Global Carbon Project

The Science Framework and Implementation

Editors:
Josep G. Canadell, Robert Dickinson, Kathy Hibbard, Michael Raupach, Oran Young

Prepared by the Scientific Steering Committee of the Global Carbon Project* and others:
(*) Michael Apps, Alain Chedin, Chen-Tung Arthur Chen, Peter Cox, Robert Dickinson, Ellen R.M. Druffel, Christopher Field, Patricia Romero Lankao, Louis Lebell, Anand Patwardhan, Michael Raupach, Monika Rhein, Christopher Sabine, Riccardo Valentini, Yoshiki Yamagata, Oran Young, Riccardo Valentini

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For comments on this draft, please, email Pep Canadell at pep.canadell@csiro.au

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2. Introduction

This document outlines the research Framework of the Global Carbon Project (GCP), a joint research project on the global carbon cycle of the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the World Climate Research Programme (WCRP). The GCP is also one of the first projects established under the Earth System Science Partnership (ESSP) sponsored by IGBP, IHDP, WCRP, and Diversitas. This document is, therefore, addressed to the large research community including multiple disciplines of natural and social sciences, and policy makers.

This section gives an overview of the project, the motivation, vision, and the main strategic elements. Section 3 outlines the three proposed science themes, and for each one the relevant knowledge base, present research areas, areas of uncertainty and suggested research priorities. An initial Implementation Plan for the GCP is described in Section 4. There are also a number of appendices at the end of the document with supporting documents on national and international programmes and networks relevant to global research of the carbon cycle.

The Carbon Challenge

The carbon cycle is central to the Earth system, being inextricably coupled with climate, the water cycle, nutrient cycles, and the production of biomass by photosynthesis on land and in the oceans. This production sustains the entire animal kingdom, including humans through their dependence on food and fibre. Hence, a proper understanding of the global carbon cycle is critical both for understanding the environmental history of our planet and its human inhabitants, and for predicting and guiding their joint future.

The Vostok ice core record (**Figure 1**) illustrates the limits and patterns of natural variability of atmospheric carbon dioxide (CO_2) and the correlation of atmospheric CO_2 and methane (CH_4^+) concentrations to inferred temperature over the last 420,000 years. From about one-half million years ago until about 200 years ago, the climate system has operated within a relatively constrained range of temperature and the concentrations of atmospheric CO_2 and CH_4. In the pre-industrial world, atmospheric CO_2 concentrations oscillated in roughly 100,000-year cycles between 180 and 280 ppmv (parts per million by volume), as the CO_2 climate system pulsed between glacial and interglacial states. The ice core record clearly illustrates that atmospheric composition and climate (especially temperature) are closely linked.

Comparison of the Vostok record with contemporary measurements of atmospheric CO_2 concentration reveals that the Earth's System has dramatically left this regular domain of glacial-interglacial cycling (**Figure 2**). Atmospheric CO_2 concentrations are now nearly 100 ppmv higher than at the interglacial maximum, and the rate of increase has been at least 10 and possibly 100 times faster than at any other time in the past 420,000 years. Concentrations of other greenhouse gases, including CH_4 and nitrous oxide, are increasing at comparable rates. These increases are unquestionably due to human activities, and are already having consequences for climate. For example, a temperature record for the past millennium indicates that the contemporary climate system is now responding to changing greenhouse gas concentrations in the atmosphere. Far greater changes are predicted over a time-scale of centuries, with a confidence that has increased substantially between the Second and Third Assessments of the Intergovernmental Panel on Climate Change (IPCC 1996; 2001a,b,c). These changes indicate that the Earth system has moved well outside the "operating range" of the carbon cycle, over the past half million years. Change has been uni-directional and of unprecedented rate; i.e. humans have pushed the Earth system into uncharted territory.

The role of humans in the carbon cycle is not new. Human activities have influenced it for thousands of years through agriculture, forestry, trade and energy use in industry and transport. However, only over the past two or three centuries have these activities become sufficiently widespread and far-reaching to match the great forces of the natural world. Moreover, human societies and institutions (social, cultural, political, economic) are not uni-directional drivers of change: they are impacted by carbon cycle and climate changes, and respond to these impacts in ways that have the potential to feed back on the carbon cycle itself (**Figures 3**). One example is the attempt to manage greenhouse gas emissions as part of the global atmospheric commons.

Efforts to identify the location and magnitude of carbon exchanges between atmosphere, land and ocean illustrate the complex interactions between the natural and human aspects of the system, and the difficulty of separating them. The locations of current terrestrial sinks (uptake of CO_2 by land from the atmosphere) may be largely due to patterns of past land-use change, and their magnitudes the result of physiological response to repeated disruption. Patterns of oceanic sinks may also be modified by atmospheric transport of iron-laden dust from continents which, in turn, is influenced by land-use and climatic variability. Areas where humans may manipulate the carbon cycle include enhancing sequestration of carbon in terrestrial ecosystems and the oceans, and minimisation of the massive emissions from fossil fuel combustion.

Present investigations aim to monitor and understand these patterns and processes in the global carbon cycle, and their environmental impacts. A variety of resources and methods are used by different research communities. For example, satellite data, air sampling networks and inverse numerical methods ("top-down" approaches) allow us to study the strength and location of the global-scale and continental-scale carbon sources and sinks. Surface monitoring and process studies ("bottom-up" approaches) provide estimates of land-atmosphere and ocean-atmosphere carbon fluxes at finer spatial scales, and allow examination of the mechanisms that control fluxes at these regional and ecosystem scales (**Figure 4**). An understanding of the natural dynamics and the potential for mitigation will ultimately allow exploring decarbonization pathways using policy instruments and international regimes.

The Vision

The central vision of the GCP is to develop comprehensive, policy-relevant understanding of the global carbon cycle, encompassing its natural and human dimension and their interactions.

This will require co-ordination by the international scientific community across all relevant disciplines and regions, and application of a large number of available resources and techniques. At present, there is not one single international research programme that provides this framework. The GCP was created to fill this gap and provide an overall coordination platform to address highly interdisciplinary and complex problems of the carbon-climate-human system.

Figure 5 shows this complexity and the length to which the GCP wants to take an interdisciplinary approach by understanding a) the natural unperturbed carbon cycle, b) the perturbed carbon-climate-human system, and c) the feedbacks among societies' perceptions, actions we may take on control points, and the dynamics of the natural system.

Through a series of workshops in 1999 and 2002, the scientific community identified three broad science themes for carbon cycle research, which define the scientific scope of the GCP. Each theme is described by an overarching question, as follows:

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

Mandate and Approach

To implement the GCP vision and cover the major three themes, the GCP will be driven by the following scientific mandate:

- To develop a research framework for integration of the biogeochemical, biophysical and human components of the global carbon cycle which recognizes the need for work across disciplines, and temporal and geographical boundaries.
- To synthesize and communicate in a timely fashion new understanding of the carbon-climate-human system to the wide research and policy communities.
- To develop tools and conceptual frameworks to couple the natural and human dimensions of the carbon cycle.

- To provide a global coordinating platform for regional and national carbon programmes to improve observation and research network design, data standards, information and tools transfer, and timing of campaigns and process-based experiments, including the development of data-model fusions schemes.
- To strengthen the carbon-related research programmes of nations and regions, and those in international programmes such as IGBP, IHDP, WCRP and the observation community, through better coordination, articulation of goals, and development of conceptual frameworks.
- To foster research on the carbon cycle in regions that are still poorly understood yet they are believed to play a critical role in the global carbon cycle.

Approach: The GCP will implement its research agenda through collaborative efforts with national and regional carbon programmes and funding agencies, and by leading a limited number of new research initiatives that are feasible within a 3-5 year framework on difficult and highly interdisciplinary problems of the carbon cycle.

Scientific Guidance: The work of the GCP is guided by a Scientific Steering Committee (SSC) made up of scientists covering the main interdisciplinary areas of the GCP Science Framework. The SSC will also consider recommendations made by its sponsor programmes and projects within.

Governance and Time Frame: The GCP answers to the Committee of Chairs and Directors of its three sponsoring Programmes (IGBP, IHDP and WCRP). A time frame of 10 years is envisioned for the GCP, commencing at the beginning of 2002. A mid-term review by the three sponsoring programmes will assess how well the project has met its near-term objectives, monitor progress towards the longer-term goals, and suggest modifications needed to enhance the effectiveness of the Project.

Institutional Linkages: In a broader context, *research* on the carbon cycle is an essential component of many activities addressing the environmental science of the whole Earth system and sustainable development agenda at an international level. The GCP will establish formal and informal partnerships to work with a number of observation, assessment and policy bodies:

1. An integrated strategy for *observation* of the global carbon cycle (Integrated Global Carbon Observation (IGCO)) is under active development within IGOS-P contributions by the Global Observing Systems: Ocean Global Observing System (GOOS), Global Terrestrial Observing System (GTOS), Global Climate Observing System (GCOS), and the GCP. See Appendix B for an executive summary of the IGCO strategy.

2. *Assessment* of scientific research on the carbon cycle, and its interpretation for the policy community, is carried out by the IPCC as requested by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nationals Framework Convention on Climate Change (UNFCCC), the Millennium Assessment (MA), and other assessment programmes.

3. The global carbon cycle has enormous *policy* relevance for greenhouse issues, sustainable development and the provision of ecosystem services, both at national and international levels. There is a need to connect, through appropriate assessment bodies, with international and national policy communities.

3. Science Themes

The Science Framework of the GCP is organised around three themes: (1) patterns and variability; (2) processes and interactions; and (3) management of the carbon cycle. Within each theme, this section describes the acknowledge base (what we already know from past work), current or planned research, and the main areas where important knowledge is lacking, described here as areas of uncertainty. The definition of areas of uncertainty leads finally into a number of questions that define research priorities for each theme. It is notable, however, that many of the research questions bridge across the three themes.

Theme 1: Patterns and Variability

Motivation

The basic structure of the carbon cycle is determined by the flows of carbon among major pools, including carbon in the atmosphere (mainly as CO_2); in the oceans (surface, intermediate waters, deep waters and marine sediments); in the terrestrial ecosystems (vegetation, litter and soil); in rivers and estuaries; and in fossil carbon, which in this era is being remobilised by human activities. Both the flows of carbon among these stores and the store contents themselves have a rich spatial and temporal structure because natural dynamics and human activity (**Figure 6**). An understanding of the patterns and variability in this structure is crucial to defining the basic anatomy of the carbon cycle, to provide diagnostic insight into the driving processes, and to underpin reconstructions of the past and predictions for the future – especially a future subject to anthropogenic perturbations outside the range experienced by the Earth system in recorded history.

Knowledge Base

Present understanding of the patterns and variability of global carbon fluxes is based on (1) global observations, including the atmospheric concentrations of CO_2 and other gases, satellite observations, and *in-situ* terrestrial and oceanic measurements; (2) modelling of atmospheric and oceanic dynamics and biogeochemical processes; and (3) mass balance principles. Together, these have provided strong evidence to support the following points (IPCC 2001a, Field and Raupach 2003; CDIAC 2003):

1. The global fossil fuel emissions have been rising since pre-industrial time and were 5.2 PgC in 1980 and 6.3 PgC in 2002 with the vast majority occurring in the Northern Hemisphere.
2. About half of the CO_2 emitted to the atmosphere by fossil fuel sources is taken up by a combination of terrestrial and oceanic sinks.
3. Observed distributions of atmospheric CO_2 and O_2/N_2, together with atmospheric model inversion studies, suggest that the terrestrial sink occurs predominantly in the northern mid-latitudes.
4. Land-use change results in significant emissions of atmospheric CO_2 in tropical latitudes, whereas it is responsible for a significant carbon sink in northern mid-latitudes.
5. Tropical and boreal forests together account for approximately 75% of the world's plant carbon and for 31% of the non-wetland, non-frozen soil carbon.
6. For the last few decades, observed changes in atmospheric CO_2 concentrations have varied widely (**Figure 7**). The implied rate of carbon accumulation in the atmosphere varies between years by nearly as much as average annual fossil fuel emissions.
7. The interannual variability in carbon exchange with the atmosphere is believed (with some uncertainty) to be dominated by terrestrial ecosystems rather than the ocean.
8. Imports and exports of cereals, wood and paper products accounted for about 0.72 PgC yr^{-1} of "embodied" carbon trade in 2000, and thus affecting regional sinks (production), sources (consumption), and temporary storage (e.g., furniture) (**Figure 8**).
9. Observations show that the net global air-sea flux is 2.2 PgC (-19% to +22%) into the ocean for the reference year 1995, and ocean models and observations suggest that the interannual variability of the global ocean CO_2 flux is around 0.5 PgC yr^{-1}. The largest interannual variability appears to occur in the equatorial Pacific Ocean.
10. The broad pattern of oceanic sources and sinks of atmospheric CO_2 are known: tropical waters generally act as sources and higher-latitude waters act as sinks. The strongest oceanic CO_2 sink is the North Atlantic Ocean. The strongest source is in the Equatorial Pacific Ocean.

11. Lateral fluxes in rivers and trade/commerce are important in explaining patterns and distribution of the carbon sources and sinks. Carbon exports from rivers to the coastal ocean are higher than 1 PgC yr^{-1}.

Current research

The above conclusions are largely based on observation and modelling. This section describes continuing work on these two aspects of carbon cycle patterns and variability, including observations of human interactions with the carbon cycle and strategies for combining observations with models.

a. Global Monitoring

Long-term monitoring is an essential research tool for detecting, attributing and predicting the spatial and temporal patterns in the global carbon cycle. Major time series have become touchstones for the science of the carbon cycle and the Earth system (IPCC 2001a). Examples include the multi-decadal records of atmospheric composition (notably CO_2 concentrations) from baseline observing stations at Mauna Loa, Cape Grim and elsewhere (e.g., Keeling and Whorf 2000); and the 420,000-year Vostok ice core record shown in **Figure 1** (Petit et al. 1999). Spatial data is also critical, for instance, the global net terrestrial primary production (NPP) inferred from satellite observations and Dynamic Global Vegetation Models (DGVMs) (**Figure 6a**).

The global observation tools necessary to understand the Earth system (including the global carbon cycle and human impacts upon it) are being assembled in a cooperative global observing strategy, the Integrated Global Observing Strategy and its Partners (IGOS-P). The principle behind IGOS-P is to develop a strategy for coupling major Earth- and space-based systems for global environmental observations of the land, oceans and atmosphere.

As part of the IGOS-P, a strategy for international global carbon cycle observations over the next decade is being developed through an Integrated Global Carbon Observation (IGCO) theme in close collaboration with the GCP. This strategy will (a) integrate remote and *in situ* observations; (b) link ocean, terrestrial and atmospheric observing strategies; and (c) involve close collaboration with the international carbon cycle research and assessment communities (**Appendix B**). Towards these goals, a Terrestrial Carbon Observation (TCO) component of the Global Terrestrial Observation System (GTOS) component has already been developed to provide information on the spatial and temporal distribution of carbon sources and sinks in terrestrial ecosystems, using data obtained through ground and satellite-based observations.

The new products from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board of TERRA and AQUA satellites NASA's Earth Science Enterprise will provide an important dynamic long-term record of the terrestrial and ocean metabolism. This will include a number of consistent, calibrated and near-real-time measures of major components of the global carbon cycle including global Net Primary Productivity (NPP) at 1x1 Km resolution every 8 days (**Figure 9**).

b. Atmospheric Observations

Atmospheric trace gas concentration measurements are currently sponsored by numerous countries, in most cases as part of research programmes. These data have made pivotal contributions to the awareness and understanding of climate change. The atmosphere is an excellent filter of spatially and temporally varying surface fluxes, integrating short-term fluctuations while retaining the large-scale signal (Tans et al. 1990). The distribution of CO_2 in the atmosphere and its time evolution can thus be used to quantify surface fluxes.

Regional carbon budgets are currently calculated from CO_2 measurements at about 100 sites, supplemented by a few tall towers and aircraft programmes, using atmospheric inversion methods. Among the most significant impacts to date of network observations (and their interpretation by inversion methods) has been the discovery of major CO_2 net sinks in the Northern Hemisphere, both terrestrial and oceanic (IPCC 2001a; Gurney et al. 2002.) However, due to the sparseness of the existing network, retrieval of the space-time patterns of surface fluxes is highly uncertain. Without the use of additional constraints, it is not possible to resolve sources or sinks within latitude zones between oceans and continents, even at the most densely sampled northern mid-latitudes. Even when such constraints are available from local process-oriented studies (e.g., Wofsy et al. 1993), it is difficult to connect this understanding to global CO_2 patterns, because the atmosphere is so under-sampled (Braswell et al. 1997). Without a comprehensive spatial coverage of CO_2 measurements, uncertainties cannot even be localised unequivocally to transport model or data error, or inversion procedures.

To overcome accuracy and consistency problems in these measurements, GLOBALVIEW-CO_2 was established as a cooperative atmospheric data integration project. It presently involves approximately 24 organisations from 14 countries (**Figure 10**). An internally consistent 21-year global time series has been compiled so far. In addition to CO_2, the observing system includes measurements of $\delta^{13}C$ and $\delta^{18}O$ in CO_2, CH_4, CO, the O_2/N_2 ratio, and many other species. Measurements of $\delta^{13}C$ and O_2/N_2 provide information on the partition of net carbon fluxes into the atmosphere between fossil-fuel emissions, land-atmosphere exchange and ocean-atmosphere exchange. Measurements of $\delta^{18}O$ are used to estimate gross primary production, as opposed to net ecosystem exchange. The CH_4 and CO measurements are used to estimate the contribution of combustion, in addition to the significance of CH_4 as a greenhouse gas. In addition, the emerging strategy, GLOBALHUBS has outlined a plan for global intercalibration of CO_2 concentrations and isotopes.

Three significant developing contributions to atmospheric observation are as follows:

1. Continental and opportunistic measurements of atmospheric composition will extend the network of observations not only for CO_2 but also, to some extent, for other gases mentioned above. Existing atmospheric observing networks focus largely on measurements in the remote marine boundary layer, to avoid contamination by local sources and sinks. These data are invaluable in providing a baseline. Studies have highlighted a particular need, however, for additional measurements over the continents. These are more complicated, due to strong variability in space and time, caused by surface heterogeneity and diurnal cycling of the atmospheric boundary layer between convective and stable states, affecting the mixing of CO_2. Developments in sampling strategies are likely to progressively overcome these difficulties. Such measurements are commencing, using a combination of flask-sampled and continuous data from FluxNet sites (see below), commercial and specially deployed aircraft, and ships of opportunity. For continuous CO_2 measurements, a key technological development is the recent availability of lightweight, low-maintenance CO_2 sensors with precision comparable to present continuously attended baseline instrumentation.
2. Methods for network optimisation will improve the next generation of upgrades to existing sampling networks. These rely as a primary technique on the use of data-assimilation methods to optimise network design.
3. The measurement of CO_2 from space will have major impacts in filling the present sparse and uneven ground-based atmospheric sampling network, on land, at sea and in the atmosphere which, as noted above, severely limits the atmospheric-inverse approach (Rayner and O'Brien 2001).

c. Satellite Observations of Atmospheric CO_2

Remote sensing of the earth's surface and atmosphere by space-borne instruments will improve all aspects of carbon cycle research. Two new infrared instruments for operational meteorological soundings are currently being developed for the measurement of CO_2 from space: the Atmospheric Infrared Sounder (AIRS), launched on board of EOS-Aqua in March 2002; and the Infrared Atmospheric Sounder Interferometer (IASI), on board the first Meteorological Operational Polar Satellite (METOP) in 2005. Both instruments will measure most of the infrared spectrum at high spectral resolution, and will be accompanied by the Advanced Microwave Sounding Unit (AMSU), a microwave sounder that can be used synergistically with either AIRS or IASI. The significance of this is that AMSU detects only the atmospheric temperature, while AIRS and IASI are also sensitive to CO_2 concentration. It is anticipated that additional properties of CO_2 will be retrieved from these sensors.

A proof of concept study has been completed with existing instruments such as the TIROS-N Operational Vertical Sounder (TOVS), flown on board the U.S. National Oceanic and Atmospheric Administration (NOAA) polar meteorological satellites since 1978. Despite the quite limited spectral resolution of these space-based radiometers, clear signatures of the seasonal cycles and trends in CO_2 and other greenhouse gases (N_2O and CO) may be extracted from TOVS measurements and interpreted in terms of seasonal and annual variations of their atmospheric concentrations (Chedin et al. 2002a,b).

Also important for retrieving CO_2 concentrations from space is the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) launched on the Envisat platform in 2002 (Bovensmann et al. 1999). This instrument will provide high-resolution spectra of the sunlight reflected by the Earth, including the absorption bands that are being considered for retrieving the greenhouse gases CO_2, CH_4, N_2O, H_2O and CO. The estimated total column precision of the above listed gases is about 1% for CO_2, CH_4 and H_2O and about 10% for CO N_2O (Buchwitz et al. 2000). The horizontal resolution of the SCIAMACHY nadir measurements is typically 30km x 120km for relevant gases (30km x 240km at high latitudes). A similar passive differential absorption technique has also been recently proposed for the CARBOSAT satellite (with greatly improved spatial and spectral resolutions).

The key assignment for each of these missions is a set of column CO_2 measurements of individual precision better than 1% (< 3ppmv). Simulations show that satellite measurements improve measurement of the carbon fluxes by a factor of up to ten as compared to the network of surface stations. The greater coverage in time and space provided by the satellite data will improve existing estimates even though the precision of individual measurements may be an order of magnitude lower than those estimated from satellites (Rayner and O'Brien 2001).

d. Terrestrial Observations

Traditionally, the exploitation of biomass resources has been the primary reason for terrestrial carbon observations, motivating many countries to establish inventories (Cannell et al. 1999; Houghton et al. 2000) and monitoring networks to support the sustainable use of forests, croplands and grasslands. In parallel, national research programmes have initiated long-term ecophysiological observations at numerous sites, and increasingly use remotely sensed observations of land-cover.

Currently, there are a number of existing internationally coordinated networks relevant to terrestrial carbon observation (data provides), including both ground networks of global scope and satellite-based observations (**Appendix C**). Among the ground-based networks the FluxNet programme coordinates a global network of over 200 sites, at which tower-based eddy covariance methods provide continuous measurements of the land-atmosphere exchanges of CO_2, water vapour, heat and other entities (**Figure 11**). At many of these sites, complementary measurements are made of carbon stores and fluxes in vegetation, litter and soil pools, and other ecophysiological variables. Flux tower data with scaling techniques have been already applied successfully to calculate continental-wide fluxes (Papale and Valentini 2003) and are yielding important insights on the controls of seasonal and interannual dynamics. FluxNet is also becoming an important validation tool for the new MODIS products (e.g. net primary productivity) which will be generated every eight days.

The International Long-term Ecological Research Network (ILTER) provides a far more extensive network of lower-technology ecophysiological observations, together with measurements of ecological changes. Harmonisation of regional ground observation programmes is being addressed by the Global Terrestrial Observing System (GTOS), as part of the GT-Net programme (**Appendix C**). Some research programmes are also addressing the harmonisation of data collected nationally, for example, a comparison of national forest inventories in North America and Asia (Goodale et al. 2001), and soil organic matter (Smith et al. 2001).

A sample of current *data users*, or programmes requiring information on the carbon cycle in terrestrial ecosystems, is also given in **Appendix C** as an illustration of the breadth of the user community. Data requirements differ in coverage (global, continental, national), type of product and the user group. It should be noted that for some activities, national agencies require consistent information beyond their territories.

In addition to the above acquisition and product generation programmes, a number of projects have been undertaken that contribute to the development of systematic global observing capabilities, such as the Global Observations of Forest Cover (GOFC) project; the World Fire Web, providing data and information about biomass burning; the GTOS Net Primary Production (NPP) project, providing data to support NPP estimation; and the IGBP NPP-intercomparison project, contributing to the improvement of algorithms for ecosystem productivity (Cramer and Field 1999).

Several major emerging trends in the observation of terrestrial carbon pools and fluxes are likely to accelerate in the next few years:

1. Increased attention will be given to methods for combining measurements at multiple scales, such as eddy covariance, ecophysiological and process-level data, and remotely sensed data (See also, g.Scale Interactions. in Theme 2).
2. A closely related direction will be the synthesis of observations and models, through inversion, data assimilation and multiple-constraint approaches applied to a combination of terrestrial models and observations (see also g.Synthesis of Observations and Models in Theme 1).
3. The use of isotopes and other tracers (^{13}C, ^{14}C, ^{18}O, ^{15}N, ^{2}H, ^{3}H) will provide additional measurement possibilities and constraints on models.
4. There will be an increasing diversity of terrestrial observations, as nations implement carbon monitoring programmes for determining stocks and fluxes in the mandated categories for greenhouse gas emission estimations under the Kyoto Protocol.

e. Ocean Observations

Traditional shipboard oceanographic surveys are a necessary element of any sampling strategy, providing continuity with historical data and the capability for full water column sampling, high accuracy and precision laboratory measurements, and detailed process studies. A continuing global survey programme is under way, to be coordinated by the Ocean Carbon Dioxide Advisory Panel (sponsored by the Scientific Committee on Ocean Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) and the GCP, working in tandem with the CLimate VARiability and Predictability Project (CLIVAR) to make plans to re-occupy some of the World Ocean Circulation Experiment (WOCE) hydrographic lines.

Higher resolution shipboard spatial data is available for some *in-situ* surface measurements, in particular the sea surface CO_2 partial pressure (pCO_2) required for air-sea carbon flux estimates. Shipboard underway pCO_2 systems are commonly used on oceanographic research cruises (a recent example being the WOCE-Joint Global Ocean Flux Study (JGOFS) hydrographic survey), as well as a growing Volunteer Observing Ships (VOS) effort. The quantity of such measurements will increase in the future and will need better coordination to optimise the basin-scale and global coverage.

Because of their expense and logistic requirements, large-scale shipboard surveys are conducted only infrequently. Such temporally limited measurements offer a picture of the approximate average state of the ocean but do not resolve well the variability on seasonal, interannual and decadal time scales. To resolve these temporal patterns, long-term time-series measurements of carbon and other biogeochemical variables at fixed locations are crucial. The best-known open-ocean time series at present are the more than decade-old US JGOFS stations near Hawaii (Hawaii Ocean Time-series programme - HOT) and Bermuda (Bermuda Atlantic Time-series Study- BATS). The HOT and BATS monthly data include carbonate system parameters and other traditional biogeochemical data, such as primary productivity, chlorophyll, nutrients, and near-surface sediment traps. They have led to a number of key discoveries, including the demonstration of increasing surface dissolved inorganic carbon (DIC) concentrations and the importance of nitrogen fixation in the subtropical Pacific Ocean. To be most effective, these time-series sites should be thoroughly integrated into the hydrographic and VOS survey programmes, including measurements from moorings and drifters. The time-series data can provide the temporal context for the spatial surveys and *vice versa*.

A number of satellite data sets have direct applicability to the ocean carbon system (**Appendix C**). The most obvious are ocean colour data, which were collected beginning with CZCS (1979-1986) and has been greatly expanded in recent years (OCTS, 1996-1997; POLDER; SeaWiFS, late 1997 to present). Relevant physical data sets include sea surface altimetry (TOPEX/Poseidon, ERS) for mesoscale variability and physical circulation, sea surface temperature (Pathfinder AVHRR and other platforms), and surface wind speed (NSCAT, QuickScat). New developments may make it possible for measuring salinity from satellites.

Major emerging directions for ocean observations include the following:

1. Continuing expansion of ocean observations, in temporal and spatial density, and in the range of chemical and biological parameters measured. Based on satellite data on Sea Surface Temperature (SST), winds and ocean colour will continue to provide critical information on large-scale patterns and variability of upper-ocean physics and biology. For those quantities that cannot be resolved from space, *in-situ* autonomous measurement/sampling technologies are being developed. Particularly promising directions for *in-situ* chemical sampling include new autonomous sensors (for example, pCO_2, Dissolved Inorganic Carbon (DIC), nutrients, particulate inorganic carbon, Particulate Organic Carbon (POC), bio-optics) and ocean platforms (such as moorings, drifters, profiling floats, gliders, and autonomous underwater vehicles).

2. Enhanced methods for the interpretation of ocean observations will provide additional information on regional interannual variability in air-sea fluxes. Such information is now emerging from repeat observations of surface water pCO_2. Estimates of changes in ocean carbon inventories and transports are needed to contribute to basin-scale carbon budgets for the ocean.

3. The development of a comprehensive ocean carbon observing system can be advanced through improved organisation and coordination. This will involve (1) identifying and supporting those programme elements that are currently in operation (such as time-series stations, hydrographic sections and VOS lines) or in the planning stages; (2) convening and encouraging international meetings of expert groups to refine observing system requirements for scientific and operational monitoring goals; and (3) developing cooperative relationships with other physical, chemical and biological ocean field efforts, with special emphasis on CLIVAR and GOOS. Projects are presently underway in both the North Atlantic and North Pacific to continuously monitor the basin-

scale links from Volunteer Observing Ship (VOS) lines. However, these programmes need long term support to build and maintain available datasets.

4. The development of ocean carbon assimilation and inverse models is advancing rapidly (as for atmospheric and terrestrial observations).. The inclusion of enough process-level information will be critical to address spatial-temporal patterns and detection-attribution of controls of fluxes. As the observational programmes mature, they will provide an unprecedented data stream that can be quickly fed into data-driven models. These models can help provide the time and space scale interpolation to evaluate global fluxes and inventories of carbon.

f. Observations of Human Interactions with the Global Carbon Cycle

The human components of the global carbon cycle include emissions, sinks, lateral flows, commodity production and consumption. These human-induced carbon fluxes interact with a range of other human variables including population, wealth, energy systems, technological pathways, and environmental values and constraints (Dietz and Rosa 1997). Such interactions occur both through perceptions of the consequences of human-induced changes in the carbon cycle, and through other major factors such as economic and social drivers, and water and food supplies.

A range of existing systems provide relevant data on these human-mediated carbon fluxes. These include national emissions inventories, forestry and land-use inventories, national carbon accounting systems, regional environmental reporting, and trade and commodity production data. The challenge is clearly to integrate these disparate and often indirect data sources.

In the area of observations of human interactions with the carbon cycle, major emerging directions include:

1. the differing roles of countries, regions and sectors in the carbon cycle. For example, the vast majority of fossil fuel emissions occur in the Northern Hemisphere, while land use-driven changes tend to originate in tropical latitudes. International corporations are key contributors of data and analyses of such trends.
2. increasingly refined assessment of regional impacts and vulnerability to climate and carbon-cycle changes. Although there are already different documents on this issue, a major challenge will be to explore the ways in which different regions, sectors, ecosystems and social groups will be confronted by, and/or be able to manage, changes in the carbon cycle (O'Brien and Leichenko 2000).

g. Synthesis of Observations and Models

Only a few of the observations described above give direct information on the fluxes and stores that constitute the global carbon cycle, and none offer an adequate direct picture of spatial and temporal patterns. It is therefore necessary to infer these indirectly. Several methods have been developed for this, all based on the use of information from both observations and models as mutual constraints. These approaches include:

1. *Inversion methods:* Global atmospheric inversions use observations of atmospheric composition from global *in-situ* networks, together with global atmospheric transport models, to infer spatially averaged net fluxes of CO_2 and other entities between the surface and the atmosphere (e.g., Gurney et al. 2002). The principle is to seek the source-sink distribution of a passive tracer (CO_2), which, together with a transport model, provides maximum consistency with available, globally distributed concentration measurements.

Atmospheric inversions provide constraints on total carbon sources and sinks, but do not offer information on the processes responsible. Currently, their spatial resolution is extremely coarse. They can partition between the tropics and Northern and Southern Hemisphere extra-tropical regions, and between land and ocean exchanges, but they do not provide a tropical carbon balance and cannot resolve satisfactorily longitudinal patterns. Their regional resolution is highly limited by data, particularly the tropics and the interiors of continents. There is an ongoing effort to use vertical profiles to help fill this gap. Inversions also depend on the choice of atmospheric transport model, especially on scales of ocean basins, continents, or smaller.

Atmospheric inversion methods have also been applied regionally, using mesoscale models (Gloor et al. 2001) and atmospheric boundary-layer budget approaches (Raupach et al. 1992). Plume studies of forest fires and urban areas have also been used to give otherwise unavailable information on gaseous sources, through species and isotopic measurements. Applications at the scale of vegetation canopies have been used to partition sources and sinks between vegetation and soil (Leuning 2000).

Ocean inversions use similar principles to infer ocean-atmosphere CO_2 exchanges working from ocean pCO_2 and other data. They are subject to broadly similar data requirements as for atmospheric inversions. In particular, the accuracy and density of measurements is a major issue, and results are sensitive to the ocean transport model employed.

2. *Data assimilation methods:* A second broad approach to the synthesis of observations and models is data assimilation. Here, time series of global data are used to force a dynamic model into optimal conformity with the data at a given time, while respecting the conservation requirements on the various fields represented in the model, for example, conservation of mass (le Dimet and Talagrand 1986). These methods are used extensively in atmospheric and oceanic circulation models to generate "four-dimensional data assimilation" fields for physical quantities (Chen and Lamb 2000), but their use in carbon cycle modelling is still in the future.

3. *Multiple-constraint methods:* A third emerging direction is the multiple-constraint approach (Raupach et al. 2002). While observations (even of multiple kinds) do not give complete, direct information about the space-time distributions of the fluxes and stores constituting the global carbon cycle, carbon cycle models can predict these fluxes and stores. This is subject to the availability of certain key process parameters that are time-independent or only weakly dependent on time. However, the parameters are often poorly constrained by data, process understanding or both. The observations constitute data sets that (a) constrain the process parameters in a carbon cycle model and (b) challenge the model to produce predictions consistent with all available data. This presents an opportunity to combine measurements and models, using the methods of inverse theory. A variety of approaches are available for parameter optimisation, including use of model adjoints, gradient-based search methods, genetic algorithms and the Kalman filter. Several preliminary applications of this approach have already been made, including the combined use of atmospheric concentrations and surface data at continental scale (Wang 2002); investigations of the combination of atmospheric composition and eddy flux data at global scale (Rayner et al. 2001); use of genetic algorithms to constrain terrestrial ecosystem models of the global carbon cycle with ecological data at continental scale (Barrett et al. 2001); and applications at the scale of vegetation canopies (Styles et al. 2002).

Multiple-constraint approaches are generalisations of the atmospheric inverse approaches described above, in which source-sink distributions at large scales are determined directly from measured concentration distributions alone, without parameterising a process-based carbon cycle model. The atmospheric inverse problem is linear, because of the linearity of atmospheric mixing processes. However, the multiple-constraint problem is usually nonlinear, because the carbon cycle model is generally nonlinear. The multiple-constraint approach relies on access to multiple sources of constraining data with vastly different spatial, temporal and process resolutions, thus producing more constrained predictions. The approach potentially offers a means for discriminating between important and less important avenues for research, to improve the process representations in the carbon cycle model, because the inverse techniques yield uncertainties on estimated parameters. A reduction in these uncertainties constitutes an increase in the information content of the overall prediction of the model. Potential data sources can be assessed for the reduction in uncertainty they provide for model parameters. Importantly, this approach requires the uncertainty characteristics of the data but does not require actual data to be available, allowing preliminary tests of experimental designs.

Major emerging directions in the synthesis of data and models include:

- Extension to other reasonably passive tracers will offer increased understanding of the carbon cycle (noting that all available carbon cycle-related tracers are still not utilized).
- Improvements are occurring and will continue, in measurement density, calibration and interpretation, particularly for these other tracers, but also for atmospheric CO_2 and ocean pCO_2.
- Improved data coverage will allow downscaling to regional estimates, but regional estimates will also require improved knowledge of the global background. Roughly, improvement anywhere hinges on improvement everywhere.
- There are three promising technologies to collect more data relevant to regional inversions: (1) continuous measurements, to allow synoptic variations in transport to provide regional source signatures; (2) potential global coverage of CO_2 column integrals from space; and (3) potentially disposable light-weight sensors for use in low-maintenance environments. All these technologies can interpolate gaps in the current network but must be well linked to it. The great expansion in data flow, associated with these technologies, will require a major data management effort, which has to be international.

- Inversions regionally and in “campaign mode” can provide information on processes, for instance, via atmospheric plume studies from fires or urban areas and regional ocean transport studies.
- Multiple-constraint approaches will be applied to the modelling of combined physical, biological and biogeochemical processes.
- Development of carbon cycle process models, for use in multiple-constraint studies, will be focussed on modelling at an appropriate level of parameterisation, noting that most fully process-based models are over-parameterised for use in this way.
- Developments will be needed in practical nonlinear search methods.
- There will be more rigorous testing for model inconsistencies by the use of subsets of multiple data sources.
- Uncertainty analyses will be further developed, particularly in the context of nonlinear inversions

Areas of Uncertainty and Research Priorities

Despite progress over the last decade, substantial uncertainties remain.

1. Existing global models and observations are unable to determine carbon sources or sinks with acceptable accuracy at regional, continental or interannual time scales largely because of the sparse observing network. For instance, the partition of the Northern Hemisphere terrestrial sink between North America and Eurasia remains unclear.
2. There is no systematic and convincing agreement between "top-down" and "bottom-up" approaches to determining the spatial patterns of major fluxes in the carbon cycle. Budgets at regional, continental or basin scales are not consistent with the global analysis, with major uncertainties in key regions such as the Southern Ocean and terrestrial tropics. Further, estimates of some critical fluxes, such as those associated with land-use change, are only obtainable by bottom-up methods and remain highly uncertain in the global context. Recent evidence suggests a much larger role of lateral transport and the coastal zones for regional carbon budgets than previously thought.
3. The temporal patterns of the major carbon fluxes, and their consequences for stores, are poorly understood at time scales greater than a few years. It is unclear which major stores, whether resolved regionally or biogeochemically, contribute to the long-term variability in atmospheric CO_2 evident in the Vostok ice core record (**Figure 1**) or in shorter records (**Figure 7**).
4. Global estimates of oceanic flux patterns must currently be obtained from data collected over several decades, during which time the spatial pattern of fluxes has changed. This leads to considerable uncertainty in the estimates for any given year, or even decade. Results are dependent on the assumptions made to interpolate both in time and space between the often sparse measurements.
5. There are uncertainties in the spatial and temporal distributions of human-induced fluxes, and the influence of human decision processes. Examples are the fluxes associated with land clearing and anthropogenic terrestrial sinks, and fossil-fuel emissions (IPCC 2000a,b).

In summary, while there may be a general consensus about global and hemispheric distributions of carbon fluxes between the land, ocean and atmosphere, there are large uncertainties in the geographic and temporal distribution of those fluxes at local to regional scales, as well as the human drivers of those fluxes.

The above assessment prompts the following research priorities for Theme 1:

Theme 1: W*hat are the current geographical and temporal distributions of the major stores and fluxes in the global carbon cycle?*

1. *What are the spatial patterns of carbon fluxes and stores at large scales (continents, ocean basins)?*
    a. Determine the carbon budget of the terrestrial tropics, and particularly constrain carbon emissions due to land use change.
    b. Determine the longitudinal distribution of Northern Hemisphere terrestrial sink between North America and Eurasia, and within Eurasia between Europe and Asia.

   c. Determine the spatial patterns and magnitudes of ocean carbon sources, sinks and stores, particularly in the Southern Ocean.
   d. Determine the fluxes and stores of carbon associated with water flow from land to terrestrial water bodies to the coastal zone, and exchanges between the coastal zone and open oceans.
   e. Determine the consequences for the global carbon budget of the uplift, transport and deposition of sediments by both water and wind.
   f. Determine the role of non-CO_2 gases (methane, VOCs) in the global carbon budget.
2. *How do regional and subregional patterns in carbon fluxes interact with the global-scale carbon cycle?*
   a. Determine the space-time dynamics of the biological and solubility pumps in the oceans, and their relative roles in regional and global ocean carbon balances.
   b. Determine current trends in the carbon budgets of key terrestrial biomes (tropical, savannah, mid-latitude, boreal, tundra) which are changing as a result of global-scale changes in the coupled carbon-climate system.
   c. Develop methodologies for using regional and subregional carbon budgets to constrain the global budget, and *vice versa*.
3. *What are the seasonal- to decadal-scale temporal variations in the fluxes and stores making up the carbon budget at global and regional scales, and what are the causes of these variations?*
   a. Determine the relative roles of the oceans, the terrestrial biosphere and fluctuations in human emissions.
4. *What are the space-time patterns of human influences on the carbon cycle, including emissions from fossil fuel burning and land-use practices?*
   a. Quantify the carbon fluxes and stores associated with critical regions and sectors of human influence. Here regions include both rural and urban areas (especially megacities), and sectors include both industrial and agricultural activities.
   b. Resolve discrepancies in measurements of the historical and current rates and patterns of land-use and land-cover change.
   c. Determine the role of human activities in the terrestrial tropics, especially carbon sources due to land use change.
5. *What are the social impacts of changes in the carbon cycle?*
   a. Analyze the social and regional patterns of vulnerability and adaptation to the changes in the carbon cycle.

Theme 2: Processes and Interactions

Motivation

The behaviour of the fluxes and stores that make up the carbon cycle is governed by a set of processes. These include: (a) physical processes in the atmosphere, oceans and terrestrial hydrosphere; (b) biological and ecophysiological processes in the oceans and on land; (c) biogeochemical transformations; (d) a range of natural and anthropogenic disturbances to terrestrial ecosystems, such as fire, agriculture and clearing; and (e) the processes associated with the release of fossil carbon by humans (i.e., energy systems). Some of these emerge as crucial controls on the global carbon cycle and its responses to anthropogenic forcing (e.g., terrestrial sink saturation, the stability of the thermohaline circulation, and the behaviour of the oceanic biological pump).

An understanding of these processes is needed at the level of their basic mechanisms and also of factors which emerge when they act in combination. Such acknowledge is central to understand current and future dynamics of the carbon cycle by learning from the past, through the recognition and interpretation of interactions and feedbacks among key processes and mechanisms. Process understanding is required to develop diagnostic and prognostic tools (Activity 1.2, 2.2, 2.3) that will eventually integrate the dynamics of both biophysical systems and human behaviour. These tools will allow exploring critical system thresholds (e.g., vulnerabilities) beyond which it may be unwise to proceed (Activity 2.3) and to identify mitigation options and their contribution to stabilize atmospheric CO_2.

Knowledge Base

There is already a wealth of understanding of many of these processes, especially at the level of detailed mechanisms. This understanding has been obtained through field observations, laboratory studies, manipulative experiments in the field and process modelling. Carbon cycle processes which are well understood include the following (Walker et al. 1999, IPCC 2001a; Field and Raupach 2003):

1. Net ocean-atmosphere exchanges of carbon are largely controlled by physical processes involving ventilation of thermocline and deeper waters (the solubility pump), with additional influences by biological processes that redistribute carbon from surface to deep waters (the biological pump) (Volk and Hoffert 1985)
2. A key biological control of the biological pump is the large phytoplankton cells which are responsible for much of the export of particulate carbon to the deep ocean (**12**). Apart from large scale changes in ocean circulation on the biological pump, future oceanic uptake of carbon from the atmosphere is expected to increase as atmospheric CO_2 levels rise.
3. A suite of feedback processes control the coupled energy, water and carbon exchanges between terrestrial surfaces and the atmosphere, causing the response of these fluxes to perturbations (such as land-cover transitions or changes) to be significantly scale-dependent. Significant feedbacks in this context include plant physiological responses to atmospheric temperature, humidity, and soil temperature and moisture.
4. The current Northern Hemisphere carbon sink is due to multiple process including forest regrowth, CO_2 and N fertilization, climate change, soil erosion and accumulation in freshwater bodies among others. The relative importance among them is not well known (**Figure 13**).
5. The strength of the terrestrial sink may eventually level off and then decline, despite some potential to increase due to anticipated atmospheric and climate change over the next decades.
6. Under sufficiently elevated atmospheric CO_2 concentrations (>550 ppm) in conjunction with commonly limiting environmental conditions such as water and nutrients, photosynthetic assimilation by terrestrial plants quickly becomes physiologically saturated.
7. Deliberate land-surface modifications will constitute a large forcing of both physical climate and the carbon cycle in the short-term future (a few decades). The climate response to this forcing may feedback onto land management practices.
8. At large (regional to continental) scales, several factors determine the magnitude and direction of CO_2 exchange between terrestrial ecosystems and the atmosphere:
    - extreme climate events such as drought, large shifts in seasonal temperatures, or changes in radiation, induced by large-scale perturbations in levels of atmospheric aerosols (e.g., volcanic eruptions);

- changes in the frequency of fire, clearing and other large-area disturbances that lead to large, short-term carbon losses followed by a long, slow recovery of carbon stocks. Global net primary production (NPP) by land plants is about 57 PgCyr-1 of which approximately 5-10% returns to the atmosphere through combustion (fuel, wildfires, etc).
- changes in plant species' distributions and biome boundaries, induced by environmental forcing or human land-use changes, which affect carbon storage and turnover over large areas (Archer 1995) (e.g., the conversion of evergreen to deciduous forest, forest to grassland or grassland to woodland);
- losses of biodiversity and invasions by exotic species that may effect the use, efficiency and retention of carbon, nutrients (particularly N) and water (Schulze et al. 2000).

9. Instabilities and multiple equilibrium states can potentially occur in the coupled biophysical and biogeochemical system, consisting of the physical climate, hydrological, carbon and nutrient cycles. These can arise primarily due to the nonlinearities and feedbacks involved in the exchanges of energy and matter between atmosphere, land, oceans and ice. Suggested examples include changes to the ENSO phenomenon; potential slowdown or shutdown of the thermohaline circulation in the North Atlantic; ice-albedo runaway (Ghil 1994); and desertification (Ganopolski et al. 1998).
10. There are strong interactions among climate, atmospheric greenhouse gas concentrations and human perturbations to the carbon cycle. This is leading to human intervention at an international level, in the form of the UNFCCC and the associated Kyoto Protocol. Both are international institutions working toward the reduction of net emissions of greenhouse gases into the atmosphere (**Figure 14**).

Current Research

In a biophysical context, observational and manipulative experiments are key tools in formulating and testing hypotheses on the mechanisms that control the flows and transformations in the carbon and related cycles (water, nutrient and energy). They also underpin the formulation of parameterizations in models. In the context of human dimensions, process studies play an analogous role by motivating and testing hypotheses and models describing aspects of social, economic and organisational human behaviour.

The following subsections describe process experimentation and process model development that are key for global carbon cycle studies.

a. Terrestrial Ecophysiological Processes

There are a number of networks of physiological studies which include the already described FluxNet programme, and the ILTER. Fluxnet is providing insights on the daily, seasonal, and inter-annual controls on fluxes of carbon, water and energy. In addition, the Global Change and Terrestrial Ecosystems project (GCTE) of IGBP has established a number of other physiological and experimental networks to study controls processes under current and future global environments. The Biosphere-Atmosphere Stable Isotope Network (BASIN) studies isotopic discrimination in the process of photosynthesis and respiration in order to use atmospheric isotopic signatures to constrain global carbon source/sink estimates and to partition ecosystem fluxes. For instances, BASIN has shown that water availability is a key control on atmospheric $^{13}CO_2$ and highlighted the potential of delta ^{13}C of ecosystem respiration as a useful tool for integrating environmental effects on dynamic canopy and ecosystem processes (Pataki et al. 2003).

In addition, manipulative experiments play a critical role in developing and testing ecophysiological/biogeochemical models. These experiments include warming experiments of both soils and canopies, Free-Air CO_2 Enrichment (FACE) experiments, alteration of the water balance by irrigation or rainfall exclusion, and nutrient enrichment (Canadell et al. 2002, Norby et al. 2001, Rustad et al. 2001). An important contribution of these experiments is yielding insights on ecosystem changes and emerging critical drivers under future environmental conditions. For instance, some of these studies are suggesting that saturation of the CO_2 fertilization effect will take place between 500-600 ppm atmospheric CO_2, a much lower concentration than the natural physiological saturation point at around 1000 ppm (Mooney et al. 1999).

Another emerging issue from these experiments is the response of terrestrial respiration to environmental controls such as temperature, moisture, and nutrient cycling. Temperature responses, in particular, have been questioned recently (e.g., Valentini et al. 2000), leading to the suggestion that terrestrial respiration rates have been overestimated in global carbon cycle models (Cox et al. 2000). Interactions between soil respiration and dry and warm soil conditions are yet to be fully understood and modelled, as well as understanding the effects of rains after dry periods, and the effects of snow packs and length of growing season.

Important long-term drivers of carbon exchanges between land and atmosphere are different from those controlling short-term exchanges, and include changes in ecosystem structure due to biome re-distribution and altered disturbance regimes. Critical issues here are transient effects of biome shifts forced by climate change and the dynamics of large scale biome redistribution given the fragmentation of current ecosystems.

b. Disturbance, Land-Use and Management Practices

Disturbances and changes in land use/cover are important controls of carbon storage. Shifts from one land use/cover type to another are responsible for large carbon fluxes in and out of the terrestrial biosphere (Houghton 1999; Pacala et al. 2001) and shifts on disturbance regimes can drive a region from being a carbon sink to a source (e.g., Kurz and Apps 1999).

A large body of research is taking place to understand the effects of sink strength and carbon storage of multiple land uses (IPCC 2000; Canadell et al. 2002) as efforts on deforestation conservation become more important and land-based mitigation options are explored to help slow down the build up of atmospheric CO_2. Land uses include deforestation, agricultural practices, succession on abandoned agricultural lands, afforestation and reforestation.

Biomass burning, wildfires and other disturbances are estimated to be major sources of CO_2, carbon monoxide (CO), and methane (CH_4). Efforts are underway to quantify changes in historical disturbances regime and their contribution of greenhouse gases to the atmosphere, in some years, comparable with the CO_2 production from fossil fuel. Timber resources of regions such as Siberia, and farming land in Amazonia and tropical Asia are increasingly vital to the economies of countries at the same they drive major changes in the frequency of disturbances and carbon potential of the altered ecosystems. The interaction of human impacts, logging, deforestation, fire, and climate variability and change are complex and are the attention to a number of efforts in Siberia, in the Long-term Atmosphere-Biosphere experiment in Amazonia (LBA), and parts of tropical Asia to cite some. Special attention is paid to carbon emissions from drained or burned peatlands.

c. Controls on Air-Sea Fluxes and Upper Ocean Biogeochemical Processes

In oceanic ecosystems, interannual-to-decadal climatic oscillations (Arctic, Atlantic, North Pacific and Southern Oscillations) and their interconnections have been identified as major controls on upper-ocean biogeochemistry and air-sea fluxes of carbon (Doney et al. 2000). Process-study tools to address the physical and biological mechanisms that control air-sea fluxes include repeat hydrographic surveys, time-series stations and other sustained ocean observations that incorporate an integrated programme for carbon, hydrographic and tracer measurements. The Southern Ocean Iron Release Experiment (SOIREE) showed the importance of iron limitation in high nutrient/low chlorophyll (HNLC) regions by deliberate iron fertilisation experiments in the Equatorial Pacific and Southern oceans. Such experiments found phytoplankton responses up to six weeks after iron was applied as a fertiliser in surface waters of the Southern Ocean (Boyd et al. 2000). Additional investigations into the role of iron limitation used SOIREE results to probe climate switches to and from ice ages (Watson et al. 2000). Of particular relevance for future oceanic process studies are insights gained into export fluxes and their dependence upon (a) community structure (diatoms versus background microbial community); (b) geochemical functional groups (nitrogen fixers, calcifiers); (c) physical variability (tropical instability waves, mesoscale eddies); and (d) trace micronutrients.

d. Atmospheric Isotopic and Tracer Studies

Interpretation and integration of isotopic information has been an invaluable tool both for understanding processes and also for diagnosing the large-scale patterns and variability of carbon fluxes (this discussion also pertains to Section 3.1). In both areas, isotopic studies will continue to be of great importance. Some highlights include:

- Studies of atmospheric CO_2, ^{13}C, O_2/N_2, together with mass balance calculations and atmospheric inversions, have quantified carbon fluxes into the atmosphere, due to fossil fuel, land-atmosphere exchange and ocean-atmosphere exchange (IPCC 2001a, Schimel et al. 2001). In particular, atmospheric ^{13}C observations suggest that a large portion of the change in the growth rate of atmospheric CO_2 is due to variations in carbon exchange in the Northern rather than the Southern Hemisphere, and the interannual variability in this growth rate is dominated by terrestrial ecosystems rather than the ocean.

- There are, however, substantial uncertainties presently attached to the oxygen budget. It has become clear that a major problem with the interpretation of O_2/N_2 measurements is accounting for the secular changes in O_2 storage occurring in the oceans, due to (1) increasing temperatures; and (2) changing circulation patterns. The current IPCC (2001a) estimates of ocean and atmospheric sink sizes, for example, appear to be in error because of this.
- Global, and to some extent regional patterns of excess CO_2 storage by the ocean, on decadal time scales, are constrained by a variety of techniques, including numerical models (often calibrated with ^{14}C and other transient tracers), temporal evolution of DIC and ocean ^{13}C fields, and data-based anthropogenic DIC estimates (Sabine and Feely 2001).
- Estimates of terrestrial gross primary productivity (GPP) and the NPP/GPP ratio have been obtained from ^{18}O in CO_2 (Ciais and Meijer 1998).

e. Economic and Ttechnological Developments Governing Fossil Fuel Emissions

Fossil fuel emissions are often taken to be an external forcing on the carbon cycle. On this level, accurate quantification is very important (Marland et al. 2000). However, the future trajectory of the global carbon cycle will be determined by *interactions* between fossil fuel emissions and the carbon-climate system, as humans react to perceived dangers from inadvertent intervention (**Figure 3**). Hence, to incorporate fossil fuel emissions into models of the carbon-climate-human system is a major challenge for future predictions (Vellinga and Wieczorek 2000).

f. Local Interactions Between Institutional Regimes and the Carbon Cycle

In seeking a full understanding of the feedbacks between land management, fossil fuel emissions and the carbon cycle, it is important to recognise and include the social and economic drivers of both proximate causes. For instance, a study in Chilean mixed grazing and farming systems identified the means by which biophysical, socio-political and economic variables influence land-use and vulnerability of rural populations to climate variations (McConnell et al. 2001). Rugged topography and pedeogenically undeveloped soils characterise the bulk of communal lands in this area, which are typically dedicated to annual crops, while private holdings, generally located in richer, flatter valleys, are devoted to perennial crops such as vineyards, and control almost all of the water rights. Location and crop types are thus two of the criteria that can be used to identify property regimes. The sensitivities and likely responses of these two regimes to climate change are substantially different.

Implications of this kind of study for present and future carbon stores and fluxes emerge upon integration with process-level understanding. A comparative examination of case studies (for example, tropical deforestation, agricultural intensification) will provide a clearer overview of the human drivers of land-cover changes and the ways that they depend on geographic and historical contexts.

g. Scale Interactions

Process studies and models are always implicitly specific to particular space and time scales (for instance, in the case of terrestrial ecosystems, the spatial scales defined by cell, leaf, canopy, patch, region and globe). It is often necessary to apply information from one scale to a different (smaller or larger) scale in space or time. The information to be transferred across scales may include model parameters or process descriptions encapsulated in the equations of a process model. If the transfer of information is from smaller to larger scales, this is known as "upscaling" or "aggregation", while "downscaling" or "disaggregation" is the reverse.

Common examples of aggregation problems include estimation of plant canopy net photosynthesis from leaf-scale models, prediction of terrestrial carbon sources and sinks for national greenhouse gas inventories from point-based models, and the specification of grid-cell averages of fluxes in large-scale atmospheric models. These problems have been the subject of major reviews in several disciplines (Bolle et al. (1993) and Michaud and Shuttleworth (1997): meteorological problems; Ehleringer and Field (1993): plant physiological problems; Kalma and Sivapalan (1995): hydrological problems).

Several recent and ongoing initiatives are defining methodological approaches to scaling and aggregation, and gathering data to test these approaches:

- Over the past decade, several large-scale campaign experiments on interactions between terrestrial ecosystems and the atmosphere have gathered numerous data at a range of scales (Hutjes et al. 1998).
- The BigFoot project is a major current effort with the goal of exploring validation protocols and scaling issues that would lead to an improved understanding of several satellite products.
- In the context of scaling models of carbon and related fluxes in terrestrial ecosystems, systematic approaches to aggregation are now being developed (Baldocchi et al. 1996; Raupach et al. 2002).

Emerging directions for work on scaling issues include several strands: (a) time-series studies (to upscale results in the time domain and to address variability issues); (b) global observations from a variety of satellite sensors (to address spatial and temporal variability of biological and physical processes that control global CO_2 dynamics); (c) connections between models at different scales; (d) and improvements in parameterisations of high-frequency temporal and spatial variability in carbon cycle models.

h. Vulnerability of the Carbon Cycle: nonlinear dynamics, thresholds, and regime shifts

Dynamics of the carbon-climate-human system are likely to contain unknown surprises and thresholds induced by nonlinear feedbacks and interactions among major compartments and processes of the system (Charney 1975; Claussen 1998). These include:

- the stability of ocean circulation (e.g., through possible slowdown or shutoff of the thermohaline circulation);
- the ability of terrestrial ecosystems to sequester carbon in the future as mechanisms responsible for current sinks saturate (CO_2 fertilization; forest regrowth after abandonment) (Cramer et al. 2001);
- permanence of current terrestrial carbon stocks due to changes on control processes such as switches due to phenology, soil respiration, changes in the water table, drought, absence/presence of snow, fire;
- feedbacks between terrestrial and marine systems such as ocean NPP enhancement due to dust deposition from land;
- the societal and policy drivers for the changes in carbon systems and for carbon management (linked with the perceptions of risk, due to changing climate and consequent development of new institutional regimes to control greenhouse gas accumulation in the atmosphere).

Most of these processes are the result of interactions between the changing climate, human systems and the global carbon cycle with the potential for accelerating or decelerating the build up of atmospheric CO_2. The implications of these feedbacks are large for the magnitude and timing of the quantities of fossil fuel emission reduction and carbon sequestration required to achieve a given stabilization scenario.

Although such interactions are likely to occur their quantification is difficult and restricted to subsets of their components for the Earthy system because fully coupled carbon-climate-human models do not exist (see section i. Integrative Model Development). Coupled carbon-climate models, however, have provided major insights on the types of possible nonlinear responses showing a slow down of the terrestrial sink strength by the middle of this century which becomes a source by the end of the century (Cox et al. 2000, **Figure 15**).

i. Integrative Model Development

Understanding the global carbon cycle through Earth system modeling is motivated both by our limited knowledge about the consequences of the feedbacks and interactions between biophysical components of the system and by the need to assess the importance of large-scale perturbations of the Earth system by human activities (such as fossil fuel combustion and changes in terrestrial vegetation cover). Feedbacks between changes in the Earth system and the perception of a problem by humans are equally important as they are likely to generate major changes in policy and attitudes on the way we manage and use our energy systems.

Earth-System Models of Intermediate Complexity (EMICs) are simple enough to permit numerical integration over many millennia but complex enough to yield a realistic picture of the Earth system, achieved by the inclusion of more interactions than are possible using comprehensive fully coupled process-based models. To date EMICs have focussed largely on the biophysical components of the Earth system (geosphere, atmosphere, some with biosphere) with prescribed human components, such as land-use and CO_2 emissions. Emerging directions the inclusion of the abiotic world (geosphere), the living world (biosphere) and the human dimension (anthroposphere). The spatial (regional) resolution required by this models to properly capture processes with global significance remains an issue.

Comprehensive three-dimensional climate models of the atmosphere/ocean/land (GCMs) which full coupled carbon cycle are now being developed. These provide the most realistic descriptions possible of atmospheric and oceanic transport processes and integrate the terrestrial vegetation processes into the biophysical parameterizations used in these models. Hence, they provide an interactive representation of how the physical environmental parameters affect the biological ones and vice versa, and in the long run may have the most promise as predictive tools.

A major issue of any large complex model is validation. Prognostic model components need to be robust in climates that differ from both the present and the past. Confidence in the robustness of an integrated model is currently built in four ways. First, individual components (terrestrial, oceanic, atmospheric, economic, social) are tested within and beyond the range of calibration data. Second, the ability to reproduce historical trends, either the glacial-interglacial record for the biophysical components, or the industrial era for the fully coupled model, is a key test of understanding. Third, through a strategy that encourages a variety of interchangeable models or submodels, it is possible to assess the degree to which outcomes depend on the assumptions of particular models. Finally, regional model intercomparisons provide tests at the sub-global scale by exploiting the variety of biophysical and social conditions that occur at regional scales.

Other models that incorporate socio-economic aspects with a carbon cycle perspective include integrated assessment models such as the IMAGE model (Leemans and van den Born 1994), models of political systems that project social responses to the Kyoto Protocol based on game theory and models of industrial/energy systems and industrial transformations.

Areas of Uncertainty and Research Priorities

Major gaps still exist in our understanding of the processes, controls and interactions that influence the global carbon cycle.

1. The mechanisms underlying a number of critical biophysical processes remain poorly understood, and are therefore inadequately represented in current models. They include:
    - the interplay between land-use, ecosystem physiology and disturbances controlling carbon fluxes in and out of land systems; and the relative importance of the full suite contributing to current and future carbon sinks and sources.
    - the dynamics and environmental responses of terrestrial carbon allocation in various components of the ecosystem;
    - the dynamics and environmental responses of heterotrophic respiration in terrestrial and ocean systems;
    - the lateral transport of carbon across landscapes and into the coastal and open ocean;
    - the roles of ocean circulation, chemistry and ecosystem dynamics in modifying the amount and pattern of ocean uptake in response to increasing CO_2;
    - the structure and dynamics of ocean ecosystems (phytoplankton and their predators at higher trophic levels);
    - the processes driving nutrient dynamics in different ocean basins (which appear to vary in time and between basins (e.g., nutrient-deficient waters in the North Pacific Ocean can switch between N and P limitation with associated ecosystem-level changes that seem to be responsible for variations in climate);
    - the biological, chemical and physical interactions that move carbon through the continuum of atmosphere, upper-ocean and deep-ocean.
2. The scientific community is only beginning to identify the proximate and ultimate drivers of carbon-cycle-relevant changes in human systems and institutions including consideration of human decision processes at

international, national, regional and local scales. This is crucial because many of the largest sources of uncertainty and largest opportunities for intervention lie in the human domain.

3. It is known from ice-core records that global atmospheric levels of maintained a range between about 180 and 280 ppmv over the last half million years. However, the mechanisms that determined these apparently well-constrained "clamp points" are still a matter of debate.
4. Although all processes mentioned above are important, their implications for the emergent behaviour of the global carbon cycle and its links with climate, other major biogeochemical cycles, and human actions remain uncertain. This makes an integrated assessment of the interactions and feedbacks between the processes acting in the carbon cycle and the resulting whole-system emergent behaviour a fundamental requirement.

The above assessment prompts the following research priorities for Theme 2:

Theme 2*: What are the control and feedback mechanisms - both anthropogenic and non-anthropogenic - that determine the dynamics of the carbon cycle?*

1. *What mechanisms controlled paleological and pre-industrial concentrations of atmospheric* CO_2*?*
    a. Determine the controlling features and simulate the temporal dynamics of the glacial–interglacial carbon-climate system.
2. *What are the multiple mechanisms responsible for current aquatic (ocean and freshwater) carbon sinks? What are the relative contributions of these mechanisms, and their interactions?*
    a. Quantify interactions among mechanisms controlling the biological pump, including the effects of nutrient fertilization (iron, silicon and other elements) on net carbon uptake through changes in the structure and function of aquatic ecosystems, and the effects of climate variability and change.
    b. Quantify interactions among mechanisms controlling the solubility pump and carbonate chemistry, including changes in freshwater fluxes (ice melting, river flows, and precipitation) into the upper ocean; lateral transport and subduction of surface waters; ocean-atmosphere exchanges of energy, water and CO_2, and the dynamics of climate variability.
    c. Identify the interactions between sediment carbon stores and aerobic and anaerobic decomposition pathways in freshwater bodies.
3. *What are the multiple mechanisms responsible for current terrestrial carbon sinks? What are the relative contributions of these mechanisms, and their interactions?*
    a. Identify the multiple sink mechanisms responsible for the current terrestrial sink and their interactions, including climate changes (such as precipitation, temperature, humidity, radiation, climate variability); changes in atmospheric composition and atmospheric inputs (such as CO_2 and nitrogen fertilisation); and changes in land use and land management (such as past and present clearing and fire management).
    b. Assess how both natural and anthropogenic disturbances (fire, herbivory, harvest, storm damage) affect the sequestration and release of carbon to the atmosphere.
4. *What mechanisms control horizontal carbon fluxes in air, oceans and terrestrial water bodies?*
    a. Quantify feedbacks between changes in the global carbon cycle and oceanic and atmospheric transport of carbon and energy.
    b. Quantify the key processes driving land-coastal-open ocean carbon exchange, and their interactions.
5. *What are the likely future dynamics of current sink mechanisms? Will current terrestrial carbon sinks saturate or reverse, and how will oceanic carbon pumps evolve over coming centuries?*
    a. Using multiple data streams and improved prognostic models, develop regionalised future scenarios for the terrestrial carbon cycle on the basis of assumed scenarios for the evolution of the global carbon-climate system.
    b. Integrate and test these regional scenarios for global consistency, thus constraining and feeding back on global scenario development.
    c. Use long-term ocean observations (existing and future hydrographic surveys, time series stations, remote sensing records) to validate and improve prognostic ocean carbon models; then use these models to develop scenarios for the future of ocean carbon pumps over coming centuries.
6. *What mechanisms control anthropogenic carbon fluxes and storage?*
    a. Explore the driving forces of different pathways of regional development on carbon stocks and fluxes.
    b. Explore the drivers of patterns of production/consumption and land use change that give rise to anthropogenic emissions of greenhouse gases.

   c. Explore and explain the drivers of the energy intensity of the production of wealth, and the carbon intensity of the production of energy.
   d. Identify the factors explaining the mix of fuels used in the generation of electricity.
   e. Determine how public and private activities and their interactions drive rates of deforestation and influence land-use practices.
   f. Explain the factors governing variability in residential pattern of heating and cooling systems.
   g. Quantify and explain variations in the character of transport systems.
   h. Understand the effect of changing climate cycles (e.g. ENSO, PDO, NAO) on anthropogenic CO_2 fluxes (fossil fuel, land use, fire, other).

7. *How do feedbacks between natural and human processes magnify or dampen both anthropogenic and non-anthropogenic carbon fluxes?*
   a. Develop simple (low-dimensional) models of the coupled carbon-climate-human system, including interactions between natural and human terrestrial processes, interactions between ocean biology, carbonate chemistry and ocean circulation, and the consequences of changes in the carbon cycle for human activities.
   b. Develop Earth system models with fully coupled carbon, climate and human systems, including components of soci-economics, human behaviour, and institutions.
   c. Explore with modelling tools possible feedbacks and thresholds leading to unstable behaviour that the climate-carbon-human system may possibly cross. Can critical points for such abrupt and significant changes be identified?

Theme 3: Management of the Carbon Cycle

Motivation

The future dynamics of the carbon cycle will be determined by the combined result of the natural dynamics of the biogeosphere and the net carbon balance of anthropogenic activities. Past, present and future dynamics of the perturbed carbon cycle have been dealt in Theme 1 and 2. Theme 3 will specifically focus on the science of managing the carbon cycle as the intervention point for humans to stabilize atmospheric CO_2.

In addition, the capacity to generate worthwhile predictions or scenarios for the future has policy implications at international, national and regional levels. These are the direct consequences of several factors (1) human activity is one of the primary drivers of perturbations to the global carbon cycle, and decisions made by people introduce key uncertainties into projections of its future evolution; and (2) human-induced changes in the global carbon cycle have the potential to alter the global climate system, and thence affect water and food resources, environmental resilience, biodiversity, health, and international political stability. The global carbon cycle has therefore become an important policy issue placed well beyond climate mitigation alone, but as an important part to the wider agenda on development, sustainability, and equity. A capacity to build the components of scenarios (e.g., policies, capacity of mitigation options) and perform robust analyses of future scenarios is a key interface between science and policy required for the success of CO_2 stabilization goals of the FCCC (**Figure 16**).

Knowledge Base

A summary of the existing knowledge base in this theme consists of a set of "scenario elements" and estimates of technological development and innovation. Plausible trajectories and mitigation capacities result from a number of analyses using integrative assessment models coupled to carbon cycle models, analysis of current trends and inductive reasoning (IPCC LULUCF 2000; IPCC SRES 2000?, IPCCa,b,c 2001; Field and Raupach 2003).

1. Greenhouse gas concentrations will continue to increase for many decades, irrespective of any global mitigation actions. Even with major emission abatement measures, a levelling-off of atmospheric CO_2 at twice the pre-industrial level would be a major achievement.
2. The world energy system delivered approximately 380 EJ (1018) of primary energy in 2002 (BP Statistical review of World Energy 2002). Of this, 81% was derived from fossil fuels.
3. There is no single technology or path that will take nations and regions to a low carbon emission future. Each nation will need to choose their own path given their socio-economical, political, and environmental circumstances.
4. A range of potential human responses are possible to the threat of undesirable climate change, most of which are likely to be used at a significant scale over the next century:
    - changes in CO_2 emissions by switching from conventional to unconventional fossil fuels, either increases with exploitation of oil shales and tar sands, or reductions with methane clathrates;
    - improvements in energy use efficiency and life-style changes;
    - increasing use of renewable energy sources (bio-energy, solar, wind);
    - biospheric carbon sequestration in forests;
    - engineered carbon sequestration in geological formations and the deep ocean;
    - alterations to agricultural practices to reduce net greenhouse gas emissions (intensification or extensification).
5. Continuous energy efficiency improvement, afforestation, low-carbon energy, and natural gas will play a central role in reducing carbon emissions during the first part of the 21st Century. Innovative non-fossil fuel technology will be required to complete stabilization.
6. Conservation and sequestration in forests could be as high as 60 to 87 PgC by 2050 and 44 PgC could be further sequestered in agricultural lands. This amount is equivalent to 10% to 20% of the project fossil fuel emissions during that period.

7. Humans respond to threats to their welfare from undesirable climate change. They have begun to do so with the 1997 Kyoto Protocol (though the impact of the Protocol on greenhouse gas concentrations will be slight in the first commitment period. The human response to the climate change threat will increase over the next century, although at an uncertain rate and under uncertain institutions and compliance levels.

Current Research

Portfolio of Carbon Mitigation Options

There is no one single technology or approach to mitigate carbon that will solve universally the climate problem. Instead, nations and regions need to find the right mix of options according to their socio-cultural and environmental circumstances. An understanding of the multiple options available and their capacities for mitigation is driving a large body of research. There are five categories of mitigations in which current research is taking place (IPCC-LULUCF 2000; IPCC 2001c; Field and Raupach 2003):

1. *Conservation and increased efficiency*. A number of changes in technology, policy and human behaviour can reduce energy demands, with benefits or at most small costs for economic productivity. Examples include more efficient appliances, transport (e.g., hybrid vehicles which electrically recover lost mechanical energy), better urban planning (e.g., improving public transport), cogeneration (recovery and use of low-grade heat from electric power stations) or changes to diets that require less energy inputs (e.g., shifting diets towards vegetarian). The technical potential carbon gains in energy efficiency from these options are large, in many cases from tens to hundreds of percent on a sectoral basis.
2. *Non-fossil-fuel energies*. These include hydropower, wind, solar, geothermal, tidepower and biofuels, the latter producing carbon emissions when is generated but with a similar amount of minimal carbon uptake by the fuel crops. Up to 500 Mha of land (around 3% of the global land area) could be made available for biofuel crop production by 2100 and displace between 3-5 Pg C during that time. Research on more advance non-carbon technologies such as nuclear fission or fusion, spaced solar power, and geoengineering, is also underway with the hope these technologies can play an important role in the future in climate mitigation.
3. *Land-based options including disturbance reduction and biological sequestration*. There is a large interest for these options because the potential for ancillary benefits on other environmental concerns (e.g., increased soil fertility) and development (e.g., forestry activities). The potential carbon sequestration using reforestation, afforestation and land restoration, the land-based options accepted under the Kyoto Protocol, is in the order of 1PgC y^{-1} by 2010, and changes in forest management could sequester carbon at 0.175 PgC y^{-1}. Reduction of net deforestation has also a large potential as deforestation contributes about 20-25% of total anthropogenic emissions. However, although ending forest deforestation is a laudable goal, it has proved difficult or impossible to implement in many regions. Research is underway to explore tangible socio-economic incentives and the ultimate drivers of deforestation (such as markets and policy climate) as points for intervention. Finally, mitigation options in the agricultural sector can avoid some of the 20% contribution to the total of anthropogenic greenhouse gases. The global potential for this strategy on agricultural soils is estimated between 40-90 PgC.
4. *Biological sequestration in oceans*. The efficiency and duration of carbon storage by ocean fertilisation remain poorly defined and strongly depend on the oceanic region and fertilizer (iron, nitrogen, phosphorus) used. The maximum potential of iron fertilisation has been estimated as 1 PgC yr^{-1} by continuous fertilisation of all oceanic waters south of 30°S (Sarmiento and Orr, 1991), but the uncertainties and ancillary impacts are potentially enormous. This is as a very active research field which requires substantial advancing before this option is seriously considered by policy makers.
5. *Engineered CO_2 disposal on land and in oceans*. Deep ocean injection of pure liquid CO_2 is still at its infancy but deserves attention as we try to build a comprehensive portfolio of options. There is still little understanding on the potential effects of the instability of CO_2 deposits in the deep ocean, and of negative effects of the formation of CO_2-clathrates and a substantial lowering of pH on deep ocean biota. Conversely, geological storage in sediments and rocks is in a much more advance technical development offering the potential for large CO2 disposal in exhausted oil and gas wells and in saline aquifers. This is a relatively clean solution provided there are not CO_2 escapes, dissolution of host rock, sterilization of mineral resources, and unforeseen effects on groundwater.

Technical versus Achievable Mitigation Potential

The maximum mitigation that can be achieved by a strategy is its technical mitigation potential. This is based solely on biophysical estimates of the amount of carbon that may be sequestered or greenhouse gas emissions avoided, without regard to other environmental or human constraints. However, the achievable mitigation potential is less (often very much less) than the technical potential, because of a range of economic, environmental, and social drivers and constraints which lower the extent to which a technology can be deployed or accepted by societies (**Figure 17**). For instances, an analyses of a number of constraints on global implementation of carbon sequestration and energy cropping showed that only between 10-20% of the technical potential 2000–5000 Mt Cyr^{-1} offset could be realistically achieved (Cannell 2003). A highly integrative new research field is currently emerging to assess the sustainably achievable potential for deploying and implementing a number of mitigation options and the immediate benefits to climate mitigation. Likewise, adaptation strategies to climate change are critical and policy makers will likely need to weigh the pros and cons of the relative merits of these two types of policy options, including seeking for win-win situations of adaptation and mitigation.

Some of the constraints on achievable potentials are price dependent (not for the theoretical capacity), implying that a higher carbon price would increase the viability of the carbon management strategy. Some of the constraints are (IPCC 2001c; Raupach et al. 2003):

1. *Economics.* Economic factors include (a) access to markets for carbon relevant products; (b) the nature of those markets; (c) the influence of pathways of industrialisation and urbanisation on existing and new carbon relevant economic sectors; (d) the existence or absence of crisis prone economic conditions; and (e) the indebtedness of many countries, especially in the developing world. Economic markets play an important role in governing access to resources and, used intelligently by governments, can provide important incentives to switch to lower carbon energy portfolios.
2. *Environmental requirements for other resources.* The need for resources to supply essentials, such as food, timber and water, can reduce the estimated technical potential.
3. *Environmental constraints:* Mitigation activities can incur environmental costs such as waste disposal and ecological impacts.
4. *Social factors.* Differences in social factors between countries and between urban and rural locations exert strong influences on mitigation outcomes. On an individual level, class structure and lifestyles are often related to increase consumption and use of carbon relevant commodities as cultural symbols such as cars and travel. Lifestyle is also linked to poverty and lack of access, for instance to technical alternatives. On a society level, values and attitudes determine the level of support for carbon management strategies, through education and societal self-image (such as frontier, pro-modernization, pro-conservation).
5. *Institutional factors.* Institutions determine the structure of incentives influencing any management option, both in terms of taxes, credits, subsidies, sectoral strategies, property rights regimes and other formal components, and also in terms of the policy climate or informal policies within which management strategies are designed and implemented. Examples of "policy climate" include the level of performance, and the presence or absence of corruption, and the extent and nature of powerful vested interests. To illustrate the last point, significant constraints can arise within both public and private sectors which affect the speed of technology deployment and the choices of alternative systems. Owners of existing energy technologies can use their considerable financial and technological influence to block the development or deployment of alternative systems. Similarly, government regulators may use their powers to control the flow of investment in mitigation technology or its application in their country in order to protect perceived national interests.
6. *Institutional and timing aspects of technology transfer.* Some features of technology transfer systems, like the patenting system, do not allow all countries and sectors to access best available technology rapidly or at all. The timing of technology transfer is an issue, as many technological paradigms need 50-70 years to be completely established.
7. *Demography.* The density, growth, migration patterns and distribution of the population can form another constraint, especially in countries with high levels of social segregation.

Development of Global Emission Scenarios

Given the unexpected nature of moving into the future, emission scenarios are descriptions of possible futures that can be analysed by today's policy-makers. The analyses consider alternative trajectories departing from current trends and that result in different models of societies, and degrees of climate mitigation and development. They are not a way to predict the future, but to explore the long-term consequences of taking (or not taking) specific actions and developing policies. Some of the most recent analyses have been done by Nakicenovic et al (1999) and the IPCC Special Report on Emission Scenarios (IPCC 2000a).

An important research field is the use of scenarios to explore the pathways and costs to closing the gap between carbon emissions that are anticipated to occur in a world that places no value on carbon (or other baseline scenarios of business as usual) and emissions required to stabilise at a specific concentration level (as it is the intent of the FCCC). Even the business as usual scenario IS92a, which assumes 75% power generation carbon free by year 2100 and commercial biomass providing more energy than the combined global production of oil and gas in 1990, do not achieve CO_2 stabilization during this century (Richels et al. 2003). Thus, any emission scenario to achieve atmospheric CO_2 stabilization by the end of this century will require an enormous development of new technologies and policies that would not take place otherwise by business as usual. Analyses of these scenarios with coupled socioeconomic and carbon models will allow exploring the dimension and cost of the changes required and the best timing for some of these changes to be pushed.

Scenarios are also critical tools to understand the requirements of institutions at various levels of social organization for implementing large technological changes. This will help to identify the prospect for designing, getting agreement on, and implementing a more effective climate regime that will allow achieving atmospheric CO_2 stabilization.

Areas of Uncertainty and Research Priorities

Before attempting to steer the development of *energy systems* along one of many alternative paths, societies need to consider carefully the consequences for many areas of society. These include aspects of environment, technology (production, distribution, and consumption), investment, consumer preferences, corporate interests, energy producer and distributor interests, employment, regulators' interests, energy safety, and energy security. Choosing one path over the others implies solving trade-offs between efficiency, equity, and sustainability. Clarifying these trade-offs requires the development of scenarios in which combined technological, economic, institutional, environmental, and social factors are analysed in detail.

In much of the world***,*** *transportation systems* are dependent upon fossil fuel combustion, which directly connects the human need for transportation with changes in the carbon cycle. Transportation accounts for 25-30% of anthropogenic emissions of carbon dioxide. Vehicular manufacture, construction of roads, and cement production also add a significant fraction. Questions about redesign of transportation systems arise from three perspectives: (1) technological, (2) the scale and complexity of the region, and (3) institutional (OECD/ECMT, 1995). These need to be considered as a set of complex, dynamic relationships in which change in one component is likely to effect change in another.

Therefore, research on future scenarios or trajectories involves developing and testing "scenario elements" such as those listed earlier, and then studying the interactions and feedbacks (including qualities and inconsistencies) between them. Providing reliable risk-assessment information in the form of better decision support tools for policy makers is key to these issues.

It is also important to realize, however, that the selected CO_2 stabilization path and final target concentration will not be the result of a command and control process given the large number of biophysical and socioeconomic constraints that will play out in ways difficult to be predicted. Thus, there is a need for developing an adaptive system able to identify and take advantage of points of intervention and windows of opportunity to act as they come, making the final CO_2 stabilization pathway and target concentration an emergent property of the system.

Such uncertainties prompt the following research priorities for Theme 3:

Theme 3: What are the likely dynamics of the global carbon cycle into the future and what points of intervention and windows of opportunity exist for human societies to manage this system?

1. *When and how will humans respond to changes in the carbon cycle (throughout the perceived changes in the climate system)?*
    a. Design portfolios of mitigation options that are most feasible in different geographic, environmental, social and economic circumstances?
    b. Explore the potential for unintended consequences of carbon mitigation options and assess the sustainably achievable potential once negative effects are taken into account.

   c. Identify collateral benefits of mitigation options and their interactions with adaptation policies (e.g., win-win mitigation-adaptation options).
   d. Study the relative merits of various policy options (e.g. emissions trading, carbon sequestration).
2. *How natural dynamics of the carbon cycle and human activities will feedback to influence future atmospheric* CO_2 *concentrations?*
   a. Determine the potential range of pathways for CO_2 stabilization given the predicted dynamics of the natural carbon cycle into the future.
   b. Assess the carbon and climate consequences of adopting a portfolio of mitigations, and the resulting feedbacks of changes in human behaviour.
   c. Implications of non-technical factors (e.g., social and economic drivers of land-use, property rights) on future directions of net terrestrial greenhouse gas emissions?
3. *What infrastructural factors need to be overcome to encourage alternatives to a totally fossil fuel-based economy?*
   a. Study the effects of slow and rapid energy substitution, and how it influences energy intensity.
   b. Identify the differences in energy use between industrialised and non-industrialised countries, and social, cultural, economic, and technological conditions that account for differences in energy intensities.
   c. Identify and quantify the technical, economic, and social driving forces that direct the private energy sector towards the development of low carbon technologies and markets.
   d. Identify what drives consumer needs and preferences in the field of energy and material use.
   e. Explore how the need for mobility can be partly or completely de-coupled from effects on the carbon cycle.
4. *What is the role of institutions (at various levels of social organization) in determining the nature and consequences of human responses to changes in the carbon cycle (climate)?*
   a. What institutional, socio-psychological and technical arrangements would influence the purchasing, investment and lifestyle towards significantly lower detrimental environmental effects?
   b. Explore the institutions, monitoring mechanisms and compliance mechanisms needed to achieve effective stabilisation of greenhouse gas concentrations. Can the broad characteristics of their evolution be predicted?
   c. Study the implications and the effectiveness of instruments proposed in the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol.
   d. Explore the prospects for designing, getting agreement on, and implementing a more effective climate regime.
5. What are (and will be) the different social, regional impacts of the changes in the climate-carbon system given the medium- to long-term impacts of climate change?
   a. How vulnerable will social and economical sectors and regions will be to such changes?

4. Implementation Plan

The Implementation Plan is organised around three foci, congruent with the science themes of (1) Patterns and Variability; (2) Processes and Interactions; and (3) Management of the carbon cycle. Each Focus is divided into three Activities which are the main research areas the GCP will develop over the life of the project. Within each Activity there are a number of Tasks as discrete units of implementation or components of a step-wise approach to achieve an overall goal **(Figure 18).** In addition, there are project-wide efforts to develop timely synthesis of the global carbon cycle or parts of it, and the development of specific products for communication and outreach for the multiple audiences of the GCP.

The section describes only an initial set of activities from the larger portfolio that will be developed over the .1+1years as the GCP matures. The GCP website (www.GlobalCarbonProject.org) will be used to provide periodic updates of the implementation plan and specific information on the development of the various activities.

Focus 1: Patterns and Variability

Activity 1.1: Enhancing observations of major carbon stocks and fluxes

Many regional and national carbon cycle programmes have the potential to complement and strengthen one another by the establishment of common protocols, sharing of data, rapid transfer of information on new applications and techniques, and leveraging resources in joint projects. However, at present these programmes largely rely on the efforts of individual investigators for coordination. Many countries are seeking to contribute to a coordinated international research effort, but information on existing national and regional plans is difficult. In addition, there is not a global strategy that points to missing elements and overlaps, and that can provide recommendations accordingly.

In this environment, the GCP will make the following contributions in partnership with national and regional observational and experimental programmes:

- provide opportunities for coordinating research campaigns to enhance the value of measurements;
- promote standardization of techniques and methods to increase the comparability of results;
- foster rapid transfer of results and methodologies among programmes,
- include attention to non-CO_2 pathways for transporting carbon, in addition to atmospheric CO_2;
- include observations of the human (athropospheric) dimensions of the carbon cycle;
- provide means of integrating across observations of the oceanic, terrestrial, atmospheric and anthropospheric aspects of the carbon cycle, through model data fusion and related approaches (see also Activity 1.2).
- provide recommendations for improved network design and coordination among national and regional carbon programmes.

This will require developing partnerships with multiple groups studying regions or individual components of the carbon cycle (see “links” below) with various degrees of formal agreements.

One important aspect of this activity will be to facilitate the standardization of techniques and measurements in order to allow for inter-comparisons and quality assessment/control. In many measurement and experimental programmes, for example, primary standards do not exist, or links to SI units are compromised by methods required to propagate the standard and/or make the measurement. Of particular concern is a widespread inability to merge data from laboratories/methods at optimum precision levels.

Task 1.1.1: Coordination and standardisation of stocks and flux measurements in the land, ocean, atmosphere, and anthroposphere

Ocean: A collaborative effort between the GCP and the SCOR-IOC Ocean CO_2 Advisory Panel has been established with the name of International Ocean Carbon Coordination Project (IOCCP). The IOCCP and Ocean will foster coordination of global-scale ocean carbon monitoring efforts including reoccupation of the World Ocean Circulation Experiment (WOCE) sections and surface pCO_2 observations on ships of opportunity. Similar coordination will take place with air-sea fluxes and ocean-sediment measurements. The IOCCP is already colleting and building upon the existing Web information to establish a model for coordinating activities including periodic workshops to facilitate international collaborations. This will require active solicitation for updates on the latest national plans and international projects, and constant vigilance to find programmes that have possible conflicts or offer opportunities for better collaboration and more efficient use of limited resources.

Land: The GCP will promote standardisation of terrestrial measurements, calibration, and data treatment for a number of networks and global datasets compiled by individual nations such as, forest inventory data, flux towers (Fluxnet), land use change (FAO, UNFCCC), biomass burning (fire working group), and manipulative experiments. The GCP recognizes the fact that this effort is well underway within a number of groups (e.g., GTOS), and will work with them to facilitate the continued success of this effort. The GCP will also provide an important link for the coordination of the terrestrial observations with the atmospheric and oceanic observation networks as appropriate.

Atmosphere: There are several global programmes to improve standardisation of atmospheric observations that the GCP will work with to foster quality assessment/quality control, and comparability and data quality. This includes GLOBALVIEW which harmonizes measurements from over 100 sites run by 14 countries and the GLOBALHUBS strategy for atmospheric composition measurements that foster standardisation of methodologies and calibration (arising out of measurement expert meetings coordinated by the WMO and IAEA). The GCP will also work with other groups dealing with measurements of O_2/N_2, Atmospheric Potential Oxygen (APO), stable isotopes (GCTE-BASIN), water and heat, and others. Finally, the GCP will engage in the development of measurements of CO_2 from space, their linkages to data assimilation approaches, and validation schemes.

Anthroposphere: There are a number of stocks and fluxes associated with human activity that need to be standardised and made compatible with critical users such as budget and atmospheric inverse calculations. These measurements include appropriate spatial and temporal coverage of fossil fuel emissions, emissions from land uses including deforestation, landfills, agricultural practices, and many others. The GCP will work with the diverse groups working on specific sectors and ensure the coordination of national and regional efforts and the linkages to critical applications.

Task 1.1.2: Observations of lateral movement of carbon by fluvial transport, aeolian transport, and trade

Fluvial transport. The GCP will work on two priority research areas:
- Carbon sinks in freshwater bodies. Until recently it was believed that fluvial carbon was largely oxidized during transport and in coastal zones. However, there is now good evidence that some of this carbon is deposited in large water catchment impoundments and so contributing to the current terrestrial carbon sink. The GCP will engage in research to improve the regional and global poorly constrained estimates of carbon transferred between land and water impoundments, and the sink strength of these water bodies.
- Coastal zones as carbon sources or sinks. There are still large uncertainties as to whether coastal zones act as sinks or sources. The GCP will engage on new research to generate and collect new datasets of the carbon dynamics in these regions in order to (i) quantify horizontal carbon fluxes in different types of continental margins, (ii) to evaluate the importance of carbon deposition on the continental slope, and (iii) to produce an overall synthesis and assessment of carbon fluxes on and across continental margins.

Aeolian transport. Aeolian transport of carbon is a minor component of the global carbon budget. However, major dust storm events can remove large amounts of carbon from regions, along with important nutrients such as iron and phosphorus, which in turn have an affect on carbon sources and sinks in the regions where get deposited (e.g., oceans). The GCP in partnerships with erosion research networks will quantify the removal of carbon in regions prone to dust storms, and the sink/source implications of the nutrients transported to freshwater bodies and coastal zones. A set of case studies will be selected.

Trade. Most of fossil fuels are mined and much of the world ecosystems are harvested, an in some cases very intensively. Carbon in the form of fossil fuel, lumber or food is transported laterally in domestic or international trade circuits, and CO_2 is lost to the atmosphere (e.g., fossil fuels or food) or accumulated (e.g., furniture) in places other than where the carbon was fixed. Although carbon sources and sinks due to trade have no global effect they contribute to the patterns and variability of sources and sinks at the regional level. The GCP will coordinate and synthesis datasets to be able to map the carbon fluxes due to trade into geo-referenced data products using forestry and agricultural statistics.

Task 1.1.3: Observations of other relevant carbon compounds
The GCP will work on two priority research areas:

- Non-CO_2 gases also contribute substantially to the global warming and their shorter atmospheric life time and higher warming potential make them good candidates as targets for near-term warming mitigation. The GCP will synthesize available datasets and contribute to enhance the observational system in order to constrain regional and global budgets for a number of these gases with an emphasis on CH_4.
- Black carbon. Resulting from vegetation fires, black carbon can contribute to a long-term carbon sink due to its highly resistance structure. The GCP will synthesize datasets and encourage new research to better understand the quantities and quality of black carbon production in a number of fire prone regions in the world including savannas, temperate and boreal forest. Better constrained global estimates will be produced.

Deliverables of Activity 1.1:

- An Internet Carbon Portal with information on all major national, regional and global carbon programmes and projects.
- A web-based interactive tool that will allow up-to-date information on ocean cruises to be displayed, and recommendations for better coordination. The website will provide the basic information for the International Ocean Carbon Coordination Project (IOCCP) of the GCP- CO_2 Panel.
- A periodic set of recommendations to optimise resources for observations and identify the potential scientific benefits of a coordinated observation programme (based on gaps, duplications, and needs in carbon observations).
- Guidelines for best observational practice and consistency requirements, developed in partnership with observational (e.g.,, IGOS-P) and regional/basin programmes.
- Standardised datasets, including oceanic, terrestrial, atmospheric and anthropospheric carbon observations, for constructing global carbon budgets and model validation.
- Compilation and update of existing global database riverine dissolved inorganic and organic carbon transport, and new estimates for sediment burial in reservoirs and coastal shelves.
- New estimates and methods for estimating the magnitudes and temporal trends of carbon transfers due to trade, including harmonization of data on statistics of agriculture and forestry products.
- Compilation and synthesis of existing databases on anthropogenic driven compounds affecting sources and sinks (e.g., CH_4, black carbon).
- A number of validation products for major new data streams such as NPP from MODIS/AQUA and column CO_2 measured from space.

Links to other projects and activities:
This activity will require working in partnership with multiple national and regional programmes, and international projects already coordinating individual components of the carbon cycle. On carbon ocean research, the GCP will work with JGOFS, the new IGBP/SCOR Oceans, SOLAS, CLIVAR and with links with the final phase of the World Ocean Circulation Experiment (WOCE). The IOC/SCOR CO_2 Panel will be a full partner project in ocean coordination throughout the IOCCP activity. For lateral transport, the GCP will work with LOICZ and the JGOFS-LOICZ joint Continental Margins Task Team (CMTT). On land issues, the GCP will work with GCTE (e.g., Biosphere-Atmosphere Stable Isotope Network, Erosion Network), LUCC, the new LAND project, Fluxnet, IT, and others. Work on CO_2 from space will be done with GEWEX. A critical interface has been established with IGCO and GTOS-TCO with regarding coordination, standardization, and new operational observation requirements. START. South China Sea Regional Carbon Project in collaboration with the Southeast Asia Regional Committee of START (SARCS), and a number of national and regional projects on carbon cycle research.

Activity 1.2: Model development and Model-data fusion

Model-data fusion is emerging as a primary tool for synthesising data and process information to predict space-time patterns and variability in the carbon cycle. Model-data fusion techniques also provide a powerful new toolkit for integrative analysis of process studies, especially from studies in which large number of processes and parameters are studied simultaneously. That is, the application of multiple constraints to our understanding. This activity centres on the development and implementation of methods for assimilating atmospheric, oceanic and terrestrial data into biophysical and biogeochemical models. A particular emphasis will be on the application of multiple constraints, from the simultaneous use of atmospheric, oceanic and terrestrial data and models, to the problem of determining patterns and variability in the carbon cycle.

Task 1.2.1: Improvement of forward and inverse models

This task will produce a new generation of improved models by using model-intercomparison and model-data intercomparisons, and by including new roles of anthropogenic disturbances such as land abandonment and subsequent succession, fire suppression, and nutrient fertilization. Models will require prognostic capabilities with the appropriate observation and experimental datasets to calibrate them.

The task builds on a series of existing activities initiated under the umbrella of the Global Analysis Integration and Modeling (GAIM-IGBP). These include:
Atmospheric Trace Transport Model Intercomparison (TransCom). The goals of TransCom are to quantify and diagnose the uncertainty in inversion calculations of the global carbon budget that result from errors in simulated atmospheric transport, the choice of measured atmospheric carbon dioxide data used, and the inversion methodology employed. Analyses conducted in previous TransCom3 experiments allowed a rigorous assessment of the estimated source/sink distributions and their sensitivity with respect to the different transport models. In the future, TransCom3 will run sensitivity analyses to other aspects of the inversion set-up, such as data selection and errors, definition of prior assumptions, their covariances, and the mathematical procedures to solve the inversion problem. Future efforts will include incorporating non-CO_2 measurement constraints and so moving towards a data-assimilation model described in Task 1.2.3.

Ocean Carbon Intercomparison Project (OCMIP). The goals of the OCMIP activity are to improve the identification of global ocean CO_2 fluxes and understand differences between existing 3-D global ocean carbon cycle models. The OCMIP activity will continue to run a number of model intercomparisons with up to 12 participant groups all using standard protocols of natural and anthropogenic CO_2 simulations. Subsets of the OCMIP-2 group will undertake new modeling studies including (i) the Northern Ocean Carbon Exchange Study (NOCES); (ii) Constraining the air-sea exchange of natural and anthropogenic CO_2 by inverse modelling; and (iii) Developing the Automated Model Ocean Diagnostic Facility (AutoMOD) for ocean model outputs.

The Ecosystem Model/Data Intercomparison Activity (EMDI). The EMDI activity provides a formal opportunity for a wide range of terrestrial global carbon cycle models to be compared with observed and measured net primary production (NPP) and Net Ecosystem Production (NEP). The primary questions addressed by this activity are to test simulated controls and model formulation on the water, carbon, and nutrient budgets with the observed NPP and NEP data providing the constraint for autotrophic fluxes and the integrity of scaled biophysical driving variables. EMDI will organize new model-data intercomparsions using new datasets that include a global litter database, additional interannual NPP observations, eddy-covariance flux intercomparisons, mean annual and interannual analyses for gridded data, and the MODIS NPP product.

Task 1.2.2: Development of model-data fusion techniques

Model-data fusion can be defined as the introduction of observations into a modelling framework, to provide (1) improved estimates of model parameters or state variables, (2) uncertainties on parameters and model output, and (3) the ability to reject a model, through a measure of goodness of fit. The term embraces a number of approaches, including inverse methods (atmospheric, oceanic, biogeochemical), data assimilation, parameter estimation, and multiple-constraint approaches. Such approaches have the potential to link process studies, observations and models, towards a global synthesis of the carbon cycle.

Major emphases in this task will be:

- Use of appropriately parameterised process models (many fully process-based models are over-parameterised for use in this way);
- Development of ”upscaling” methods for using small-scale process information in model-data fusion;
- Development of improved methods for parameter estimation from complex datasets;
- Development of uncertainty analyses in the context of nonlinear inversions;

- Synthesis of carbon-cycle-relevant information from a wide range of observations to provide cross-checks for model consistency;
- Development of methods for use of data products for CO_2 column concentration measurement from new satellite sensors;
- Development of linkages with online data assimilation for weather forecasting, towards the inclusion of carbon cycle data in these assimilations;
- Development of network design methods, based on improving the cost-effectiveness of observation networks and process studies by appropriate sensitivity analyses.

Deliverables of Activity 1.2:

- Novel data-model fusion schemes using new applied mathematics approaches and data streams;
- Evaluation of current and planned observing systems and analytical approaches, within a formal framework of model-data fusion.
- A new generation of scientists from many different disciplines trained in model-data fusion techniques and observing systems issues. This effort will be supported by a number of Research Institutes organized in different centres around the world. Each institute consists of 2-4 weeks of talks and practical research training, and deals with data assimilation of one of the three compartments of the global carbon cycle: atmosphere, oceans, and land. The last institute will deal with data assimilation at the scale of the Earth System.
- An integrated 4D data base for research and education applications with a web based interface;
- Tutorial materials and simulations for model-data fusion analyses;
- Publications including initial reviews on data assimilation approaches for biogeochemistry cycle research and available global databases.

Links to other projects and activities:
Critical partnerships with a number of operational observation programmes will be established, largely through coordination with IGCO (of IGOS-P), and with specific partnerships with GTOS (and its Terrestrial Carbon Observing project – TCO) and Oceans programmes. Because the diverse datasets involved in data-assimilation, partnerships will need to be developed with many groups as appropriate including GAIM, GCTE, new LAND, LUCC, SOLAS, JGOFS, new OCEANS, CLIVAR, and others. GEWEX-Global CO_2 measurements from space. Efforts on global modelling will be done in closer coordination with GAIM. Partnerships will also be developed with a number of regional carbon projects developing model-data fusion schemes such as CarboEruope and the North American Carbon Programme (NACP).

Activity 1.3: Comprehensive national, regional and sectoral carbon budgets

The GCP will actively promote the harmonization of existing approaches to national, regional and basin scale carbon budgets to ensure comparability amongst regions having different social, economic and environmental conditions and histories. This activity will start with existing national, regional and sectoral approaches, to provide complete analyses of the carbon budget (stocks and fluxes) of a given region. Approaches will be modified as Activity 1.1 (Enhancing Observations) and Activity 1.2 (Model-Data Fusion) mature. This activity also links to activity 3.3 (Urban Development) by documenting the human factors driving the changes in the carbon, and how they are spatially distributed among key sectors and regions of the world and so providing information on potential control points for carbon management. Activity 1.3 will (1) compare regional budgets to gain insights on global patterns and variability, (2) use regional carbon balance estimates to constrain global estimates, and (3) and promote coordinated development of robust carbon budgeting systems for a number of space scales. This latter focus will emphasize multiple constraint approaches (Activity 1.2) relevant to assessment and verification requirements for carbon accounting under the United Nations Framework Convention on Climate Change (greenhouse gas inventories) and its Kyoto Protocol, and as a contribution to the application of the new IPCC good practice guidance report for greenhouse gases inventories. The culmination of the activity brings together the results of the two previous activities in focus 1 to provide a global perspective of the human-induced changes in the total carbon balance with appropriate spatial resolution.

Task 1.3.1: Development of standardized methodologies for estimating comprehensive carbon budgets (stocks, changes in stocks and fluxes) at regional and basin scales

National, regional/basin and sectoral carbon budgets have been developed for different reasons in various locations around the world over the last decade. Comparison of these analyses is limited because both the elements considered and the assumptions made differ substantially among budgets. Some terrestrial budgets include land-use change and fossil fuel emissions, while others focus only on natural ecosystems, ignoring direct human activities; some are based primarily on primary data (such as forest inventory) while others depend on process-scale model simulations.

This task will aim at reconciling the different analytical approaches and estimates to develop a set of common approaches to provide a comprehensive estimate of carbon stocks, carbon stock changes and carbon fluxes for a given region or basin that can be compared with another region or basin. Methods for integrating observational data for both stocks and stock changes (e.g., inventory data and atmospheric gradient analyses) and fluxes (e.g., from flux tower networks and ocean pCO_2 measurements) will be incorporated. Many regional and national carbon budgets, such as the country submissions to UNFCCC, are based on country statistics without explicit reference to georeferenced data. However, georeferenced data for land use and land cover, climate, ecosystem structure, site history and disturbances is needed to fully integrate direct observations to the new model approaches and to facilitate the verification requirements of international conventions.

Task 1.3.2: Developing methodologies for tracking and projecting temporal changes in regional and basin scale carbon budgets

Aimed at quantifying the space-time patterns of natural and human influences on the carbon cycle, this task will extend and complement task 1.3.1 on methodologies for carbon budgets by:

- Explicitly adding a temporal component to regional carbon budgets;
- Examining the changing contribution of different sectors of human activity (energy, agriculture, forestry, fisheries, transport, industry, households, wastewater treatment, etc.) and of natural ecosystems to the regional carbon balance over time;
- Quantifying the human and natural factors affecting the carbon cycle and how this perturbation is spatially distributed among the main regions of the globe.

Documented changes over time in social, economic and environmental conditions will be incorporated to develop historical pathways. Various time scales (seasonal, interannual, decadal and longer term changes in the regional carbon budgets) will be explored to examine the importance of different factors. Identification of regions, sectors and critical data required to reduce uncertainties will be communicated to Activity 1.1 (Enhancing Observational Knowledge).

The results of these data-driven regional scale analyses may be used to test process-scale models and new model-data fusion methods developed under Activity 1.2 (Model-Data Fusion), as well as to provide additional input information for atmospheric inversion approaches.

Task 1.3.3 Geographic and sectoral analysis of human-induced changes in the carbon cycle

This activity will actively promote an international initiative to compare and analyse changes in regional carbon budgets, their human causes and their contribution to the global carbon cycle. It will begin with an identification of critical regions of the globe using existing integrated assessment models to determine where the existing social, economic and environmental conditions suggest likely high sensitivity to change in the recent past or immediate future. Analyses using the multi-sectoral approaches will be encouraged in these vulnerable regions to perform comprehensive regional assessments, to facilitate comparisons between the different regions, and to elucidate the critical human and natural factors governing changes in regional carbon budgets. Initially based on existing regional and sectoral budgets, later analyses will incorporate the data-model fusion and multiple-constraint procedures developed under Activity 1.2.

Deliverables of Activity 1.3:

- Compile national and regional carbon budgets and assess their use as bottom-up constraints in the global carbon budget.
- Review existing national and regional approaches both on land and ocean carbon balances, and provide recommendations for improved analyses and methodologies.
- Improved carbon accounting systems with associated uncertainties analyses and verification techniques.
- Documented regional carbon balances and changes over time as case studies for use in Activity 3.3.
- Stronger interaction between national, regional, and global carbon programmes, with improved use, accessibility, and inter-comparability of data and results from multiple projects and national programmes.
- Internet Web Portal on carbon cycle resources, including information on national and regional carbon programmes, field campaigns and opportunities for collaboration and coordination, research agendas and highlights, presentations, and others.
- Improved understanding of the spatial and temporal patterns of contemporary carbon stocks and exchanges gained through coordinated research (including a set of special issues and books)

Links to other programmes and projects:

Multiple national and regional carbon research projects. Ongoing IPCC-related activities including existing tasks: 1) “Good practice guidance for land use, land-use change and forestry”, 2) “Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and devegetation of other vegetation types” and 3) “Factoring out direct human-induced changes in carbon stocks and GHG emissions from those due to indirect human-induced and natural effects”. SBSTA/UNFCC activities involving carbon sources and sinks including National Communications on GHG inventories, and Kyoto Protocol reporting. GCTE, LUCC, IT, GTOS, START, JGOFS, CLIVAR, SOLAS, CO2 Panel, LOICZ. IEA Bioenergy Task 38: Greenhouse Gas Balances of Biomass and Bioenergy Systems International Energy Agency Task

Focus 2: Processes and Feedbacks

Activity 2.1: Mechanisms and feedbacks controlling carbon stocks and fluxes

Focus 2 will promote new research and synthesis to increase our understanding of the controls of natural and human driven sources and sinks of carbon, and the spatially explicit complexities between causes and effects especially of human-driven mechanisms. Emphasis will also be placed in understanding the interactions among mechanisms and feedbacks among components of the coupled carbon-climate-human system. Such understanding is the foundation to explore control points that allow humans to modify the dynamics of the carbon cycle and to investigate future dynamics and stability of terrestrial and ocean sinks. They are both critical inter-players in the efforts to stabilise atmospheric CO_2 concentrations (Focus 3).

Task 2.1.1: Integrated study of the multiple mechanisms determining ocean carbon dynamics

This task will promote research and synthesis to identify the multiple source and sink mechanisms, their relative importance, and their interactive effects responsible for the current oceanic and freshwater net carbon fluxes. That is, how the processes of the carbon system work, individually and collectively. These processes include transport and mixing, biological carbon fixation and decomposition as well as their interaction. Particular emphasis will be given to:

- Determinants of oceanic productivity and euphotic zone community structure such as iron availability;
- Remineralization processes in the upper ocean and in freshwater bodies;
- How climate variability and climate change affect the partitioning of carbon between the atmosphere-ocean system;
- Interactions between subsystems (for example, the impact of soil aridity on Fe transport to the open ocean);
- Understanding future dynamics of these mechanisms and interactions, and in particular their implications for possible ocean sink saturation.

The products will be distributions of sources and sink strengths, and assessments of the driving mechanisms and the potential feedbacks between them. This will permit GCP to develop integrated regional carbon balances with attribution of quantities to each of the major mechanisms contributing to sources and sinks. The GCP will foster the development of these watershed and regional integrated carbon balances, through Focus 1.

Task 2.1.2: Integrated study of the multiple mechanisms determining terrestrial carbon dynamics

This task will promote research and synthesis to identify the multiple source and sink mechanisms, their relative importance, and their interactive effects responsible for the current terrestrial net carbon fluxes. Special focus will be given to:

- Developing methods for attributing, quantifying and factoring out the multiple mechanisms of the current terrestrial sink. Emphasis will be placed on indirect anthropogenic components of the terrestrial carbon sinks, such as the CO_2 and N fertilization, and regrowth from past human-induced disturbances as requested by the UNFCCC-Conference of the Parties (COP) meeting in Marrakech, 2001.
- Understanding the stability of current sink mechanisms, and in particular their implications for possible terrestrial sink saturation in the future.
- Climate change effects on heterotrophic respiration as a critical feedback to climate.

The task will produce maps of the locations and magnitude of the various sink mechanisms, together with spatially explicit assessments of the feedbacks between those mechanisms influencing terrestrial carbon sinks and sources. It will also produce integrated regional carbon balances with attribution of quantities to each of the major mechanisms contributing to sources and sinks. The GCP will foster the development of these National and regional integrated carbon balances, through Focus 1.

Task 2.1.3: Integrated study of anthropogenic carbon emissions

This task will identify the individual drivers of patterns of productivity/consumption and land use change that give rise to anthropogenic emissions of greenhouses gases, and study the interactions, synergies and nonlinearities between different human drivers and carbon emissions. This will allow constructing globally- representative case studies that can be aggregated and extrapolated to larger regions. The studies will include historic and recent tendencies of carbon change and its most relevant human drivers and their interconnectivity between regions (e.g., deforestation driven by increased beef demand in other parts of the world).

Deliverables of Activity 2.1:

- Better understanding of mechanisms and their interactions, suitable for (i) use in models and model-data fusion, and (ii) carbon mitigation options and identifying windows of opportunity for intervention.
- Spatially explicit attribution of ocean and terrestrial sink mechanisms, and their interactions, consistent with to observed global carbon flux patterns (Focus 1);
- A state-of-the-art synthesis on the effects of CO_2 and N fertilization and forest age structure, and a consistent suite of tools available for attributing these mechanisms to observed terrestrial sinks, and engagement in the SBSTA request on this issue.
- Synthesis on warming effects on heterotrophic respiration and recommendations for modelling improvement.
- Synthesis of human drivers that rise greenhouse gases emissions (i.e., drivers of productivity/consumption and land use change).

Links to other projects and activities:
The study of biophysical mechanisms will be strengthened and developed in collaboration with GCTE, the new LAND project, JGFOS, new OCEANS, SOLAS, LOICZ. The research agenda on human drivers of emissions will be closely developed with LUCC, IT, IDGEC, IPCC WGII and III, and the Assessments of Impacts and Adaptations to Climate Change (AIACC). Close collaboration will be established with SBSTA-IPCC.

Activity 2.2: Emergent properties of the coupled carbon-climate system

Emergent properties are system behaviours that arise from interactions among the subsystems or components of a system. They may include the existence of multiple equilibrium states and instabilities, as found in box models of oceanic thermohaline circulation; quasi-periodic oscillations such as glacial-interglacial cycles in the carbon-climate system; sudden non-linear changes such as rapid climate change events; and even homeostatic processes as in James Lovelock's Daisyworld model. Similar behaviours are expected to become apparent when coupling human perturbations and responses in our modelling projections, and forcing models into future novel conditions brought about by global change.

This activity will focus firstly on the development of better understanding of the past variability in the carbon-climate system by decomposing and modelling the glacial-interglacial cycles climate and carbon behaviour and the coupling of the current and project human perturbation of the climate system via the carbon cycle. This new knowledge will help to constrain better predictions regarding the future of this system. A critical organizing question in this activity will be: Could human interventions in the carbon cycle delay or accelerate the next ice age?

Although many mechanisms have been suggested to have played a key role in glacial-interglacial cycles, there is no definite understanding of this dominant mode of variability in the Earth system. The GCP will consider existing simple models of long-term variability in the carbon-climate system, in the context of the information-rich ice-core records. A key objective will be to determine how the paleoclimate record constrains internal model parameters, and thereby sets bounds on the behaviour of the "natural" carbon cycle in the future.

Secondly, this activity will investigate what additional system properties emerge when the perturbed carbon cycle is included as an interactive element in the full carbon-climate system, and in particularly, whether thresholds, instabilities and surprises could emerge from this full system coupling. Until recently, General Circulation Models of the climate system (GCMs) have neglected climate-carbon cycle feedbacks, instead assuming that ocean and land uptake will be insensitive to climate change. In contrast, the first GCM experiments to include the carbon cycle as an interactive element suggest that such feedbacks could significantly accelerate increases of atmospheric concentrations of CO_2 and, as a result, intensify climate change in the 21st century. However, the associated uncertainties are large. In this part of the activity, simplified models of the carbon-climate system (developed in the context of the glacial cycles, see above) will be used to elucidate some of the key sensitivities to human drivers, providing a focus for detailed process studies. In addition, this task will also specifically explore the likely trajectories of the ocean and terrestrial uptake of anthropogenic CO_2 under global warming (and other global change forcings) with the mechanistic attribution gained in activity 2.1 and model development gained in this activity and activity 1.2. Special attention will be paid at the possible saturation of the ocean and terrestrial carbon sinks.

Deliverables of Activity 2.2:

- Review on the development of coupled carbon-climate models, and further fostering of collaborative research between the climate and carbon scientific communities.
- Model intercomparisons and utilisation of available instrumental records and palaeo-data for model validation and development.
- Promote the development of appropriate data assimilation procedures for coupled models linked to activity 1.2.
- New constraints on climate-carbon cycle feedbacks from past climate and CO_2 records, and stronger links to stuides on future carbon-climate feedbacks such as soil carbon dynamics, large-scale vegetation dynamics, an ocean circulation.
- A better understanding of possible surprises or abrupt changes that may arise in the carbon-climate-human system under new domains of human intervention.

Links to other projects and activities:
This activity will be developed in close association with the Coupled Climate-Carbon Cycle Model Intercomparison Project (GAIM/WCRP-C4MIP), WCRP-GAIM Working Group on Climate Models (WGCM), and PAGES. Strong links to activity 1.2 and particularly on data-assimilation, and Task 2.1 on mechanisms.

Activity 2.3: Emergent properties of the coupled carbon-climate system

The coupling of models of the physical, biochemical, and human components of the carbon cycle is in its infancy. This Activity will help to initiate cross-disciplinary research in this area, by highlighting novel behaviours that emerge when all these subsystems are coupled together. It will therefore stimulate the development of more detailed predictive tools and conceptual frameworks including ranging from more sophisticated models (e.g. General Circulation Models of the climate system coupled to carbon models as the next step from Activity 2.2), to agent-based models, toy models and conceptual frameworks that can allows us to explore the emerging properties of the fully coupled system. The activity will also provide a conceptual framework with which to interpret the results from these more complex models.

This activity will foster the construction of coupled carbon-climate-human models from both directions: introducing physical and biogeochemical feedbacks into agent-based models of human actions, and at the same time introducing human interactions and responses into differential equation-based models of the climate-carbon system. This will be a significant challenge since models of the various subsystems have different basic structures. For instance, models of physical climate and biogeochemistry, are normally based on continuous differential equations, while models of human systems are often agent-based adaptive models. The activity will also use other simpler modelling tools and conceptual non-quantitative frameworks in order to explore the system behaviour under a number of scenarios of human perturbations. The resulting models will provide complementary views, and requiring consistency amongst these approaches will yield additional constraints on each of them.

Some of the approaches above include (1) General Circulation Models of the climate system (GCMs) coupled to carbon models, (2) Models of Intermediate Complexity, (3) Integrative Assessment Models, (4) Agent-based models, (5) Environmental economics coupled to simple climate models (6) Dynamic-system and game-theory approaches, (7) Optimality/control theory, (8) Conceptual frameworks, and (9) Interactive simulators to explore system behaviour.

Agent-based models are a specific promising area for investigating coupled systems because they can more directly represent adaptive or evolutionary behaviour of agents in a system, whether they are individual farmers, national or global institutions.

The GCP will (1) identify the current status of efforts to model those aspects of the human systems that most closely couple to the carbon system. Where serious deficiencies are noted, further development of such models will be encouraged; and (2) use these approaches to explore for new system behaviour of the perturbed climate-carbon system with an emphasis on feedback responses which may yield rapid changes and non-linearities.

Deliverables of Activity 2.3:

- A review book on current and promising new approaches to couple the climate-carbon-human system including dynamical systems, optimality/control theory, game theory, agent-based models, and others.
- A new generation of tools (including new models) and approaches to study the coupled climate-carbon-human system, including a contribution towards the development of Earth System models.
- Identification and characterization of key interaction mechanisms influencing the carbon-climate-human system, especially relating to management of the carbon cycle.
- A better understanding of possible surprises or abrupt changes that may arise in the carbon-climate-human system under new domains of human intervention.

Links to other projects and activities:
This activity will be developed in close association with the Coupled Climate-Carbon Cycle Model Inter-comparison Project (GAIM-C4MIP), WCRP-GAIM Working Group on Climate Models (WGCM), and PAGES. A number of IHDP initiatives using agent-based modelling including LUCC and IDGEC. It will also contribute to Focus 3 of the GCP.

Focus 3: Management of the Carbon Cycle

Focus 3 will help to complete the overall scientific vision of the GCP, by integrating observational knowledge (Focus 1) and process understanding (Focus 2) for effective management of the carbon cycle. In this way, Focus 3 responds to the critical need expressed in the policy community and the various international and national processes related to climate change for scientific inputs regarding the future evolution and dynamics of the carbon cycle and the opportunities for intervention. The evolution of this system through the 21st century will be the outcome of a three-way coupling among natural processes, anthropogenic drivers, and human responses.

Activity 3.1: Identification and sustainable potential of mitigation options

This activity deals with (i) the identification and assessment of specific points of intervention by which the future evolution of the carbon cycle may be influenced, and (ii) provides a critical assessment of the achievable mitigation potential of the various options once sustainable development concerns (i.e., triple-bottom-line) are considered.

In policy discussions *mitigation* is used to refer to efforts to regulate and ultimately to reduce emissions of greenhouse gases with the objective of avoiding significant anthropogenic changes in the carbon-climate system, thereby eliminating climate change as a policy problem. In other words, mitigation options represent points of intervention in the carbon cycle whereby humans can influence the future trajectory of atmospheric CO_2 (Task 3.1.1 and 3.1.2). Other points of intervention are related to consumption patterns which are in many ways the ultimate drivers of carbon emissions (Task 3.1.3).

Task 3.1.1: Control points in terrestrial and ocean exchanges

Purposefully induced long-term storage of carbon on land and oceans provides a critical intervention point by which humans can modify the dynamics of the carbon cycle and, to some extent, influence the current upward trends of atmospheric CO_2 concentration. This includes (i) reduction of carbon emissions from land disturbance (e.g., deforestation avoidance), (ii) sequestration of carbon in terrestrial or oceanic biological sinks, and (iii) engineered disposal of CO_2 in geological and oceanic repositories.

In addition to the effects on greenhouse mitigation, large-scale carbon sequestration and disposal projects will have other cost and benefits to the environment, economy and socio-cultural values. On one hand, there are large gaps between the technical mitigation potential of the various options and the mitigation that is realistically achievable once implementation constraints and concerns on sustainable development have been met. For instances, it is likely that reduced river flow and biodiversity due to large-scale mono-specific forest plantations will limit the extent to which plantations can be used in semi-arid and arid regions. On the other hand, positive collateral effects might make it possible for mitigation options to be financially viable and more socially acceptable. For instance, large-scale reforestation may increase soil fertility and decrease soil salinization which can bring additional interest from stakeholders and institutions on such projects. In the end, it is likely that ancillary costs and benefits will determine the viability of a given mitigation option to be implemented.

The GCP will conduct a series of analyses for a number of projects and mitigation options against environmental, social, and economic (triple-bottom-line) criteria which includes: (1) effectiveness in reaching climate goals; (2) technological feasibility; (3) economic viability; (4) social acceptability; (5) environmental performance against criteria other than climate benefits. Effectiveness in reaching climate goals will not only focus on the quantitities of carbon sequestered but also on stability, permeance, and verification of the new carbon stores. Theses analyses will provide a more realistic and sustainably achievable mitigation potential in contrast to the technical (or theoretical) mitigation potential which have been provided in recent international assessments.

The analyses will be developed for:

- Large-scale sequestration projects as case studies in which the triple-bottom-line analyses will be considered as part of the feasibility and efficiency assessment of the projects.
- Some globally important regions (e.g., SE Asia)
- Globally

Task 3.1.2: Control points of fossil fuel emissions

There is a range of options for altering both the carbon intensity of energy production as well as the energy intensity of economic output. These include, for example, non-fossil-fuel energy generation options such as renewables, nuclear (fission) and fusion; as well as options for increasing energy use efficiency (for example through co-generation and distribution systems in the standing energy sector, and hybrid and non-fossil-fuelled vehicles in the transport sector). As in Task 3.1.1, assessment of mitigation options needs to consider environmental, social and economic (triple-bottom-line) criteria.

The GCP will develop a similar series of analyses as in task 3.1.1 for a number of projects and mitigation options in order to better assess the sustainably achievable mitigation potential when all the ancillary costs and benefits are taken into account. These analyses, in addition to consider the triple-bottom-line criteria, will need to include an analysis of the potential speed and extent of technological change, as one of the key variables of energy-economic models. The analyses will be done using:

- Large scale projects as case studies.
- Global analyses of the achievable potential for specific mitigation options.

Task 3.1.3: Consumption patterns as control points of carbon emissions

Consumption patterns are the root drivers of fossil fuel emissions, as well as other environmental pollution problems. At the same time, consumption patterns arise due to more fundamental pressures of human wants, needs, values and preferences, which can be eventually translated into marketplace activity and production behaviour. Environmental pollution has typically been addressed through intervention on the production side, with reasonable success. On the other hand efforts to change behaviour and bring about societal transformations have been often unsuccessful. In the case of fossil fuel emissions, it is likely that substantial response might require fundamental changes in consumption patterns.

The GCP will undertake a number of case studies on the evolution of consumption patterns, and production – consumption systems. This will provide insights into ways by which more sustainable consumption patterns might be fostered, in particular, whether and how changes in these patterns would, in turn, influence the entire production system, with attendant environmental and carbon consequences.

Deliverables of Activity 3.1:

- A set of analyses published in peer reviewed papers on the realistic and sustainably achievable carbon mitigation potential for a number of options. The analyses will be organized by major categories of mitigation options: (i) Terrestrial biological sequestration and disturbance reduction; (ii) Biological sequestration in the oceans; (iii) engineered CO_2 disposal on land and oceans; (iv) non-fossil fuel energy sources; and (v) energy conservation and efficiency. The analyses will be globally in scope but specific nations and regions will be targeted as per their regional and global importance.
- A set of analyses and recommendations on potential points of intervention at the level of consumptions patterns.

Links to other projects and activities: National and international energy programmes; IPCC; IDGEC and IT; GCTE, LUCC, new LAND, SOLAS, new OCEANS, Integrative Assessment Community, the International Energy Agency (IEA).

Activity 3.2: Carbon management in the context of the whole Earth System

The overall success of any given carbon mitigation or portfolio of options will depend on a number of issues including the effectiveness in climate mitigation, the balance of negative and positive collateral effects, and on the human processes which aid or act against implementation of biophysically appropriate measures. All the issues have a strong spatial and temporal scale which will require the development of unique mixes of mitigation options for a given region and the development of the institutional capacity to take advantage of windows for implementation.

This activity will develop a formal framework to assess the best mitigation options in a full system analyses framework (Task 3.3.1), design dynamic portfolios of carbon mitigation options for specific regions (Task 3.2.2), and provide an analyses and design of appropriate institutions for carbon management to improve the portfolio effectiveness (Task 3.2.3).

Task 3.2.1: Framework for designing integrated mitigation pathways

The task will develop a formal framework/s for analysing CO_2 stabilization pathways within the full range of carbon-climate-human interactions. This will include the effects of synergisms and antagonisms between carbon mitigation, adaptation, and other sustainable development objectives. Adaptation and mitigation strategies for climate change need to be considered in a comprehensive and integrated manner. This is not only because many mitigation strategies (for example improved agricultural practices, forest management or cleaner energy) are likely to provide benefits in coping with the impacts of climate change, but also because of the linkage between adaptation and developmental activities. As a result, it is important to evaluate adaptation and mitigation options jointly, with particular attention to issues such as ancillary costs and benefits in the light of sustainable development. Such evaluation might lead to the identification of trade-offs as well as possible win-win or no-regrets strategies. This approach will also lead to examine the implications of these activities for the range of other ecosystem functions and services such as provision and conservation of biodiversity, soil fertility, food and fibre, non-timber forest products, climate regulation and flood and storm protection. These services and functions are critical, and are also intimately tied to local communities and sustainable livelihood issues.

A conceptual framework will be developed with specific tools and approaches (e.g., computer simulation tools) that can directly support carbon management in general, and more specific to design and assess mitigation portfolios in task 3.2.2. These will include methodologies for assessment and evaluation of trade-offs and policy options; approaches for stakeholder involvement in policy formulation; trade-off decision making, as well as tools for envisioning the consequences of alternative policies and development pathways. A good example is Integrated Assessment which has rapidly emerged as an approach of choice for addressing complex, multi-disciplinary issues to produce policy-relevant insights. The creation of methods and tools will include:

- Integrated assessment models and approaches, including simulation tools.
- Scenario-building and scenario-based reasoning.
- Transitions management, adaptive management and learning-by-doing.
- Participatory approaches.

For those research areas which are already active on their own right the GCP will seek to contribute a carbon perspective to these efforts, for example, Integrated Assessment Models that would have a carbon cycle component.

Task 3.3.2: Designing portfolios of mitigation options

Stabilising atmospheric greenhouse gases will require major changes in energy systems, management of forests and agriculture, and other human activities. No single technology or approach can achieve this goal. Instead, a portfolio of mitigation options will be required to successfully achieve stabilization in the larger context of development, sustainability, and equity. Regions and countries will need to design specific portfolios of mitigation options in accordance to their environmental, socio-economic, and institutional circumstances. It is unlikely that two regions or countries in the world will design identical portfolios although general similar patterns may emerge for regions and countries with more similar realities.

This activity will use the framework and tools developed in task 3.3.1 and build upon the results on achievable mitigation capacity in activity 3.2 to design the “best” mix of options for a number of contrasting and globally relevant regions. Designing the mix requires to define and maximize benefits, utility and well-being, at the same time minimize a generalised cost including environmental ones. It will also need to consider the right incentives (and barriers) for mitigation and using windows of opportunity as they emerge. Finally, it will be important to have a long-term vision which ensures results beyond the immediate needs (e.g., first commitment period for Kyoto Protocol signatory nations).

A preliminary list of regions for this analyses includes selected countries in the Asia Pacific region (China, Japan, Philippines, Thailand), Africa (Senegal), Europe (Germany, Spain), and North-South America (US, Mexico, Argentina).

Task 3.3.3: Designing carbon management institutions

The effectiveness and success of any carbon management strategy depends on a complex set of technological, organizational and institutional factors, at a variety of levels – local, sub-national, national and international. Valuable insights can be obtained by evaluating different institutional structures and designs that have been formulated and implemented in the past for managing environmental and related resources. This will require identification of metrics, assessment tools and evaluation paradigms. The analyses will provide insights into what works and what does not, and will also enable adoption of learning-by-doing strategies. This task will include the analysis of institutional, organizational and technological options and strategies. At the international level, it will include how far regimes are changing policy, shifting behaviour, and inclining nation states towards compliance with international agreements.

A set of case studies will be selected and analysed in light of what can be learned for carbon management. The case studies will include the successful Montreal Protocol, acid rain, and an analysis of the evolution of the Kyoto Protocol up to now.

Deliverables of Activity 3.2:

- A formal framework for assessing portfolios of mitigation options including the development of a computer simulation tool to test policy consequences in the carbon-climate system.
- Portfolios of carbon mitigation options for selected countries and regions. A preliminary list: Asia Pacific region (China, Japan, Philippines, Thailand), Africa (Senegal), Europe (Germany, Spain), and North-South America (US, Mexico, Argentina).
- An analysis of the relative merits of various policies options (e.g., emission trading, carbon sequestration) and the potential benefits of combining the portfolios of mitigation and adaptation options.
- A number of papers with lessons learned for carbon management from the analyses of past international environmental agreements.
- A set of detailed studies of the effectiveness of the Kyoto mechanisms - emissions trading, joint implementation, the clean development mechanism, carbon sequestration options - together with a systematic comparison between these mechanisms and alternative approaches to reducing overall emissions of greenhouse gases.
- Recommendations on new institutional design to minimise the gap between the required mitigation to achieve a given stabilization scenario and the achievable mitigation potential with current institutional arrangements.

Links to other projects and activities:

IDGEC, GCTE, LUCC, new LAND, and START. SCOR and new OCENS for ocean carbon sequestration. WGII (Impacts, Adaptation, and Vulnerability) and WGIII (Mitigation) of the Intergovernmental Panel on Climate Change (IPCC), the UNFCCC SBSTA, and the UNFCCC Secretariat. APN, IAI, and ENRICH.

Activity 3.3: Carbon consequences of regional development pathways

Pathways of regional development are sequences of interrelated changes in social, economic and political systems. They vary from place to place and over time, in ways that are likely to have different net consequences for carbon stocks and fluxes, which in turn may constrain or in other ways feed back upon development processes.

Urbanization and physical planning are key processes for integrating carbon management into development. Although cities and surroundings only occupy a small part of the earth's surface they play large and growing role in driving changes to the carbon cycle. The way cities are designed and managed over the next several decades will have a large influence on the future of the carbon cycle. On the one hand, well-designed cities provide many technical opportunities to reduce per-capita carbon emissions. On the other hand, cultural and life-style changes associated with urbanization, tend to increase levels of consumption, fossil fuel use, water use and waste production.

Although one could imagine carbon management becoming a significant part of development planning, it is highly likely that this will need to consider trade-offs with not only economic and social development goals, but also with the capacity to maintain other ecosystem goods and services upon which livelihoods of the poor and the wealthy depend on either directly or through long chains of transformation, substitution and transfers. For this reason we propose a study with an emphasis on carbon, in many ways a "*carbon's eye view of development*", which however, at the same time makes a substantial effort to understand interactions, with in particular, biodiversity conservation, and the supply, demand and provision of fresh water and of food from agriculture, aquaculture and fisheries.

It is recognized that many actions taken by corporations, governments and individuals will be made for reasons other than carbon management but may still have very important carbon cycle consequences. For example, concerns with air quality in urban and industrial areas, or travel times in over-congested and extended mega-cities. A key part of this project will therefore be to explore creatively how local, regional and global goals, or private and public goals, can be aligned.

The GCP will undertake a major comparative analysis of a network of contributing regional case studies. Regions are thought to be large enough to include a range of landscape types (urban, industrial, agricultural, forest) and thus may be sub-national, national, or rarely, multinational. A special emphasis will be placed on recruiting case study regions including major cities, because of the predicted importance of urbanization for carbon emissions and sequestration.

The focus of this activity is on understanding how key social, ecological and biophysical processes unfold and interact during regional development. The motivation for seeking this understanding is to apply to the development of scenarios and policy analysis.

The key questions the Activity will address are:

1. What are the consequences of different pathways of regional development on carbon stocks and fluxes?
2. What are critical processes and interactions in development that result in pathways with widely differing carbon consequences?
3. What are the most important trade-offs and synergies between changes in carbon stocks and fluxes, with other ecosystem services, especially the provision of food, water, clean air, and the maintenance of biodiversity?

The first step in this activity will be to:

- Establish an international network of regional case studies which would allow structured and coordinated comparisons of the carbon consequences of different development pathways.
- Identify small key set of variables (or clusters of processes and sequences) that need to be measured and understood to be able to address the research questions from a comparative perspective.
- Recruit an initial set of 6-12 regional case studies from around the world which agree to conduct joint analyses based on minimum datasets and shared protocols. This should include a high proportion of sites with cities so that urbanization issues can be addressed.

The analyses of the case studies will encompass two tasks:

Task 3.3.1: Drivers of development and its carbon consequences

- Identify the main structures and processes that help explain why different regional development pathways have different consequences for carbon stocks and flows.
- Identify the main differences between case studies with potential to affect carbon stocks and flows.
- Use variety of methods, including models and sensitivity analyses, statistical decomposition, and in-depth review of historical processes (eg related to energy use and policy) to identify both proximate and underlying causes of differences.

Task 3.3.2: Carbon management options and future scenarios

- Explore options for how carbon management could be integrated into development and suggest ways this could be tested through scenario and policy analysis.

- Identify the main trade-offs and synergies between "carbon management" goals and various services, especially those important for human well-being, from historical experiences in the case studies

Deliverables of Activity 3.3:

- The Global Change System for Analysis, Research and Training (START) and the GCP will organize a number of research/summer institutes on the topic, being the first one schedule for July 2003 in Boulder, Colorado (USA) on the topic "Urbanization, emissions, and the global carbon cycle".
- A well coordinated set of regional case studies from around the world, many encompassing major cities, and set in a diverse economic and political contexts, (i) including full carbon budgets (by sector and over time if possible), (ii) analysis of factors driving the carbon balances, and (iii) data to parameterise, formulate and text climate-carbon-human coupled models.
- Book or special issue of a journal documenting the case study analyses and synthesis;
- Development-oriented policy papers on theme of integrating carbon management in regional development: where and when is it worthwhile?

Links to other projects and activities:
This activity will build on past work of IT, the new activity on Urban Ecosystems and Biogeochemistry in GCTE (and the new LAND) and the cross-cutting activity on Urbanization in IHDP, and other programmes such as START, IDGEC, IGAC-cities. Regional partnerships will be established with APN, IAI, and ENRICH.

Synthesis and Communication

The GCP will deliver high-level syntheses of information on the carbon cycle, including patterns and variability (Focus 1), processes and interactions (Focus 2), and management of the carbon cycle (Focus 3). Although a large portion of the synthesis will be aimed to the research and assessment communities, specific written products and web-based resources will be developed for policy makers, high education communities, and general public. Specific products for multi-disciplinary audiences will be also developed in order to foster a common understanding and language.

High-level synthesis. The main objective will be to deliver the state-of-the-art synthesis on the integrated view of the carbon-climate-human system and specific components of it. This will be done by organizing synthesis workshops or commission synthesis to individuals or groups of scientists with a rapid turn-over time publication in order to provide quick feedback to research directions. Collaborative synthesis projects will be developed with the Scientific Committee on Problems of the Environment (SCOPE).

Issues in carbon cycle research. This task will produce synthesis and discussion papers dealing with unresolved issues in the global carbon cycle such as biospheric respiration responses to increasing temperature, or emerging tools to study the coupled carbon-climate-human system. The focus is not only to synthesize the latest understanding on a specific issue, but also to provide information on the development and use of new research tools and approaches.

Communication products. Given the importance of some of the findings resulting from the three implementation Foci and synthesis activities, products will be developed to suite audiences other than the highly specialized research communities, such as policy makers, governments, high education, and general public. Such products will include brochures, posters, computer presentations developed with the involvement of communication experts and scientific writers. Two other specific products will be developed to increase communication and dissemination of research results: (1) a project webisite, and (2) an Internet Carbon Portal which will provide a number of resources on the carbon cycle relevant to research, policy and education.

Deliverables:

- A collection of synthesis, special journal editions and books on high level and topical information of the carbon cycle, including state-of-the-art understanding and methodological issues. The first effort will be on the Rapid Assessment Project on the Carbon Cycle (SCOPE-GCP) in 2003 which will produce a state-of-the-art synthesis of the entire carbon cycle including carbon-climate and human interactions. Similar efforts will follow on terrestrial carbon sinks and global oxidation pathways.
- A collection of brochures, posters, and web-based materials to communicate research findings to a variety of audiences including multi-disciplinary research communities, policy makers, assessment, high-education, and general public.
- A website for the GCP and an Internet Carbon Portal with multiple carbon resources.

Capacity Building

The GCP will develop a number of capacity building activities associated with the main research Foci. This will promote the development of a new generation of young and no-so-young scientists on highly interdisciplinary topics of the carbon cycle. A good example of this activity is the already underway "summer institutes on data assimilation" which will be a major contribution to capacity building in this new field (see Activity 1.2).

The GCP will work in close coordination with the Global Change System for Analysis, Research and Training (START) as the programme partner sponsored by IGBP, IHDP, WCRP, and Diversitas. From this partnership, a major "research institute" is being planned for 2003 on "Urbanization, emissions, and the global carbon cycle" (see Activity 3.3). Other linkages will be established with IAI, APN, and ENRICH, and other regional programmes to foster research on the carbon cycle in less developed regions where little carbon research is currently taking place.

Timetable

The GCP has developed an initial timetable of activities and deliverables based upon the most pressing priorities and a number of already on going activities (**Figure 19**). Most of the specific activities (e.g., workshops, capacity building courses, etc.) are presented in the various sections of the Implementation Plan and Figure 19 summarizes them all. Subsequent versions of the timetable and the entire implementation plan will be posted in the GCP website. A major mid-term review will take place in 2005.

- Figure 19 about here -

Management Structure and Execution

The work of the GCP is guided by a Scientific Steering Committee (SSC) made up of scientists covering the main research areas of the GCP Science Framework and Implementation. The SSC also consider recommendations on implementation activities made by their sponsor programmes and projects within. The SSC is appointed for a two-year term with possible extensions up to six years. The SSC is co-chaired by 3 scientists who were initially appointed by each of the sponsor programmes (IGBP, IHDP, and WCRP). One or more executive officers coordinate the execution strategy and implementation of the GCP. Below is the list of the SSC-2003.

CO-CHAIRS
Michael Raupach (IGBP)
CSIRO Earth Observation Centre
Canberra, AUSTRALIA
E-mail: Michael.Raupach@csiro.au

Oran Young (IHDP)
University of California
Santa Barbara, CA, USA
E-mail: young@bren.ucsb.edu

Robert Dickinson (WCRP)
Georgia Institute of Technology
Atlanta GA, USA
E-mail: robted@eas.gatech.edu

SSC MEMBERS
Mike Apps
Canadian Forest Service
Victoria, CANADA
E-mail: Mapps@nrcan.gc.ca

Alain Chedin
Ecole Polytechnique
FRANCE
E-mail: chedin@araf1.polytechnique.fr

Chen-Tung Arthur Chen
National Sun Yat-sen University
CHINA, Taipei
E-mail: ctchen@mail.nsysu.edu.tw

Peter Cox
MetOffice
UNITED KINGDOM
E-mail: Peter.Cox@metoffice.com

Ellen R.M. Druffel
University of California, Irvine
Irvine, CA, USA
E-mail: edruffel@uci.edu

Christopher Field
Carnegie Institution of Washington
Stanford, CA, USA
E-mail: chris@globalecology.stanford.edu

Patricia Romero Lankao
Universidad Autónoma Metropolitana
Mexico City, MEXICO
E-mail: rolp7543@cueyatl.uam.mx

Louis Philip Lebel
Chiang Mai University
Chiang Mai, THAILAND
E-mail:llebel@loxinfo.co.th

Anand Patwardhan
Indian Institute of Technology
Bombay, INDIA
E-mail: anand@cc.iitb.ac.in

Monika Rhein
University Bremen
Bremen, GERMANY
E-mail: mrhein@physik.uni-bremen.de

Christopher Sabine
University of Washington
Seattle, USA
E-mail: sabine@pmel.noaa.gov

Riccardo Valentini
University of Tuscia, Viterbo, ITALY
E-Mail: Rik@unitus.it

Yoshiki Yamagata
National Institute for Environmental Studies
Tsukuba, JAPAN
E-mail: yamagata@nies.go.jp

EXECUTIVE OFFICER
Josep (Pep) Canadell
CSIRO Sustainable Ecosystems
Canberra, AUSTRALIA
E-mail: pep.canadell@csiro.au

The GCP is supported by an International Project Office in Canberra, Australia, and a second one will be established in 2003 in Tsukuba, Japan. The GCP has also a number of affiliated offices with a variable degree of formal arrangements. This includes the SCOR-IOC Advisory Panel on Ocean CO_2 with the headquarters in Paris, France, and the CarboEurope office in Jena, Germany (shared with the Concerted Action on Greenhouses Gases office based in Viterbo, Italy). Other affiliated or IPOs have been proposed in the US and China.

Global Carbon Project
International Project Office
CSIRO Land & Water
FC Pye Laboratory
GPO Box 1666
Canberra ACT 2601
Australia
Tel: 61-2-6246-5630
Fax: 61-2-6246-5560

Pep Canadell
Executive Officer
Email: pep.canadell@csiro.au

Rowena Foster
Administration Manager
Email: rowena.foster@csiro.au

Rose Davis
Administration Assistant
Email: rose.davis@csiro.au

Global Carbon Project
International Project Office
NIES, Tsukuba, Japan
Staff to be assigned.

SCOR-IOC Advisory Panel on Ocean CO_2
Affiliate Office
Maria Hood
Intergovernmental Oceangraphic Commission
UNESCO, 1, rue Miollis
75732 Paris Cedex 15
Tel: 33-1-4568-4028
Fax: 33-1-4568-5812
Email: m.hood@unesco.org

CarboEurope
Affiliate Office
Annette Freibauer
Max-Planck-Institute for Biogeochemistry
PO Box 100164
07701 Jena, Germany
Tel: 49-3641-686726
Fax: 49-3641-686710
Email: afreib@bgc-jena.mpg.de

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7. Acronyms

ACSYS	Arctic Climate System Study
AIACC	Assessments of Impacts and Adaptations to Climate Change
AIRS	Atmospheric Infrared Sounder
AMSU	NOAA-15 Advanced Microwave Sounding Unit
APN	Asia-Pacific Network for Global Change Research
AutoMOD	Automated Model Ocean Diagnostic Facility
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle
BASIN	Biospheric Atmospheric Stable Isotope Network
BATS	Bermuda Atlantic Time-series Study
BWG	Biosphere Working Group
C4MIP	The Coupled Climate Carbon Cycle Model Intercomparison Project
CARBOSAT	ESA space mission dedicated to monitoring of the carbon cycle
CCMLP	Coupled Carbon Model Linkage Project
CLIVAR	Climate Variability and Predictability Project
CMRA	Carbon Management Research Activity
COP	Conference of the Parties
CRCGA	Cooperative Research Center for Greenhouse Accounting
CSIRO	Commonwealth Scientific & Industrial Research Organization
CZCS	Coastal Zone Color Scanner Data
DGVM	Dynamic Global Vegetation Model
DIC	Dissolved Inorganic Carbon
EMDI	Ecosystem Model-Data Intercomparison
EMIC	Earth System Models of Intermediate Complexity
ENRICH	European Network for Research in Global Change (EC)
ENSO	El-Nino Southern Oscillation
ENVISAT	ESA satellite
ESSP	Earth System Science Partnership
EU	European Union
FACE	Free Air CO2 Enrichment
GAIM	Global Analysis, Integration and Modelling
GCM	Global Climate Model
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GCTE	Global Change and Terrestrial Ecosystems
GEWEX	Global Energy and Water Cycle Experiment
GLASS	Global Land/Atmosphere System Study
GLOBEC	Global Ocean Ecosystem Dynamics
GOFC	Global Observations of Forest Cover
GOOS	Global Ocean Observing System
GPP	Gross Primary Production
GTOS	Global Terrestrial Observing System
HOT	Hawaii Ocean Time-series program
IA	Integrated Assessment
IAI	Inter-American Institute for Global Change Research
IAM	Integrative Assessment Models

IAEA	International Atomic Energy Agency
IASI	Infrared Atmosphere Sounder Interferometer
ICSU	International Council of Science Unions
IDGEC	Institutional Dimensions of Global Environmental Change
IEA	The International Energy Agency
IGBP	International Geosphere-Biosphere Programme
IGCO	Integrated Global Carbon Observation
IGOS-P	Integrated Global Observation Strategy Partnership
IHDP	International Human Dimensions Programme on Global Environmental Change
IMAGES	International Marine Global Change Study
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IT	Industrial Transformation
ITLER	International LTER
JGOFS	Joint Global Ocean Flux Study
LBA	Long-term Atmosphere-Biosphere Experiment in Amazonia
LOICZ	Land-Ocean Interactions in the Coastal Zone
LTER	Long-term Ecological Research
LUCC	Land Use/Cover Change
LUCCi	Land-Use and Climate Change Impacts on Carbon Fluxes
MA	Millennium Assessment
METOP	Meteorological Operational Polar Satellite
MODIS/AQUA	Moderate Resolution Imaging Spectroradiometer
NCAR	National Center for Atmospheric Research
NEP	Net Ecosystem Production
NOAA	National Oceanic and Atmospheric Administration
NOCES	Northern Ocean Carbon Exchange Study
NPP	Net Primary Production
NSCAT	NASA Scatterometer
OCMIP	Ocean Carbon-Cycle Model Intercomparison Project
OCTS	Ocean Color and Temperature Scanner
PAGES	Past Global Changes
PEEZ	Performance of Exclusive Economic Zones
PEF	Political Economy of Tropical and Boreal Forests
PEP	Pole Equator Pole Transects
PICES	The North Pacific Marine Science Organization
POC	Particulate Organic Carbon
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SCOPE	Scientific Committee on Problems of the Environment
SCOR	Scientific Committee on Oceanic Research
SeaWiFs	Sea-viewing Wide Field-of-view Sensor
SOIREE	Southern Ocean Iron Release Experiment
SOLAS	Surface Ocean- Lower Atmosphere Study
SOMNET	GCTE Soil Organic Matter Network
SST	Sea Surface Temperature
START	Global Change Systems for Analysis, Research and Training
SVAT	Soil Vegetation Atmospheric Transfer Scheme
TCO	Terrestrial Carbon Observations
TOPEX	US-French orbital mission to track sea-level height with radar altimeters
TOVS	NOAA's TIROS Operational Vertical Sounder

Traces	Trace Gas & Aerosol Cycles in the Earth System
TRANSCOM	Atmospheric Tracer Transport Model Intercomparison Project
UNFCCC	United Nations Framework Convention on Climate Change
VOS	Volunteer Observing Ships
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment

8. Appendices

Appendix A: A Selection of Relevant Initiatives and Networks

A.1. International Programmes and Activities

The three Global Change Programmes that co-sponsor the GCP include the IGBP, IHDP, and WCRP. To date, there is a wealth of ongoing and proposed activities within and shared between the three programmes in carbon cycle research. The collaboration already initiated by the three programmes provides a strong platform for links to national and regional activities as well as to future projects in the GCP.

International Geosphere-Biosphere Programme (IGBP)
[http://www.igbp.kva.se]
The IGBP has a long-standing suite of carbon-research activities, ranging from iron fertilization experiments in the ocean, experimental studies of terrestrial ecosystem response to warming and elevated CO_2, budget approaches to coastal-zone carbon fluxes, and comparisons of a wide range of models related to the carbon cycle.

Global Analysis, Integration and Modeling (GAIM)
[http://gaim.unh.edu]
- Ocean Carbon Model Intercomparison (OCMIP)
- Ecosystem Model/Data Intercomparison (EMDI)
- Atmospheric Tracer Transport Model Intercomparison Project (TransCom)
- Global Net Primary Productivity Model Intercomparison
- Trace Gas & Aerosol Cycles in the Earth System (Traces)
- Earth System Models of Intermediate Complexity (EMICs)
- Coupled Carbon-Climate Interaction Experiment (C4MIP)
- Coupled Carbon Model Linkage Project (CCMLP)

Global Change and Terrestrial Ecosystems (GCTE)
[http://www.gcte.org]
- Effects of Elevated CO_2 on Terrestrial Ecosystems
- Effects of Warming on Terrestrial Ecosystems
- Biosphere-Atmosphere Stable Isotope Network (BASIN)
- Soil Organic Matter Network (SOMNET)
- Disturbances and Biogeochemistry
- Global Dynamic Vegetation Model (DGVM) development
- Fluxnet

Note: GCTE will finish early 2004 when a new joint GCTE-LUCC land project will be initiated.

Global Ocean Ecosystem Dynamics (GLOBEC)
[http://www.pml.ac.uk/globec/main.htm]
- North Pacific Marine Science Organization (PICES)

Joint Global Ocean Flux Study (JGOFS)
[http://ads.smr.uib.no/jgofs/jgofs.htm]
- Global Surveys: Air-sea flux of CO_2
- Continental Margins
- Time-Series Stations
- Basin Cruises

Note: JGOFS will finish at the end of 2003 and a new ocean biogeochemistry project will be initiated.

Interactive Land Ecosystem-Atmosphere Processes (ILEPS)
The IGBP and WCRP/GEWEX Scientific Committees will sponsor a new project on land-atmosphere to investigate the mechanisms underlying these land-atmosphere interactions. The project will be initiated early 2004.

Land-use Land-cover Change (LUCC) (co-sponsored by IHDP)
[http://www.geo.ucl.ac.be/LUCC]

- Land-use and Climate Change Impacts on Carbon Fluxes (LUCCI)
- Carbon Sequestration Supply from and Clean Development Mechanism Rules for Tropical Forest Carbon Sinks: A Case Study of Costa Rican LUCC

Land Ocean Interactions in the Coastal Zone (LOICZ)
[http://www.nioz.nl/loicz/]

- The Effects of Changes in External Forcing or Boundary Conditions on Coastal Fluxes
- Coastal Biogeomorphology and Global Change; The fate of carbon in coastal and shelf waters
- Carbon Fluxes and Trace Gas Emissions: Carbon transport down rivers to the coastal zone
- Economic and Social Impacts of Global Change in Coastal Systems: Coastal system sustainability and resource management issues

Past Global Changes (PAGES)
[http://www.pages.unibe.ch/]

- PAGES and Climate Variability (CLIVAR) - *joint with JGOFS and WCRP*- The carbon-climate system investigated through ice cores and deep sea sediments
- International Marine Past Global Change Study (IMAGES)
- Past Ecosystems Processes and Human-Environment Interactions

Surface Ocean-Lower Atmosphere Study (SOLAS)
[http://www.ifm.uni-kiel.de/fb/fb2/ch/research/solas/frameset.htm]

- Biogeochemical Interactions and Feedbacks Between Ocean and Atmosphere
- Exchange Processes at the Air-Sea Interface and the Role of Transport and Transformation in the Atmospheric and Oceanic Boundary Layers
- Air-Sea Flux of CO_2 and Other Long-Lived Radiatively Active Gases

International Human Dimensions Programme (IHDP)
[http://www.ihdp.org/]
IHDP has initiated a wide range of carbon-related activities through each of its four Core Science Projects: IDGEC, IT, LUCC and GECHS. These include a flagship project on the institutional dimensions of carbon management (investigating institutional issues associated with controlling greenhouse gas emissions); research on industrial transformation and the decarbonisation of energy systems; research on transformation of land-use systems and the behaviour of the terrestrial component of the global carbon cycle (and our responses to those changes); and the implications for human security of changes in carbon-cycle dynamics. For more information, please check the IHDP Global Carbon Research document found on the GCP Web site.

Institutional Dimensions of Global Environmental Change (IDGEC)
[http://www.dartmouth.edu/~idgec]

- The Political Economy of Tropical and Boreal Forests (PEF)
- Carbon Management Research Activity (CMRA)
- Performance of Exclusive Economic Zones (PEEZ)

Industrial Transformations (IT)
[http://www.vu.nl/ivm/research/ihdp-it/]

- Energy and Material Flows
- Cities/Transportation
- Governance and Transformation Processes
- The IT Project has written a document listing specific IT-related research questions relevant to the GCP. This document can be viewed at the GCP Web site.

Land-use and Land-cover Change (a co-sponsored Project with IGBP)
[http://www.geo.ucl.ac.be/]

- Land-use and Climate Change Impacts on Carbon Fluxes (LUCCI)
- Carbon Sequestration Supply from and Clean Development Mechanism Rules for Tropical Forest Carbon Sinks: A Case Study of Costa Rican LUCC

World Climate Research Programme (WCRP)

The WCRP provides the modelling tools for climate variability and change essential towards understanding internannual to intercentury variability in the carbon cycle-, the strong control of oceanic and atmospheric circulation over carbon transport and storage, as well as links between the carbon and hydrological cycles. A brief list of major activities sponsored by WCRP are listed below.

Global Energy and Water Cycle Experiment (GEWEX)
[http://www.gewex.com]

- Global Land/Atmosphere System Study (GLASS)
- Data Projects
- Global CO_2 Measurements from Space

World Ocean Circulation Experiment (WOCE-Joint with JGOFS)
[http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html]

- Uptake of excess CO_2 by the oceans
- Global description of carbon dioxide in the oceans to aid the development of ocean models
- Characterize the transport of inorganic carbon within the ocean and between ocean and atmosphere.

Climate Variability and Predictability (CLIVAR – Joint with PAGES)
[http://www.clivar.org/]

- Repeated transoceanic sections at decadal time scales of ocean physical properties and pCO_2
- Working Group on Seasonal to Interannual Prediction (WGSIP),

Working Group on Climate Models (WGCM – Joint with GAIM)
[http://www.wmo.ch/web/wcrp/wgcm.htm]

- Development of fully interactive, comprehensive Earth system models including a realistic representation of the carbon cycle.

Working Group on Numerical Experimentation (WGNE – Joint with GEWEX/GLASS)
[http://www.wmo.ch/web/wcrp/wgne.htm]

- Model intercomparisons to improve the characterization of CO_2 processes in GCMs.
- Data assimilation approaches.

Arctic Climate System Study and Climate and Cryosphere Projects (ACSYS/CliC)
[http://www.npolar.no/acsys/]

- Influences of changes in the cryosphere on the global carbon cycle.
- Greenhouse gases emissions from permafrost.
- Sink strength of the Artic Ocean.

A.2. A Selection National and Regional Programmes

National-level carbon research programmes are the fundamental blocks of research and scientific communities to develop a global strategy. Through activities to enhance comparability, leverage resources, rapid transfer of methodologies and acknowledge, the GCP hopes to further enhance the capabilities of the national and regional programmes at the same time it provides scientific leadership to bring together all the components of what is a single global carbon cycle. In this section, three examples of national and regional programmes are described. For information on other national programmes, check the GCP website.

The Australian Carbon Cycle Programme
[http://www.dar.csiro.au/dir/CCRP/bwg.htm], [http://www.greenhouse.crc.org.au]
The Australian Carbon Cycle Programme includes activities of CSIRO (Biosphere Working Group, BWG) and the Cooperative Research Centre for Greenhouse Accounting (CRCGA). Its foci are:

- Process interactions between the biosphere and the atmosphere, particularly the role of the biosphere in the cycles of biogenic greenhouse gases (carbon dioxide, methane, nitrous oxide) in the Australasian region
- Feedbacks between terrestrial, ocean and the atmospheric systems in the Australasian region, and their implications for regional climate change and variability; and
- Development and application of multiple-constraint approaches to determine regional sources and sinks of greenhouse gases and to improve coupled ocean-atmosphere-terrestrial climate models.

CarboEurope
[http://www.bgc-jena.mpg.de/public/carboeur/]
CarboEurope is a cluster of projects to understand and quantify the carbon balance of Europe, funded by European Commission DG Research - Vth Framework Programme. The objectives of the CarboEurope cluster are to advance the understanding of carbon fixation mechanisms and to quantify the magnitude of the carbon sources/sinks for a range of European terrestrial ecosystems and how these may be constrained by climate variability, availability of nutrients, changing rates of nitrogen deposition and interaction with management regimes. Research focusing on European ecosystem is complemented by investigations of the sink strength of Amazon forests. Relevant specific topics are:

- to provide a multi-disciplinary, fully integrated Framework to verify across scales, from ecosystems to regional and continental areas, the space and temporal behaviour of carbon sources and sinks and to assess their socio-economic drivers and consequences;
- to make use of state-of-the-art technologies for carbon accounting and modelling; and
- to adopt a consistent carbon accounting strategy across scales

The US Carbon Cycle Science Programme (USGCRP)
[http://www.carboncyclescience.gov]
The U.S. Global Change Research Programme has established a Carbon Cycle Science Programme. The new Programme will provide critical unbiased scientific information on the fate of carbon in the environment and how cycling of carbon might change and be changed in the future. This includes providing the scientific foundation for management of carbon in the environment. Research will be coordinated and integrated to identify and quantify regional- to global-scale sources and sinks for carbon dioxide and other greenhouse gases and to understand how these sources and sinks will function in the future, providing essential information for future predictions of the state of the Earth system.

A.3. A Selection of other International Initiatives

In addition to the national and regional programmes, several additional international initiatives and programmes are attempting to address a suite of issues related to the global carbon cycle, and climate change and variability:

Carbon Variability Studies by Ships of Opportunity (CAVASSOO)
[http://envsol.env.uea.ac.uk/temp/tracer/e072/]
The aim of CAVASSOO is to provide reliable estimates of the uptake of CO_2 by the North Atlantic, and how this varies from season to season and year to year. These will in turn assist in constraining estimates of European and North American terrestrial (vegetation) sinks, using atmospheric inverse modelling techniques.

Global Quality Control for Long-Lived Trace Gas Measurements (GLOBALHUBS)
The aim of GLOBALHUBS is to improve inter-laboratory comparability for measurement of long-lived atmospheric trace gas species, resulting in improved derivation of source/sink fluxes from spatial and temporal atmospheric composition changes.

Integrated Global Observing Strategy - Partners (IGOS-P)
[http://ioc.unesco.org/igospartners/igoshome.htm]
The IGOS-P is a partnership that develops common, integrated strategies to be implemented and coordinated by the Global Observing Systems:

- Global Ocean Observing System (GOOS) [http://ioc.unesco.org/goos/]

- Global Terrestrial Observing System (GTOS) [http://www.fao.org/gtos/index.html]
- Global Climate Observing System (GCOS) [http://www.wmo.ch/web/gcos/gcoshome.html]

The Intergovernmental Panel on Climate Change (IPCC)
[http://www.ipcc.ch/]
Recognizing the problem of potential global climate change, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The role of the IPCC is to assess the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change. It does not carry out research nor does it monitor climate related data or other relevant parameters. It bases its assessment mainly on peer reviewed and published scientific/technical literature.

The Millennium Ecosystem Assessment (MA)
[http://www.millenniumassessment.org/en/index.htm]
The Millennium Ecosystem Assessment is an international assessment activity charged with examining the processes supporting life on Earth, including the world's grasslands, forests, rivers and lakes, farmlands and oceans, with respect to the capacity of an ecosystem to provide goods and services important for human development. The goal of the four-year Programme is to improve the management of the world's natural and managed ecosystems by helping to meet the needs of decision-makers (in governments and the private sector) and the public for peer-reviewed, policy-relevant scientific information on the condition of ecosystems, consequences of ecosystem change, and options for response. In addition, the MA will build human and institutional capacities to provide information.

Northern Eurasian Earth Science Partnership Initiative (NEESPI)
[http://www.neespi.gsfc.nasa.gov]
The goal of NEESPI is to establish a large-scale, interdisciplinary programme of funded research aimed at developing a better understanding of the interactions between the ecosystem, atmosphere, and human dynamics in northern Eurasia in support of international science programmes. NEESPI partners include NASA and other U.S. agencies, the Russian Academy of Sciences and Russian and international institutions, GOFC, IGBP and other international programmes. NEESPI's approach to carbon research combines regional in-situ data, remote sensing observations and measurements, and models, including terrestrial carbon, socio-economic, landscape, and integrated models. Current carbon-related projects include:

- Modeling Carbon Dynamics and Their Economic Implications in Two Forested Regions: Pacific Northwestern USA and Northwestern Russia
- Modeling Siberian Forest Land-Cover Change and Carbon under Changing Economic Paradigms
- Determining the Contribution of Emissions from Boreal Forest Fires to Inter-annual Variations in Atmospheric CO_2 at High Northern Latitudes
- Determining the Contribution of Emissions from Boreal Forest Fires to Inter-annual Variations in Atmospheric CO_2 at High Northern Latitudes
- Modeling and Monitoring Effects of Area Burned and Fire Severity on Carbon Cycling, Emissions, and Forest Health and Sustainability in Central Siberia.
- Combined Satellite Mapping of Siberian Landscapes
- Changes in Terrestrial Carbon Storage in Russia as a Result of Recent Disturbances and Land-Use Change

The Scientific Committee on Oceanic Research (SCOR)
(http://www.jhu.edu/~scor)
In addition to co-sponsoring JGOFS, SOLAS, and the Ocean Biogeochemistry and Ecosystems project with IGBP and the Ocean Carbon Dioxide Advisory Panel with IOC, the Scientific Committee on Oceanic Research (SCOR) has several working groups on related carbon cycle research:

- Carbon Dioxide in the Atlantic Ocean (CARINA) (http://www.ioc.unesco.org/iocweb/co2panel/). CARINA is a project linked to the IOC/SCOR panel that aims to inventory and publish CO_2 data in the North Atlantic Ocean.
- Biogeochemistry of iron in seawater
- The role of marine phytoplankton in global climate regulation
- New methodologies on:
  - Surveying plankton
  - Estimating downward carbon flux from the surface ocean

The Scientific Committee on Oceanic Research- International Oceanographic Commission CO_2 Panel (SCOR-IOC)
[http://ioc.unesco.org/iocweb/co2panel/]
The Scientific Committee on Oceanic Research and the International Oceanographic Commission of UNESCO established the Advisory Panel on Ocean CO_2 in 2000 to catalyse, coordinate and communicate ocean carbon activities of common interest to the international community. Programme areas currently include:

- Coordination of observations
- Advocacy for standards and reference materials
- Information exchange on measurement technology
- Development and providing briefs on ocean CO_2 sequestration research

Appendix B: Integrated Global Carbon Observation strategy (IGCO)

An Ideal Global Operational Carbon Observing System
(Year~2020)
Executive Summary extracted from the Integrated Global Carbon Observations (IGCO) of the Integrated Global Observation Strategy Partnership (IGCO-P)

An ideal (but realistic) global operational carbon observing system should:

- Seek integrated approaches that efficiently combine both remote and in situ observations;
- Integrate observational strategies in the terrestrial, oceanic, and atmospheric compartments, and appropriate palaeo and human dimensions components/sectors of the carbon cycle;
- Be compatible and integrated with the international framework for carbon research (in particular the modelling and data assimilation components) being developed by the three international global environmental change programmes (IGBP, IHDP, WCRP) and responsive to the policy needs of the UNFCCC, with the IPCC providing the essential linkage between scientific research and assessment and policy applications;
- Be able to produce global carbon data products from operational satellites as good as those from research satellites;
- Be robust enough to provide long-term (years to decades) accurate, calibrated and continuous measurements of carbon data on both regional and global scale;
- Forge international collaboration so that harmonization of data, measurement and reporting procedure of the various national programmes are well coordinated and the efforts of our distributed community are comparable and cumulative;
- Build an end-to-end data system that provide open access to the scientific community and the public, and rapidly evolves to exploit innovative technological developments.

The global carbon cycle is a single entity, with multi-faceted aspects cutting across the three major domains: the ocean, the land surface and the atmosphere. The most successful advances made in the field involve combining dataset and models for the different reservoirs, because results from one domain often place valuable constraints on the workings of the other two.

The proposed globally integrated carbon observing system in all three reservoirs involves the following three elements:

- in-situ observations
- satellite remote sensing
- data integration via inverse modeling and data assimilation.

For in-situ operational observing system one needs to :

- Convert the Flask network to Continuous in situ CO_2 analysis with an accuracy of 0.2 ppmv, over the globe with a spatial resolution of 5°× 5° grid over land and 10°×10° grid over the Oceans, particularly in Southern Hemisphere;
- Expand Flux Net network with new towers located in complex and highly disturbed landscapes; and across gradients of succession, stand age, and land-use intensity. Inter-calibration of the instrumentation at the towers is of prime importance.
- Global soil carbon content should be updated every 5 years on a 1°×1° grid.
- On ocean surface basin-scale, an operational system of extensive in situ sampling of surface pCO_2 levels should be instituted. Atmospheric data collected along the Voluntary Observation Ship (VOS) lines do not attain the accuracy and precision levels of the order of 0.1 μatm required to better resolve global budgets based on atmospheric observations.
- Determine the vertical distribution of dissolved iron and how iron is actually cycled in the ocean is currently a major hurdle for replicating the observed distributions of phytoplankton and macronutrients in numerical models. At present, full-depth profiles of DIC and alkalinity at required accuracies are attainable

only through shipboard sampling and the use of certified reference materials (CRMs). The long-term continuity of the ocean DIC CRM programme is therefore critical.

- Build a global network of quasi-autonomous ecological, bio-optical, and biogeochemical observations; such a network would serve multiple purposes including as the basis for calibrating, validating, and adding value to remotely sensed ocean color data. There must be continued support for existing time-series stations while transitioning into a coordinated time-series network.

For remote sensing satellites, which provide quasi-global and repetitious coverage for years to decades, the following operational system is envisaged:

- ·Remote sensing measurements of ocean colour, i.e., the detection of phytoplankton pigments, provide the only global-scale focus on the biology and productivity of the ocean's surface layer. Ultimately, what is required is a global network of ecological, bio-optical, and biogeochemical observations, as the basis for calibrating, validating, and adding value to remotely sensed ocean colour data. Projects under consideration would provide an uninterrupted data-stream continuity for a 15 year period. Products will be the developed through the Ocean Biology Project initiated by CEOS and presently co-ordinated by the International Ocean Colour Co-ordinating Group (IOCCG).
- Transfer velocity is being related to satellite derived measurements of surface roughness (scatterometer and altimeter). Preliminary direct gas exchange measurements by eddy correlation confirms the general approach, but significantly more process level work needed particularly for high wind speed, bubble dominated environments. Sctterometers and Altimeters will surely enhance the operational observing system.
- Operational satellites exist and probably will exist to derive Land cover type and land use change information However algorithms are needed to be developed to map precisely the global distribution and temporal variability of:
    - wetland cover,
    - forest-no forest information,
    - global land use information,
    - biomass information,
    - seasonal growth cycle of vegetation, and
    - fires.
- Space-borne observation of the atmospheric CO_2 do not exist yet, and yet they would greatly complement the existing in-situ networks, thus strongly enhancing our ability to resolve regional sources and sinks and to invert model parameters. Two spectral domains are usable. Firstly, the Long Wave Infra Red signal, secondly, the solar Infra Red signal In both cases, new algorithm development would be needed since CO_2 content retrieval is sensitive to cloud contamination, errors in temperature and humidity profiles. In parallel to algorithm development and new space borne sensors, a surface network of remote sensing CO_2 stations should be installed, using for instance FTIR spectrometers upward looking. Validation of the concept also involves co-located aircraft or balloon soundings.
- Lidars on operational satellites will provide a complete profile of atmospheric CO_2 and other carbon molecules;
- All these efforts should be combined by:
    - an end-to-end data analysis system
    - free access to scientific community across the national boundaries, and
    - the data thus acquired should be used by global modeling community precisely diagnosing the problem of carbon sources and sinks and the eventual build-up of atmospheric CO_2 in the next fifty years.

Appendix C: Providers and users of carbon observations.

C.1. Examples of existing providers of carbon observations

Type (in situ, satellite)	**Sponsor***	**Data/products provided**	**Coverage in space, time**	**Reference**
1a. In situ terrestrial				
FLUXNET	Countries/IGBP/WCRP	Ecosystem data and fluxes; micromet. data	All continents (except Antarctica)	http://www-eosdis.ornl.gov/FLUXNET/
ILTER	Countries/ ???ICSU	Ecosystem data	21 countries	http://www.ilternet.edu/
GT-Net	Countries/ GTOS	Ecosystem data	84 countries, numerous networks	http://www.fao.org/gtos/gt-net.html
SOMNET	Countries/ IGBP	Soil data	~70 sites, 6 continents	http://www.rothamsted.bbsrc.ac.uk/aen/somnet/index.htm
1b. In situ oceanic				
GOOS	Countries/ IOC	See Appendix B	Global or regional	http://ioc.unesco.org/goos/
1c. In situ atmospheric				
GLOBALVIEW-CO2	Countries/ WMO	Trace gas concentrations	Global; ~weekly	http://www.cmdl.noaa.gov/ccgg/globalview/index.html
2. Satellite				
Fine resolution	NASA/CEOS	Images, land-cover	Global	http://ivanova.gsfc.nasa.gov/daac/
	CNES/CEOS	Images, land-cover	Global	http://www.spot.com/
	NASDA/CEOS	Images	Global	http://www.eoc.nasda.go.jp

	CSA/CEOS	Images	Global	http://www.spot.com/
Medium to coarse resolution	NASA/CEOS	Images, land-cover and change; LAI; fires; CH4, solar radiation; NPP	Global	http://ivanova.gsfc.nasa.gov/daac/ http://www.gewex.com/srb.html
	NOAA/CEOS	Solar radiation, images	Global	http://www.osdpd.noaa.gov/
	NASDA/CNES/CEOS	OCT, POLDER	Global	http://www.eoc.nasda.go.jp
	ESA/JRC (WFW)/EC	Fires	Global	http://www.gvm.sai.jrc.it/
	CNES/SNSB/OSTC/SAI/EC	Images; land-cover and change; fires; ecosystem productivity;	Global	http://www.vgt.vito.be/

* Both the direct sponsor (usually a national agency) and the international umbrella organisation are listed

C.2.. Examples of Oceanic Observing System Programmes

GOOS Carbon	IOC – WMO- UNEP	Observation system information and coordination	Global, regional, national	http://ioc.unesco.org/iocweb/co2panel
CLIVAR	WCRP	Repeat hydrographic surveys of carbon, tracers, and related variables	Global, regional, 5-10 year repeats	http://www.sprint.clivar.org/ http://www.clivar.org/organization/atlantic/IMPL/index.htm
Global Survey of CO2 in the Ocean	IGBP – JGOFS; U.S. DOE; in coordination with WOCE	Full profile measurements of the various carbon dioxide parameters on both zonal and meridional transects throughout the oceans of the world	Global, regional, 5-10 year repeats.	http://www.oasdpo.bnl.gov/mosaic/DOECO2/
Carbon SOOP	Coordinated by: SCOR-IOC CO2 Panel; WMO – IOC JCOMM	Underway measurements of pCO2, ocean colour, and related variables	Regional, seasonal track repeats	http://www.ifremer.fr/ird/soopip/instr.html
Time Series Observatory Pilot Project	OOPC – CLIVAR COOP - POGO	Moored buoys measuring carbon and related variables	Fixed-point (Eulerian) moorings or revisited stations in strategic locations; high-frequency to interannual.	http://www.wmo.ch/web/gcos/oopc.htm
Satellite remote sensing of Ocean Colour	Coordination by: IOCCG	Basin-scale surface biomass productivity; phytoplankton natural fluorescence;	Global spatial coverage, 4-8 km resolution; Coastal regions, 0.5 – 2 km resolution; Daily to weekly.	http://www.ioccg.org/
Carbon Dioxide Information Analysis Center	U.S. DOE	Data repository for ocean carbon data and information from global, regional, and national research programmes.	Global, regional, and national.	http://cdiac.ornl.gov/oceans/home.html

C.3. Examples of Carbon Information Users

Programme	Sponsor	Data used/needed	Coverage in space, time	More information
Global/ **International**				
IPCC	UN FCCC	Ecosystem productivity	Global; past, present	http://www.ipcc.ch/
IGBP (several core projects)	Countries or regions	All variables (section 4.2, 4.3)	Global; past, present	http://www.igbp.kva.se/
Forest resources assessment	FAO	Land-cover and changes, biomass, fires, productivity	Global; every ~5 years	
Global Environmental Outlook	UNEP	All variables (section 4.2)	Global; present; every 2 years	http://www1.unep.org/unep/eia/geo/reports.htm
NGOs (WRI, WCMC, others)	Various public and private	Land-cover and changes, biomass, fires, productivity	Global, regional; present	http://www.wri.org/ http://www.wcmc.org.uk/
Convention on Biological Diversity	Countries	Land-cover and changes, biomass, fires, productivity	National to global; past, present	http://www.biodiv.org/
Convention to Combat Desertification	Countries	All variables (section 4.2)	National; present	http://www.unccd.de/
National				
Carbon accounting	Countries, e.g.: Australia US Norway	All variables (section 4.2, 4.3)	Present; national; project - based	http://www.greenhouse.gov.au/ncas/ http://www.eia.doe.gov/oiaf/1605/ggrpt/

Resource planning (vegetation, forest)	Countries, e.g.: Australia Africa Canada	All variables (section 4.2, 4.3)	Present; national or sub-national	http://www.nlwra.gov.au/ http://metart.fao.org/default.htm
Resource management: fire – related	Countries, e.g. Africa, Indonesia, various others	Fires; land-cover and change; biomass	Present; national	http://www.iffm.or.id/ http://www.ruf.uni-freiburg.de/fireglobe/
Resource management: crops, water	Countries (Africa,..)	Land-cover and change, biomass, productivity	Present; national	

C.4. Status of Satellite Missions for Global Carbon Cycle Observations *

AGENCY	**MISSION**	**Carbon cycle sensors**	**CATEGORY ****
CAST	***		
CNES	SPOT-3,- 4	HRV	1
CNES, EU	SPOT-4, SPOT –5	HRG, VEGETATION	
CSA	Radarsat -1, -2	SAR	1
DARA	***		
ESA	ENVISAT-1	ASAR, MERIS, AATSR, SCIAMACHY	1
ESA	ERS-2	ATSR, AMI	1
ESA, CNES	SMOS ***	MIRAS	1
EUMETSAT	METOP –1, -2, - 3	AVHRR /3, IASI, ASCAT	1
EUMETSAT	MSG	SEVIRI	1
INPE	MECB SSR-1, -2	OBA	Planned
ISRO	IRS -1C, -1D	LISS-III, PAN, WIFS	
ISRO	IRS- P2, -P5, -P6	LISS-II (-IV), WiFS, HR-PAN, AWiFS	
ISRO	IRS- P3, -P4	MOS, WiFS, MSMR	
NASA	EOS Aqua	CERES, MODIS, AMSR-E AIRS	1
NASA	EOS Aura	HIRLDS, TES	1
NASA	EOS Terra	ASTER, CERES, MISR, MODIS, MOPITT	1
NASA	ESSP/VCL	MBLA	
NASA	ICESat	GLAS	1
NASA	QuikScat	SeaWinds	1
ORBIMAGE (NASA data buy)	SeaStar***	SeaWiFS	1
NASA	NMP/EO-1	ALI, Hyperion	4
NASA, NASDA	TRMM	CERES, VIRS	

NASDA	ALOS	ALOS/PRISM, AVNIR-2, PALSAR, PRISM	1
NASDA, CNES	GCOM – B1, - B2 ***	GLI, POLDER, IMG	2
NASDA, CNES, NASA	ADEOS-II	GLI, POLDER-2	1
NASDA, NASA	GCOM – A1, - A2 ***	SAGE-III, ILAS-II??	2
NOAA	Landsat	ETM	1
NOAA	NPOESS	VIIRS, CrIS/ATMS, CMIS, OMPS, CERES	
NOAA	TIROS-N	AVHRR, TOVS	
NOAA	GOES I,J,K,L,;M	??	1
NOAA	GOES - N,O,P,Q		1
NOAA	GOES SEI		
NOAA, NASA	NPOESS Preparatory Project (NPP)***	VIIRS, CrIS/ATMS	3

*Note: the table includes only missions directly supporting carbon observations and products; other missions may provide supporting information

** Category:

1 = confirmation and timing of missions already planned ;
2 = proposed missions using known technology ;
3 = transitioning of research instruments/missions into operational;
4 = development of new technologies, products or missions ;
5 = data and information systems

*** Not in the WMO/CEOS database

Figures Legends

Figure 1: Changes in atmospheric CO_2, isotopically inferred temperature and CH_4+ from a 420,000 year record from the Vostok ice core. For a detailed report of these measurements see Petit et al. (1999). Image compliments of IGBP/PAGES

Figure 2: The Vostok ice-core record for atmospheric concentration from Petit et al. (1999) and the ”business as usual” prediction used in the IPCC Third Assessment (Prentice et al. 2001). The current concentration of atmospheric CO_2 is also indicated.

Figure 3: Institutions and their effects on the carbon cycle (adapted from Young et al. 1999).

Figure 4: Measuring the carbon metabolism of terrestrial ecosystems: Techniques and results (Canadell et al. 2000).

Figure 5: The global carbon cycle from three perspectives over time. **(a)** During glacial–interglacial periods and before significant human activities, the global carbon cycle was a linked system encompassing stocks in the land, oceans and atmosphere only. The system was (and still is) controlled or driven through climate variability as well as its own internal dynamics. For instance, the ocean carbon system was tightly coupled to air-sea gas exchange as well as physical and biological “pumps” that transport carbon. Interactions of the land surface and atmosphere were driven by land and ecosystem physiology as well as disturbance. **(b)** Starting about 200 years ago, industrialization and accelerating land-use change complicated the global carbon cycle by adding a new stock—fossil carbon. However, humans did not initially perceive that their welfare might be endangered. Regardless of how society responds to increased fossil fuel inputs to the atmosphere, or the consequences of intensification of current land-use practices, the global carbon cycle has been seriously impacted. **(c)** Over recent decades, humans have begun to realize that changes in climate variability and the Earth System may significantly affect their welfare as well as the functionality of the global carbon cycle. The development and implementation of institutions and regimes to manage the global carbon cycle coherently provides a new set of feedbacks in the contemporary era.

Figure 6: Spatial observations critical to determining patterns and variability in the stores and fluxes making up the carbon cycle: **(a)** global map of terrestrial NPP from the IGBP Potsdam NPP Model Intercomparison, g C m^{-2} (Cramer et al. 1999); **(b)** global map of anthropogenic CO_2 emissions (Brenkert 1998 [http://cdiac.esd.ornl.gov/], map prepared by R. J. Olson, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA); **(c)** Mean annual net-air sea flux for CO_2 (mole CO_2 m^2 yr^1) for 1995 (Takashi et al. 2002); and (d) Anthropogenic CO_2 column inventory (mol m-2) (Sabine et al. 2003).

Figure 7: The CO_2 global growth rate (expressed here as 10^{15} g/yr of carbon accumulating in the atmosphere since the start of direct CO_2 monitoring) is compared to fossil fuel emissions over 4 decades. On average, 55% of the

anthropogenic carbon is retained in the atmosphere, but with large interannual variability related to the Southern Oscillation Index (SOI). (The very low growth following the Pinatubo volcanic explosion in 1991 is an exception). All CO_2 data are deseasonalised and smoothed over 650 days. The records collected by SIO/NOAA from Mauna Loa, by NOAA from 50 global sites, or by CSIRO from Cape Grim all closely track the global growth rates (Source: R J Francey, presented at the EC-IGBP-GTOS Terrestrial Carbon Meeting, 22-26 May 2000, Costa da Caparica, Portugal)

Figure 8: Sources and sinks induced by the production and metabolization of food products (gC m^{-2} yr^{-1}) (Ciais et al. 2001)

Figure 9. Global Net Primary Productivity (NPP) for the months of June and December of 2002 based on space-based measurements taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) with algorithems developed by the NASA Earth Observing team that use a suite of other satellite and surface-based measurements (Source: NASA Earth Observatory).

Figure 10: Global distribution of atmospheric CO_2 concentration flask sites. Note the paucity of stations in the Southern Hemisphere, as well as Eurasia, Africa and South America (GLOBALVIEW- CO_2 2002) [http://www.cmdl.noaa.gov/ccgg/globalview/index.html]

Figure 11: Spatial distribution of FluxNet sites and their representative sponsor countries. There is a strong movement to standardize ecophysiological and ecosystem measurements and observations among the various networks. FluxNet is a key example of how international coordination can facilitate communication and information across national boundaries and scientific disciplines. The aim of the Global Carbon Project is to encourage and foster the successful development, coordination and expansion of successful networks such as FluxNet [http://www-eosdis.ornl.gov/FLUXNET/].

Figure 12: The oceanic "Biological Carbon Pump" is a collective expression for planktonic, biological processes and feedback pathways that play a role in the carbon transfer from the photic zone (zone of light penetration) to the deep ocean. This complex ecosystem begins with phytoplankton using sunlight and dissolved inorganic nutrients to photosynthetically convert atmospheric CO_2 into biogenic matter, which forms the base of the marine food web. The autotrophic and heterotrophic organisms excrete particles and dissolved matter as they grow and die. The particles sink through the water column carrying carbon to the deep ocean. The biological pump is thus one of the pathways that regulate atmospheric CO_2 concentrations, the other being the physical "Solubility Pump". Generally, the food web is efficient and most of the produced particles and dissolved organic matter is recycled through the microbial loop to CO_2 and released back to the atmosphere (Courtesy of International JGOFS Project Office).

Figure 13: Multiple mechanisms responsible for the current terrestrial carbon sink and their expected future dynamics with increasing global change forcing (Canadell et al. 2003).

Figure 14: Decarbonising the energy system. Global environmental change driven by mainly socio-economic, demographic, institutional and technological changes causes public concern about fulfilling future needs. Meeting current and future energy demands while minimizing global environmental impacts is a challenge that requires major transformation of the energy system, including production, consumption and the incentive structures that shape the interaction between the two. Possible options for transformation include shift to renewable energies, introduction of the CO_2 emission trading and changes in lifestyle and values. (Adapted from Vellinga and Wieczorek 2000)

Figure 15: Predicted changes in global land carbon (vegetation plus soils) from two coupled climate-carbon cycle GCMs. Positive represents an increase in land storage. The Hadley Centre results are shown by the continuous lines and the IPSL model results by the dashed lines. Blue lines represent runs without climate change, and the red lines are from the fully coupled runs including climate-carbon cycle feedback (Cox et al. 2000).

Figure 16: Projected atmospheric CO_2 **(a)** emissions and **(b)** concentrations from several General Circulation Model scenarios during the 21st Century (IPCC 2000a).

Figure 17: Effects of economic, environmental and social-institutional factors on the mitigation potential of a carbon management strategy. The technical capacity (upper horizontal line, independent of cost) is reduced a combination of economic factors (markets, trade, economic structures, urbanization, industrialization); environmental factors (need for land, water and other resources, waste disposal, property rights); and institutional and social factors (class structure, politics and formal policies, informal rules, lifestyles, attitudes, behaviour). The end result is a sustainably achievable mitigation potential for the carbon management strategy being considered. This depends on the cost of carbon, which is a measure of the weight ascribed to carbon mitigation relative to other goals. The uptake proportion for the strategy is the ratio of the sustainably achievable potential to the technical potential. The figure also shows a baseline potential, representing the extent to which the carbon management strategy is deployed in a "business as usual" scenario (Raupach et al. 2003).

Figure 18: GCP Implementation Plan.

Figure 19: GCP planned activities, workshops, capacity building, and products for the next 4 years as part of the 10 year implementation plan.