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Terrestrial Carbon Observation Initiative: an integrated satellite – in situ strategy

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ABSTRACT

The terrestrial component of the global carbon cycle has become the focus of intense attention by the scientific community, international environmental organisations, national governments, and increasingly more also by the private sector. A common factor among this multitude of interests is the need for a 'system' capable of quantifying the net exchanges of carbon between the atmosphere and the terrestrial ecosystems. In this paper, we describe a recent initiative by the Integrated Global Observing Strategy Partnership (IGOS-P) aimed at establishing a systematic, long-term observing capability for estimating the spatial and temporal distribution of CO_2 fluxes between the terrestrial ecosystems and the atmosphere.

Introduction

An accurate knowledge of the global carbon cycle has become policy imperative, both globally and for individual countries. The carbon cycle is at the forefront of policy debates and scientific studies as a result of the recognition that increasing atmospheric CO_2 concentration due to human activity is an important causative factor for potential climate variability and change. The Kyoto Protocol negotiated in 1997 recognises the role of terrestrial systems as carbon sinks and sources, and it provides a basis for developing future emission trading arrangements that involve forests and potentially other ecosystems. Understanding of the pathways through which the anthropogenic CO_2 leaves the atmosphere and enters into ecosystems, thus offsetting a portion of the human-caused emissions is incomplete at best. Regardless of whether the Kyoto protocol is eventually ratified, a more accurate knowledge of carbon sequestration is critical to implementing effective climate change – related policies. Of equal importance is the ability to predict the evolution of the atmospheric CO_2 concentration in order to optimise mitigation strategies. In addition to the environmental policy dimension, the distribution and quantification of terrestrial carbon (i.e., carbon in the vegetation or soils) has important economic and resource management dimensions. The yield of agricultural, forest, and rangeland resources is directly related to the amount of carbon tied up in the aboveground biomass.

The environmental, economic and societal importance of the anthropogenically perturbed carbon cycle has led to numerous activities at national and international levels. It has become widely appreciated that appropriate responses to this issue require better understanding of the current and future evolution of the atmospheric, land and ocean carbon pools, supported by accurate observations of the magnitudes and trends of the fluxes. In 1997, the Integrated Global Observing Strategy Partnership (IGOS-P, http://www.igospartners.org/) was formed to develop and implement comprehensive approaches to systematic observations of the earth system. The Partners include the space agencies represented by the Committee on Earth Observation Satellites; UN environmental organisations; and global observing systems for climate (Global Climate Observing System, GCOS), oceans (Global Ocean Observing System, GOOS), and the terrestrial environment (Global Terrestrial Observing System, GTOS). IGOS-P developed an implementation approach based on observation 'themes', as linked sets of observations that are necessary to characterise a significant component of the global environment.

At the November, 1999 meeting IGOS-P decided to work towards a terrestrial carbon observation theme and requested that GTOS with FAO support lead the theme definition. IGOS-P also decided that a proposal for an overarching global carbon theme should be prepared. In this paper, we describe the development of the Terrestrial Carbon Observation theme which deals with the terrestrial and atmospheric components of the global carbon cycle. The definition of an ocean carbon theme has been undertaken through a parallel effort under the leadership of GOOS (Doney and Hood, 2001), and an Integrated Global Carbon Observation theme led by the International Geosphere – Biosphere Programme (IGBP) is in the initial stages of development (Steffen, 2000).

The Vision

The vision for a carbon cycle observing system is to contribute to the integrated understanding and human management of the carbon cycle through systematic, long-term monitoring of the exchanges of greenhouse gases between the land, atmosphere and oceans, and the associated changes in carbon stocks. To achieve this vision, an observing system is required which synthesises information from several types of measurements: concentration of atmospheric CO_2 and other gases, surface flux observations and other in situ measurements, and satellite remotely sensed data. The combined monitoring system will yield estimates of CO_2 sources and sinks at multiple spatial and temporal scales from global to those relevant to land use policy and resource management. These estimates should be provided with greatly reduced uncertainty relative to current practice, by designed expansions of current measurement networks and by systematic cross-checking of independent approaches.

The policy community needs information on spatial and temporal patterns of terrestrial CO_2 flux at high resolution and over large areas. These requirements imply the use of ecosystem process models linked to spatial measurements that are available everywhere, such as from satellites. Satellite data can also provide up-to-date information frequently, in relation to the rate of change of the variables of interest. In this 'bottom-up' strategy, local land processes are scaled-up in space and time using satellite imagery and other spatial data. The primary limitation of this approach is the difficulty of conclusively establishing the accuracy and reliability of the scaled-up estimates. In addition, the success of the approach depends on the availability of reliable models that represent all the important processes affecting CO_2 exchange with the atmosphere, including the impact of various land use measures. Such models are not yet available for all processes, although inventory-based methods and conversion tables currently provide an acceptable approach (IPCC, 1996). - An alternative and complementary method is to analyse the carbon budget of the atmosphere from a mass balance point of view ('top down'). Such an analysis is predicated on the availability of atmospheric concentration data and other inputs, and it can be carried out in several spatial and temporal domains. Both approaches have been used in various studies. Used synergistically, the ‘top down’ and ‘bottom up’ approaches take advantage of their strengths to compensate for their respective weaknesses (Cihlar, Denning and Gosz, 2000). The observing system thus needs to enable multiple comparisons between predictions made by process models and larger - scale observations, making it possible to disprove results of models that diagnose and predict large - scale fluxes. This ‘falsifiability’ is a necessary condition for a confident estimation of current and future atmospheric CO_2 levels. At the global scale, changes in atmospheric CO_2 are the benchmark against which all process model outputs must be tested. This constraint can improve quantitative process model estimates only if applied regionally. An integrated observing strategy therefore includes the application of multiple constraints at various spatial scales, taking advantage of process-based research, the ability of satellite data to map heterogeneous properties of the surface features, and the averaging properties of the atmosphere to quantify CO_2 fluxes over large areas.

Observation Requirements And Present Status

Observation requirements are based on needs from several perspectives: model development and validation, model application, and output product validation. These requirements were analysed in detail at a 2000 TCO workshop in Ottawa, Canada (http://www.fao.org/gtos/gtospub/pub23.htm). Table 1 provides a specification of the observation requirements, both point and gridded. It is evident that to meet these requirements, a combination of satellite and in situ observation methods will be necessary. However, in neither area are the existing capabilities satisfactory.

In the past, the interests in the terrestrial carbon cycle have been primarily economic in nature and mostly related to ecosystem productivity. The scientific interest in the carbon cycle has intensified in the recent decades, driven by the need for improved understanding of the role of carbon in the total earth system. Thus, the existing observing capabilities are primarily a combination of national resource-based inventories (mostly employing in situ observations) and scientific programs with observation components at various levels, from national to global (a combination of in situ and satellite-based methods). Traditional national inventories have evolved generally independently, based on perceived national resource development needs. The strong interest by countries in the broader aspects of the carbon cycle is recent, and has been stimulated by the concerns about the role of trace gases in climate change. Questions related to components of the carbon budget (such as land productivity) have also been important to international reporting organisations such as FAO, UNEP and others. Traditionally, these agencies have relied on summarised data obtained within countries. In many cases, additional sub-national data were obtained directly to meet specific needs, e.g. by FAO for forest resources assessment. The global observing systems begun during the 1990s require carbon cycle information to meet the needs of their clients. They all have, or are in the process of establishing initial observing systems based on current capabilities.

The development of observation methodologies appropriate for the quantification of the terrestrial and atmospheric components of the global carbon cycle has been led by the scientific community. It relied on both latest observation techniques (satellite and in situ) and simulation models. Atmospheric, ecosystem, and coupled surface-atmosphere interaction models are the key analysis/synthesis tools. Based on this research and on experience from the existing inventory systems, it is possible to define an observing system that would provide spatially detailed and consistent information for the world's terrestrial ecosystems.

Challenges In Carbon Cycle Observation

Many of the elements needed for systematic terrestrial carbon observation are now in place or under development. They include observing atmospheric and terrestrial networks, global or regional; satellite programs and associated product generation initiatives; national inventories and observing networks; and active research programs at various levels (refer to Appendices in Cihlar et al., 2001). The challenges are to ensure that important existing observations continue and key new observations are initiated; to identify activities and agencies willing to contribute to establishing global carbon observations; to build in appropriate overlaps and leverage among the disparate data sets, thus filling important data gaps; to design and implement linkages among components, activities and contributions; and to link observation and research programs so that the ongoing improvements in observations and products are made in an optimum fashion. The main observation challenges are briefly outlines below, separately for satellite and in situ data.

Satellite:

Numerous satellite observation requirements exist. Many of these have been acquired in the past, and their continuity is a primary challenge for an ongoing, systematic terrestrial carbon observation. In summary form, these are (more detail is provided by Cihlar et al. (2001)):

a) Land cover and land use and change, seasonal growth cycle, fires: Continuity of calibrated, fine resolution satellite optical measurements from both fixed-view and pointable sensors, as well as of SAR data; they should be accompanied by a consensus strategy for global satellite data acquisition at fine resolution.

b) Biomass: Ongoing availability of, and improvements in, canopy structure measurements from satellite sensors, beyond the planned VCL/ESSP mission.

c) Product generation: Institutional arrangements for product generation and quality control, including incorporation of in situ observations as appropriate, inter-calibration between missions, and reprocessing of archived data. These should also include daily to monthly solar radiation products.

In situ:

d) Ecological and soil observations: Increased density of in situ observations and more effective access to and use of data available within countries, in combination with satellite-derived products.

e) Surface-atmosphere fluxes:

- Maintaining the existing flux measurement programs for at least 10 years at a site, expanding the current network in underrepresented geographic regions and ecosystem conditions, and improving international coordination of data handling and use. In addition, continuously operating selected long-term stations to serve as anchor sites for understanding climate variability.
- Ensuring that the expanded in situ networks provide data to improve the quality of satellite-derived products and the performance of biogeochemical models.

f) Atmospheric concentration measurements:

- Ensuring the long-term continuity and stability of the global air flask sampling programs, including support for improved accuracy and inter-laboratory calibration.
- Adding sites to the existing air flask sampling network to improve results of atmospheric inversions for the terrestrial ecosystems.
- Ensuring increases in the resolution and coverage of fossil fuel emission data provided by national agencies.
- Commitment to ensure the long-term continuity and stability of the atmospheric sampling program.
- Ensure timely intercalibration of laboratories to the primary WMO standards with a goal of reducing interlaboratory differences in measured CO_2 concentrations to ≤ 0.1 ppm
- The issue is adding sites for flask sampling, based on network optimisation studies.
- The issue is continuation of vertical profile measurements begun as part of continental-scale carbon budget experiments.
- Nations need to make available location- and time- specific fossil fuel emission data.
- Archival and distribution of subgrid-scale vertical mass fluxes from operational weather analysis centres to facilitate atmospheric inverse modelling of sources and sinks.

g) Ecosystem productivity: Expanding the in situ observation networks and obtaining data to improve the quality of satellite-derived products and the performance of biogeochemical models.

In addition to the continuity challenges, many other issues are considered important to improving the carbon cycle observations. They include observations, observing approaches, and methodologies for making or using the resulting measurements. In addition to improving the continuing observations (a-g above), they are concerned with methane-related fluxes, soil moisture, canopy biochemistry, atmospheric composition and transport, and the development of new satellite and in situ sensors for measuring atmospheric CO_2 concentration. A more detailed discussion of these issues is provided by Cihlar et al. (2001).

Towards Implementation

There are four major organisational challenges in establishing a global observing capability for terrestrial carbon: continuity and improvements of satellite and in situ observations; transition from research to ongoing operations; supporting research and technology development; and coordination. Many of the needed products (or similar ones) are now generated or being planned over various geographic areas (refer to Appendices in Cihlar et al (2001)). With numerous current activities as potential building blocks for systematic global carbon observation, there is a need for a focused effort and a common vision to be pursued. The following goals have therefore been identified for TCO:

1. By 2005, demonstrate the capability to estimate annual net land-atmosphere fluxes at a sub-continental scale (10^7 km^2) with an accuracy of +/- 30% globally, and at a regional scale (10^6 km^2) over areas selected for specific campaigns with a similar or better accuracy;

2. By 2008, improve the performance to better spatial resolution (10^6 km^2) globally and an accuracy of +/- 20%;
3. In each case, produce flux emission estimate maps with the highest spatial resolution enabled by the available satellite-derived and other input products.

A successful implementation of a comprehensive terrestrial carbon observing system that assimilates various inputs and generates accurate and reliable information must necessarily be an evolving process. The most essential elements are:

- Atmospheric sampling for multiple trace gases from in situ and airborne platforms;
- Collection of spatial data and satellite imagery;
- Estimation of local to global daily carbon fluxes;
- Estimation of global to regional sources and sinks by atmospheric inverse modelling;
- In situ measurements of ecosystem carbon fluxes and pools to provide continuous long term data of carbon and energy exchanges in a range of biomes and quantify inter-annual variability of ecosystem responses to climate, to validate the derived products, and to improve the understanding and models of the processes of carbon exchange;
- Atmospheric observing campaigns to allow direct estimation of area-mean carbon fluxes and flux uncertainties over field sites for an evaluation of models and scaling algorithms;
- Data analysis, product generation and archiving centres;
- An effective data and information handling system;
- An international co-ordinating office.

An implementation and ongoing operation of such a system is a daunting challenge. The dilemma is that the system must be coherent to function in a consistent way globally, but the resources for implementation reside in individual countries and are subject to decisions at the national level. Thus, the approach adopted by IGOS-P is to achieve consensus on the observation requirements, the overall design, and the desired outputs. This global framework can then serve to support national and regional efforts that contribute to the global system. Ongoing reviews and revisions help ensure that the system evolves with changing requirements and observation capabilities. This approach has been successfully used by several UN organisations, including the FAO, UNEP and WMO.

The implementation task is somewhat simplified by the global observation capability of individual satellite missions. Earth observation satellites and the products generated from the data provide a common basis for integrating other data inputs, and also contribute substantially to the consistency of the resulting information. However, the in situ observing community which becomes very important at regional and national levels of analysis and policy making, needs considerable effort to develop capacity to make the required observations.

For the time being the earth observation community (satellite agencies) have significant responsibility in the development the carbon observing system. The main tasks involve not only the continuity and research challenges mentioned above, but also the development and use of quantitative, consistent and accurate information products. Such outputs will serve the needs of scientists, policy makers, and resource managers dealing with terrestrial carbon cycle issues, and will initiate a time series of observations and products that will serve this and the future generations.

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Table 1. Observation requirements for terrestrial carbon

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

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

Foliage lignin	2	2	2	1	needed to drive decomposition rates
Chlorophyll	2	2	2	1	needed to drive canopy photosynthesis in some models
Rubisco	2	2	2	1	needed to drive canopy photosynthesis in some models
FLUXES					
Carbon fluxes (above&near ground)	3	2	6	1	critical for model validation
Aboveground NPP	3	2	4	1	C storage flux
Belowground NPP	3	2	4	1	C storage flux
Litterfall N, P, C	2	2	2	1	C flux to soil & litterfall nutrients indicate nutrient availability
H, ET (above stand)	3	2	6	1	Important for C flux estimation
CH_4	3	2	6	1	Important for wetlands
VOC	3	2	6	1	can be significant in total carbon budget
DOC	3	2	2	1	C exchange can affect stocks and processes
Heterotrophic respiration rate	3	2	4	1	needed to validate NPP and NEP components

DOC = dissolved organic carbon, VOC = volatile organic carbon

a: 1 = external forcing variable; 2 = internal status variable; 3 = output variable

b: 1 = gridded with a resolution of 1 km or better; 2 = one or more sites for each land cover class; 3 = gridded with a resolution of 0.5-1 degree or better

c: 1, since industrialisation with desirable frequency; 2, periodical measurement once every 5-10 years; 3, one-time measurement; 4: multiple-year continuous measurement; 5, daily in calibrations years; 6, continuous

d: 1 = site measurement (including characterisation of its spatial heterogeneity as appropriate); 2 = modelling; 3 = remote sensing; 4 = existing survey or inventory