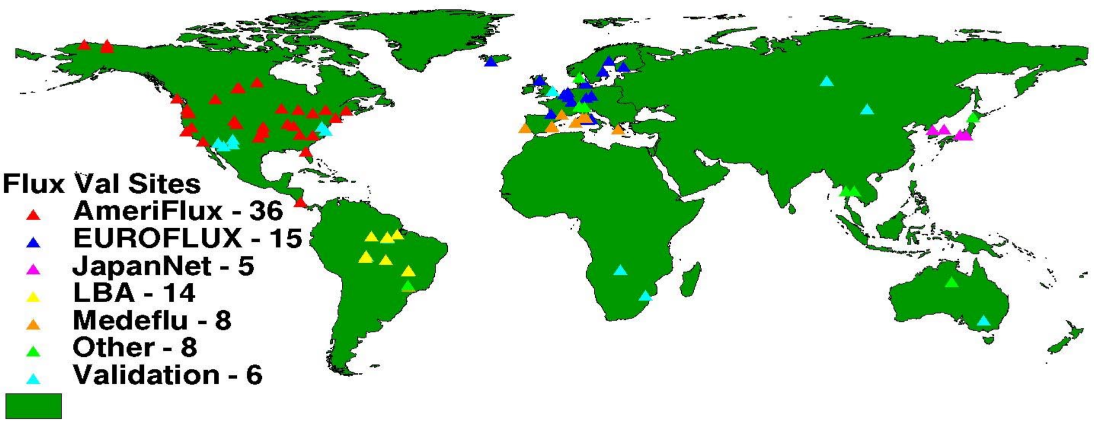
The scientific community and a variety of land management organizations provide a wealth of surface measurements for carbon stocks and fluxes. The FLUXNET network is poised to process and distribute measurements of CO2, water, and energy fluxes based on eddy covariance techniques from a worldwide collection of approximately 100 towers (Figure 1). FLUXNET receives documented hourly or half-hourly data, uses standard methods to fill in gaps created by instrument problems or data rejection criteria, and aggregates the data into daily, weekly, monthly, and annual sums. Although the flux community has focused on internal analysis prior to publishing and distributing data, it appears that there will be a significant increase in the amount of flux data available in the near future.

Measurements NPP (2500 measurements) (Figure 2), LAI (1000 measurements), litter (800 measurements), and soil biomass have been compiled for worldwide research sites and these collections are available for model development and validation. These data have been gleaned from the scientific literature and undergone review to detect those records that may be unrepresentative. The NPP data have been used in a recent workshop to compare global ecosystem models with the data. There are extensive data compiled on tree volumes and growth available from national forest inventories. Although these inventories are often restricted to that portion of the forest that will be harvested, empirical relationships have been developed to account for noncommercial vegetation, litter, and below ground production. In addition, crop yields are routinely compiled and models are available to estimate total plant carbon from the harvested component.

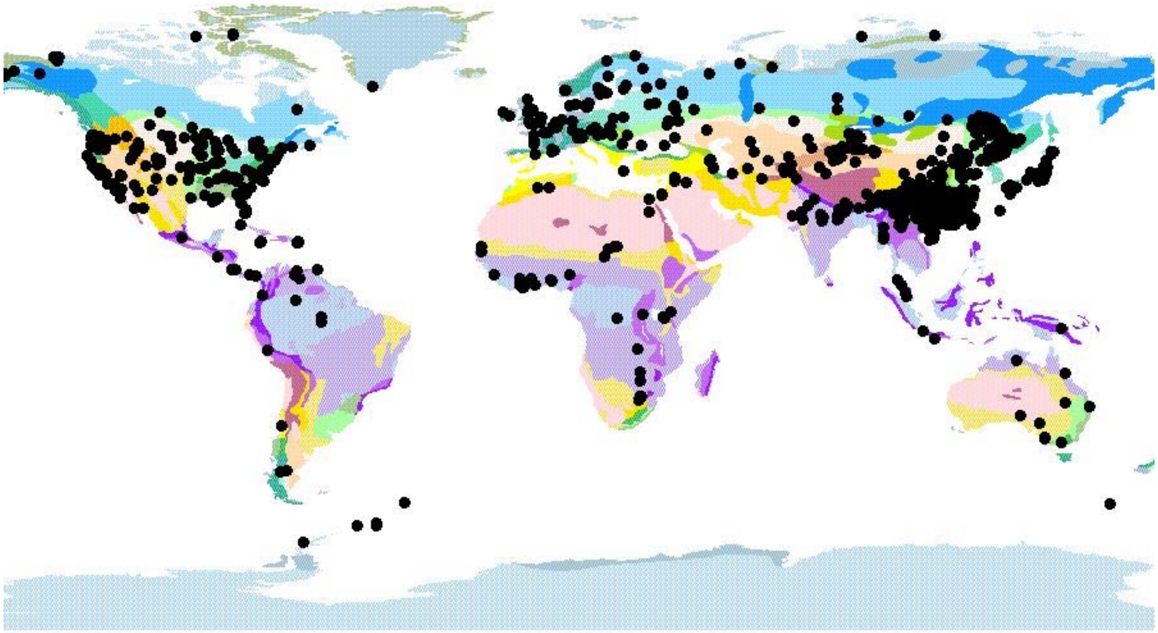
In addition to the flux network, there are other coordinated efforts to collect carbon dynamics data. A set of 24 core test sites located in representative biomes are the cornerstone to collect data for the validation of remote sensing products (e.g., NPP and LAI from the MODIS sensor on the Terra satellite) and model development. Background site data of ecosystem characteristics, remote imagery, and seasonally variable field data (biophysical parameters) are being compiled and distributed. GTOS NPP network will include up to 200 sites that are committed to compiling NPP and LAI data to aid in validation of satellite products and ecosystem models. In order to support the global modeling efforts, ISLSCP II will compile global vegetation, land cover and biophysics snow, ice and oceans, radiation and clouds, and near-surface meteorology data from a variety of sources for 0.25-1.0° grid cells for multiple years.

Most of the data described above can be accessed via the Internet, for example through the Oak Ridge National Laboratory Distributed Active Archive Center (DAAC) for Biogeochemical Dynamics (http//:www-eosdis.ornl.gov). In addition, the DAAC has developed the Mercury, which is a distributed Web-based search/retrieval system to provide early access to data, while allowing PIs to control accessibility. Metadata files are 'harvested' to create an index at the DAAC which can be searched in a variety of ways to locate data of interest (that reside at PI sites) using links embedded in the metadata files.

Flux Tower Sites



NPP-LAI Extensive Sites



Global Observation of Forest Cover: Synopsis of the Project and its Proposed Products for Carbon Budget Modeling

Frank J. Ahern

1. What is GOFC?

GOFC is the first coordinated international effort to develop institutional arrangements and operational systems to produce current, reliable, validated information about the Earth's forests using spaceborne and local data. It is a joint activity of CEOS and the Global Observing Systems (GTOS and GCOS), initiated to test the CEOS Integrated Global Observing Strategy (IGOS). GOFC is not intended to duplicate or replace existing programs. Instead, it is expected to act as a catalyst, creating linkages between existing organizations and programs to build new capabilities. In so doing, it will also identify gaps and make recommendations for filling them.

2. 1998 Strategic Design exercise, 3 components, linkages

From July 1997 to November 1998, teams of scientists, remote sensing specialists, and knowledgeable representatives from user organizations met and planned a strategy to lead to ongoing global observation of forest cover (Ahern et al., 1998). In this process, they endeavored to reach out and obtain input from a broad spectrum of user groups, in addition to drawing heavily from persons with the greatest current experience in assembling and processing large regional and global datasets. During this same period, briefing meetings were held with twenty-six international organizations, scientific bodies, forest management agencies, non-governmental organizations, and earth-observation agencies to inform them about the GOFC concept and obtain their feedback.

As a consequence of these interactions, GOFC has increased dialog between? international organizations, science bodies, forest management agencies, and non-governmental organizations which require forest information.

The essence of the GOFC strategy is to develop and demonstrate operational forest monitoring at regional and global scales by developing prototype projects along three primary themes:

- Forest Cover Characteristics and Changes
- Forest Fire Monitoring and Mapping
- Forest Biophysical Processes

Each of these themes could be implemented independently and achieve significant progress. But the natural interconnections (shown in Figure 1) make an implementation of all three components significantly stronger than simply the sum of the parts.

As part of its implementation process, GOFC is assembling teams to execute prototype projects, to develop consensus algorithms and standard methodologies for product generation and product validation in conjunction with in-situ measurements, and to develop and demonstrate procedures for improved data access for the user community.

GOFC is identifying gaps and overlaps in earth observation data, ground systems, methods, and scientific knowledge from the experience gained in developing and executing prototype projects. The ultimate objective is to lead to sustained, on-going operation.

As a result of its implementation, GOFC will:

- Create and strengthen partnerships between CEOS members and user agencies;
- Identify gaps and overlaps in CEOS member programs and make recommendations how these might be resolved;
- Lead to increased operational use of earth-observation data for policy decision making at national, regional, and global levels;
- Provide validated products which can be used to derive credible information concerning the forest component of the carbon budget for research and policy use;

- Promote common data processing standards and interpretation methods, which are necessary for inter-comparison of regional studies;
- Stimulate advances in the state of the art in the management and dissemination of large volume datasets and information from multiple sensors;
- Use data from multiple sensors, in combination with in-situ data, to produce validated prototype information products which satisfy clearly identified requirements of user agencies;
- Enhance the use of earth-observation information products for forest management and scientific research concerning forest biophysical processes.

3. A carbon focus

In 1999, the IGOS Partnership initiated the themes concept. A Terrestrial Carbon Theme was identified as a high priority for development. In response, GOFC is being asked to take on a carbon focus, and to consider expanding to include all terrestrial vegetation. A carbon focus could provide a number of benefits:

- Motivation for GOFC sponsors and participants: The understanding, adaptation, and mitigation of climate change caused by the buildup of greenhouse gasses in the earth's atmosphere will become more and more important and urgent in the years to come. To the extent that GOFC can contribute (and be seen as contributing) to this effort, GOFC sponsors will be motivated to continue and enhance their support. At the same time, GOFC participants will be motivated to work efficiently together to provide the observations necessary to contribute to the cause.

- Rigour: if GOFC products are to be used as part of carbon budget investigations, they will be subject to the rigour of the scientific process, and possibly to intense scrutiny outside the scientific community. This will result in higher quality and utility than might otherwise be the case.

- International cooperation: a carbon focus will bring additional opportunities for international cooperation with resulting benefits.

Although this must be confirmed through further study, the resulting products, or adaptations thereof, should be just as useful to non-carbon users, as long as sufficient effort is put into the development and production of fine-resolution land cover and land cover change products. However, it will be very important to convey this message outside the carbon community, or risk losing valuable support which has been developed for GOFC by non-carbon users.

4. GOFC components and products

Forest Fire Monitoring and Mapping: The global increase in wildfire following the 1997-98 el Niño event served to emphasize the urgent need for improved information from CEOS members' space systems. Data from existing coarse resolution sensors (AVHRR, VEGETATION, ATSR, MODIS) can satisfy urgent information requirements, and automated algorithms for much of the information extraction have been demonstrated (Li et al., 2000, Arino et al., 2000). Products which have been identified for near-term development, refinement, and global implementation include daily monitoring of active fires, and annual mapping of large burn scars. Additional emissions-related products have been identified, but the details need to be refined, and additional R&D is needed to develop them (Table 1).

This component of GOFC is the most advanced towards operational implementation, and can act as a pathfinder for the other components. The World Fire Web, sponsored by the Joint Research Centre/Space Applications Institute in Ispra, Italy, is being assembled to produce global data products of active fires. Plans to produce annual maps of burn scars have been announced by JRC/SAI (SPOT-VEGETATION sensor), ESA/ESRIN (ATSR), and NASA (MODIS).

Table 1. Forest Fire Information Products (Ahern et al., 2000)

	Spatial resolution	**Revisit cycle**	**Data delivery**	**Source(s) of data**
Fire monitoring	250 m – 1 km	24 h	12 hours	Coarse resolution optical (thermal)
Mapping burned area	25 m – 1 km	Annual, **monthly**	2 months	Coarse and fine resolution optical with SAR backup
fuel loads, moisture content, fire intensity, fire severity, fuel consumption, flaming vs. smoldering combustion, fire damage, emission factors, emissions rates carbon emissions (particle and gas)	250 m – 1 km	TBD	TBD	Coarse resolution optical land cover meteorological data models

Forest cover characteristics and changes: This is the most important but the most challenging of the GOFC themes. The products have the greatest appeal to the widest spectrum of users including forest resource managers, policy makers, and scientists studying the global carbon cycle and biodiversity loss. The GOFC strategy calls for a systematic program for periodic mapping of land cover at coarse resolution (250 – 1000 m) on a five year cycle, combined with periodic mapping and monitoring of forested areas at fine (~25 m) resolution. Very large datasets must be acquired, assembled, processed, and analyzed from coarse resolution optical sensors, fixed and pointable fine resolution optical sensors, and SAR sensors. Most of the needed technology has been demonstrated, but assembling coordinated systems to generate the required products represents a very major challenge.

The original GOFC products are identified in Table 2. A proposed revision is presented in Table 3. In the revision, we move away from the concept of discrete classes toward the concept of continuous fields, as demonstrated by DeFries et al. (in press). This approach avoids the problem of arbitrary classification thresholds, which invariably fail to satisfy some user groups. Continuous field products may also be more appropriate as direct inputs into carbon budget models. They can be used as intermediate products by users who need discrete classes, who are then free to set class boundary thresholds however they want.

The GOFC land cover change classes identified in the strategic design are presented in Table 4. If a "continuous fields" approach is adopted, the change classes can be modified accordingly (Table 5).

Table 2. Original GOFC Land and Forest Cover Classification Scheme

Land Cover					
Water					
Snow and Ice					
Barren or sparsely vegetated					
Built-up					
Croplands					
Grasslands					
Forest	**Leaf type**	Needle	Broadleaf	Mixed	
	Leaf longevity	Evergreen	Deciduous	Mixed	
	Canopy cover	10-25%	25-40%	40-60%	60-100%
	Canopy height	0-1 m	1-2 m	>2m	
		(low shrub)	(tall shrub)	(trees)	
Forest special theme: flooded forest					
Spatial resolution: 1 km (coarse) and 25 m (fine)					
Update cycle: 5 years (coarse and fine)					

Table 3. Revised GOFC Land and Forest Cover Classification Scheme

Land Cover		• Compatible with highest level of FAO Africover classification • More detail will be needed if GOFC expands to include all vegetation			
Water					
Snow and Ice					
Barren or sparsely vegetated					
Built-up					
Croplands					
Grasslands					
Forest	**Class name**	**Continuous field variable**	**Variable Range**	**Initial Accuracy**	**Ultimate Accuracy**
	Leaf type	Broadleaf/needle-leaf ratio	0 – 100%	~ 25%	~10%
	Leaf longevity	Evergreen/deciduous ratio	0 – 100%	~ 25%	~10%
	Canopy cover	% canopy cover	0 – 100%	~ 25%	~10%
	Canopy height	height	0 – 100 m	~ 3 m	~ 1 m
Forest special theme: flooded forest					
Spatial resolution: 1 km → 250 m (coarse) and 25 m (fine)					
Update cycle: 5 years * coarse, all land area * fine, "priority" areas ("priority" to be defined)					

Table 4. Original Forest Change Classes

	Coarse	**Fine**
Resolution	1 km initially 250 m as soon as possible	~25 m
Cycle	Annual wall-to-wall	5 year wall-to-wall 20% - 30% annual
Classes	No change Forest → non-forest Non-forest → forest	No change Forest → non-forest Non-forest → forest
Special Products	Burned forest	Forest fragmentation Forest change occurrence

Table 5. Revised Forest Change Classes (unofficial)

	Coarse	**Fine**
Resolution	1 km initially 250 m as soon as possible	~25 m
Cycle	Annual wall-to-wall	5 year wall-to-wall 20% - 30% annual
Classes	"Significant" change in one or more continuous field variables ("significant" to be defined)	"Significant" change in one or more continuous field variables ("significant" to be defined)
Special Products	Burned forest	Fragmentation Forest change occurrence

Forest biophysical processes: This theme reflects a key component of the sizeable effort to use earth observation data to understand, and eventually balance, the earth's carbon budget. With the signing of the Kyoto protocol in 1997, information on the carbon cycle now has policy as well as scientific implications. The major goal for this objective is to quantify net primary productivity of forests, combining satellite data with ecosystem process models. The products identified in the GOFC strategic design are presented in Table 6.

Table 6. Products for forest biophysical processes.

Product	Units	Accuracy Needed	Spatial Resolution	Temporal Cycle	Source of Data
LAI	m^2/m^2	± 0.2-1.0	1 km	7 days	Coarse resolution optical
PAR	W/m^2	± 2 – 5 %	> 1 km	30 min - 1 day	Geostationary optical (low and mid latitudes); Coarse optical (high latitudes).
FPAR	dimension-less	± 5 – 10 %	1 km	7 days	Coarse resolution optical
Above-ground Biomass	g/m^2	± 10–25 %	1 km	5 years	Inferred from land cover until spaceborne measurements are available
NPP	$gC/m^2/yr$	± 20-30 %	1 km	1 year	Above products plus ground and spaceborne meteorological data

5. Conclusions

At the time this appendix is being written, GOFC is approximately 2½ years old. The development of the Terrestrial Carbon Theme provides important opportunities for synergy.

The Terrestrial Carbon Theme can benefit from the experiences of GOFC as it has worked from a concept, through a design process, into early implementation. The products identified in the GOFC design process are outlined here and can provide the basis for further development by the Terrestrial Carbon Theme. In particular, the carbon budget modeling community can provide valuable guidance on those products which will produce the greatest benefit for the smallest investment of time and resources.

Participation in the development of the Terrestrial Carbon Theme provides greater awareness to GOFC participants of the current state of the art and problems associated with carbon budget modeling, atmospheric flux measurements and associated efforts to document and model the ecosystem and ecosystem processes in the vicinity of flux towers. The increased contact with the carbon budget observation and modeling community is especially useful.

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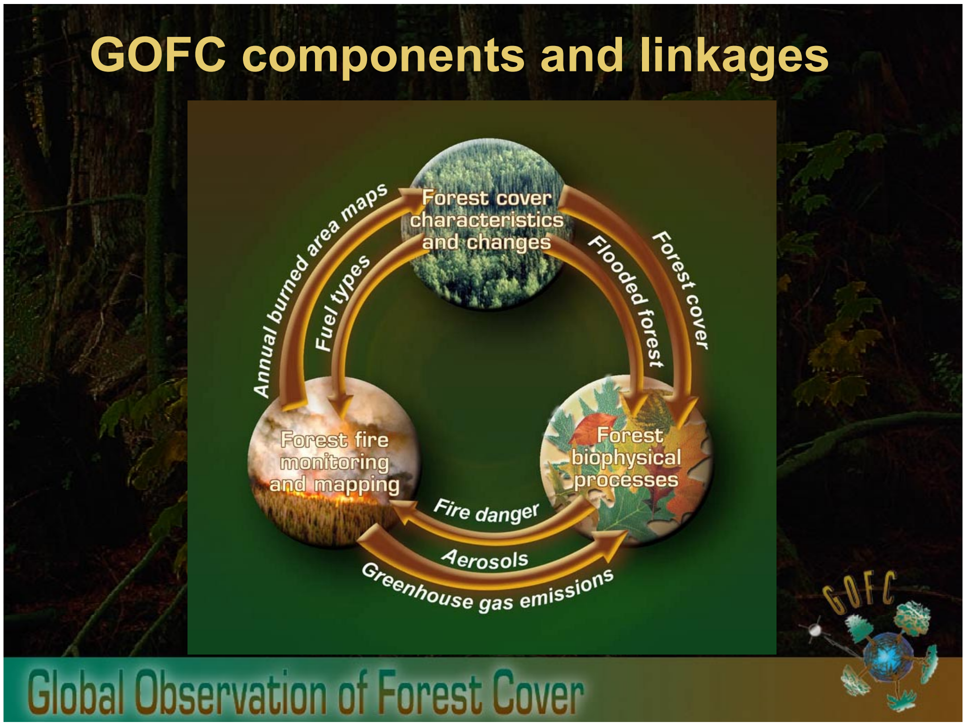

GOFC components and linkages

Forest cover characteristics and changes

Forest fire monitoring and mapping

Forest biophysical processes

Annual burned area maps

Fuel types

Flooded forest

Forest cover

Fire danger

Aerosols

Greenhouse gas emissions

GOFC

Global Observation of Forest Cover

Appendix 4: List of acronyms

AATSR	Advanced Along-Track Scanning Radiometer
AIRS	Atmospheric Infrared Sounder
ASAR	Advanced Synthetic Aperture Radar
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BDC	BioDiversity Convention
BOREAS	Boreal Ecosystem - Atmosphere Study
CBL	Convective Boundary Layer
CCD	Convention to Combat Desertification
CEOS	Committee on Earth Observation Satellites
CH_4	Methane
CLIMDB	Climatic Data Base
CO	Carbon monoxide
COP	Conference Of Parties
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWG	Carbon Working Group
DAAC	Distributed Active Archive Centre
DIC	Disolved inorganic carbon
DIS	Data and Information System
DMSP	Defense Meteorological Satellite Program
DOC	Disolved organic carbon
ECMWF	European Centre for Medium-Range Weather Forecasts
EOS	Earth Observing System
ERS	European Research Satellite
ESA	European Space Agency
ETM	Enhanced Thematic Mapper (Landsat)
FACE	Free Air Enrichment Experiment
FAO	Food and Agriculture Organization of the United Nations
FCCC	Framework Convention on Climate Change
FIFE	First ISLSCP Field Experiment
GAIM	Global Analysis, Interpretation and Modelling
GAW	Global Atmospheric Watch
GCM	General Circulation Model
GCOS	Global climate observing systems
GEWEX	Global Energy and Water Cycle Experiment
GHG	Greenhouse Gas
GLI	Global Imager
GOOS	Global observing systems for oceans
GPCP	Global Precipitation Climatology Project
GtC	Gigatonne of carbon
GTOS	Global Terrestrial Observing System
GTOS	Global terrestrial observing environment
HAPEX	Hydrological – Atmospheric Pilot Experiment
HRV	High Resolution Video (SPOT)
HRVIR	High Resolution Visible and Infrared sensor
IASI	Improved Atmospheric Sounding Interferometer
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Program
IGFA	International Group of Funding Agencies
IGOS-P	Integrated Global Observing Strategy Partnership
IHDP	International Human Dimensions Programme
IOC	Intergovernmental Oceanographic Commission

IPCC	Intergovernmental Panel on Climate Change
ISLSCP	International Satellite Land Surface Climatology project
JERS	Japanese Earth Remote Sensing
JRC	Joint Research Centre of the European Commission
LAI	Leaf Area Index
Landsat	Land Remote Sensing Satellite
LIDAR	Light Detection and Ranging Instrument
LTER	Long-Term Ecological Research
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
N_2O	Nitrous Oxide
NASA	U.S. National Aeronautics & Space Administration
NMVOC	Non-Methane Volatile Organic Compound
NOAA	National Oceanic and Atmospheric Administration
NPOESS	NOAA Polar Orbiting Environmental Satellite System
NEP	Net ecosystem productivity
NO_X	Nitrogen oxides (NO, NO_2, NO_3)
NPP	Net primary productivity
NSF	National Science Foundation
NWP	Numerical Weather Prediction
O_2	Molecular oxygen
PAR	Photosynthetically active radiation
SAR	Synthetic aperture radar
SOTER	Soil and Terrain Database
TCO	Terrestrial Carbon Observation
TEMS	Terrestrial Ecosystem Monitoring Sites
TM	Thematic Mapper
TOPC	Terrestrial Observation Panel for Climate
TRAGNET	United States Trace Gas Network
TRMM	Tropical Rainfall Measuing Mission (U.S. Japan)
UKMO	United Kingdom Meteorological Office
UNEP	UN Environmental Programme
UNESCO	UN Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
VCL	Vegetation Canopy Lidar
VOC	Volatile organic carbon
WCRP	World Climate Research Program
WiFS	
WMO	World Meteorological Organisation