Opinion

Systematic long-term observations of the global carbon cycle

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Imagine a meeting convened to avert a global financial crisis where none of the finance ministers had access to reliable information on changes in the stock market, national gross domestic product or international trade flows. It is hardly conceivable. Yet the infinitely more existence-threatening planetary social and ecological crisis we refer to as 'global change' (comprising the linked issues of biogeochemical, climate, biotic and human system change) is in an analogous situation. Our information on the profound and accelerating changes currently depends to an unacceptable degree on serendipity, individual passion, redirected funding and the largely uncoordinated efforts of a few nations. The thesis of this paper is that navigation of the very narrow 'safe passages' that lie ahead requires a comprehensive and systematic approach to Earth observations, supported by a globally coordinated long-term funding mechanism. We developed the argument based on observations of the carbon cycle, because the issues there are compelling and easily demonstrated, but we believe the conclusions also to be true for many other types of observations relating to the state and management of the biosphere.

Luck and persistence

The observation that triggered much of our contemporary concern regarding global climate change is the record of atmospheric carbon dioxide concentration (CO_2) collected at Mauna Loa since 1957 by Charles Keeling. Only the dogged persistence of Keeling ensured the continuity of this data set over a period of 30 years [1]. The precise and continuous measurements unequivocally demonstrated the accelerating rise in the concentration of this major greenhouse gas. The subtleties of the seasonal cycle and its interannual variation revealed crucial details of the global carbon cycle – such as the sensitivity to climate. The addition of carbon isotope analyses and the simultaneous measurement of the ratio of oxygen to nitrogen permitted the development of global carbon budgets based entirely on observations (as opposed to inferences), with known confidence ranges [2–4].

Comparable measurements of atmospheric composition are now collected in many places worldwide, through the Global Atmosphere Watch (24 stations in the global network) and the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Directorate Flask Network (~112 locations; Table 1). The differences in the observed CO_2 concentrations within the network at a given time, together with atmospheric transport models, are used to infer the locations and magnitudes of anthropogenic and natural sources and sinks of carbon [5]. At first, this approach was only able to discriminate between broad latitudinal belts ('boreal,' 'temperate' and 'tropical' in the Northern and Southern Hemispheres), but a larger and better-distributed set of observations, plus the addition of other model constraints such as isotopes, elemental ratios and the seasonality of ocean and land production derived from satellite observations, now permits such estimates to be constrained into large regions by longitude as well [6].

A second invaluable data set that arose largely out of the determination of a few individuals and has now grown into a series of internationally coordinated initiatives are the observations of carbon dioxide partial pressure (pCO_2) in the surface ocean. Whereas large-scale spatial and seasonal patterns in atmospheric CO_2 can span a range of ~10 μatm in an average year, large-scale patterns in the surface ocean can easily span 200 μatm. For many years, surface ocean pCO_2 measurements have been made on research vessels as they traversed the global oceans. The first global picture of surface pCO_2 distributions required ~250 000 measurements collected over 40 years to properly characterise the patterns of spatial variability [7]. This work showed that whereas average surface ocean pCO_2 values are slightly lower than atmospheric, leading to a net uptake of CO_2 from the atmosphere to the ocean, there are large regions like the equatorial Pacific Ocean that are significant sources of CO_2 back to the atmosphere [8]. It also showed the crucial role of certain regions such as the Southern Ocean, and revealed the effect of nutrient limitation on net carbon uptake by marine ecosystems [7,9].

The latest surface ocean pCO_2 climatology compiles over 3 million measurements collected using bottle and underway samples from research ships, continuous underway measurements on voluntary observing ships (VOS), and autonomous systems on moored buoys [10]. Coordination and intercalibration are just as crucial for ocean pCO_2 as it is for atmospheric CO_2 measurements. The exchange

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Table 1. Key carbon observation networks and activities mentioned in the text

Network or activity	Description	Web address
Global Atmosphere Watch	Atmospheric chemistry part of the Global Climate Observing System	http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html
Global Flask Network	Places taking monthly air samples for analysis by NOAA	http://www.esrl.noaa.gov/gmd/ccgg/flask.html
International Ocean Carbon Coordination Project	Coordinates measurements of the C cycle in the oceans	http://www.ioccp.org
Fluxnet	Network of terrestrial C flux sites	http://www.fluxnet.ornl.gov
Global Carbon Project	Project of the Earth System Science partnership to do coordinated research on the C cycle	http://www.globalcarbonproject.org
Orbital Carbon Observatory	Example of space-based carbon observations	http://www.oco.jpl.nasa.gov
Carbon Dioxide Information Analysis Center	Data centre for C-related data sets	http://cdiac.ornl.gov

of seawater standards from the Scripps Institute of Oceanography [11] and primary gas standards by NOAA plays an essential role here.

In the examples given above, the power of the observations resides in their collective geographical coverage, not in the value of any single measurement: a clear argument for consistent methods, standards and data sharing. However, in both cases, large regional uncertainties remain owing to sparse coverage, most notably on tropical land and in the Southern Ocean [12–14]. This is so because measurements in remote locations are expensive to collect, and sampling priorities tend to be dictated by national interest rather than the need to achieve balanced global coverage.

There is no direct terrestrial equivalent of the atmospheric and oceanic data sets described above. The reasons are a combination of political and ecological realities. Politically, the land is carved up into nearly 200 sovereign states, which are not always forthcoming with observations pertaining to their soil and forest resources (in much the same way as they are often reluctant to share fisheries resource data in their continental waters). The measurement methods applied in different countries are often somewhat incompatible. On the ecological side, terrestrial carbon stocks and fluxes can vary by orders of magnitude over distances of tens of meters, requiring a dense and well-distributed observation system for accurate and unbiased estimates.

The absence of systematic terrestrial carbon observations is the main reason why, until relatively recently, the land part of the global carbon cycle was estimated as the residual after the atmospheric and oceanic parts had been accounted for. The application of atmospheric O_2:N_2 and ^{13}C biogeochemical constraints now allows the terrestrial component to be better constrained by observations, albeit indirectly, than in the past [4,15].

There is a burgeoning set of terrestrial sites that measure the flux of CO_2 between land and atmosphere, based mostly on the eddy covariance technique. Despite the declining cost and widespread adoption of this approach, it is most unlikely that the network will ever be sufficiently dense to provide global coverage. Instead, they are key measurements for understanding processes that control fluxes and support the development and validation of models and satellite measurements. Satellite-derived net primary production is an important product toward a global observation capability [16]. Compared to atmospheric and ocean carbon observatories, the land carbon components are in their incipient stages.

What is the value of a carbon observation system?

Monitoring changes in carbon fluxes and pool sizes is essential for tracking human-induced climate change and predicting the future trajectories of the human-carbon-climate system. Currently, 55–65% of all anthropogenic carbon dioxide emissions are removed from the atmosphere by natural sinks. But the strength of these sinks is influenced by the rate of emissions and the changing climate [17]. Steering human efforts toward atmospheric CO_2 stabilisation requires detailed knowledge regarding both the natural fluxes and human perturbations of the carbon cycle.

A global carbon observatory would consolidate information on both anthropogenic emissions and natural fluxes. With an appropriate temporal and spatial resolution, the system would be able to resolve the contributions of individual processes and regions critical to the understanding of possible future trajectories.

Such a system would need to include close monitoring of the carbon pools on land and in the oceans most likely to change [18]. Major vulnerable pools include carbon in tropical forests, the Southern Ocean deep waters, frozen soils, peatlands (both at high latitude and in the tropics) and methane hydrates in permafrost and on continental shelves.

A carbon observatory would also enable the monitoring and verification of emissions and removals of carbon by human-induced activities at national and subnational scales. Many billions of dollars are likely to be invested in carbon mitigation efforts over the coming decades. They must be underpinned by a robust observation system to verify that the efforts have the intended outcomes. A major driver for a global carbon observatory is the growing market for carbon credits, both ‘voluntary’ and legally binding, in particular from avoided deforestation, otherwise known as reduced emissions from deforestation and degradation [19].

Inadequacies of the current approach

The elements of the global carbon cycle observation system that currently exist were developed in an *ad hoc* and uncoordinated way, largely through short-term funding to individual research projects. As a consequence, it is no surprise that the system is suboptimal. Two major shortfalls are discussed below.

First, a measure of the inadequacy of the observing system is the absolute size of the observational uncertainties in the main components of the global carbon budget, which in a well-designed system should all be of approximately the same magnitude. The following values are from the Global Carbon Project budget for 2007, and the error estimates represent half of the 95% confidence interval [20]. Currently, the annual increase in the atmospheric CO_2 stock is the best-known component (4.2 ± 0.04 PgC/y (billion tonnes of carbon per year); relative error 1%), followed by emissions from fossil fuel combustion (estimated from oil, gas and coal use statistics at 8.5 ± 0.4 PgC/y; 5%) and by ocean uptake (-2.3 ± 0.4 PgC/y; 18%) and land net uptake (-1.1 ± 1.0 PgC/y; the 90% error is distributed in a poorly known way between the gross uptake [−2.6 PgC/y] and deforestation [1.5 PgC/y] terms). To provide sufficient sensitivity to guide stabilisation of atmospheric CO_2 (e.g. below 500 ppm), the uncertainty in measuring the major fluxes to and from the atmosphere needs to be more consistent in absolute terms and, we suggest, less than 10% of the best estimate for each individual flux.

Second, the current carbon observations are not optimally distributed or measured for the purpose of attributing fluxes to processes and regions, a fundamental requirement for understanding the controls over the atmospheric CO_2 growth, and thus the necessary mitigation effort to achieve a given level of atmospheric CO_2 stabilisation.

The weaknesses of the *ad hoc*, nationally funded approach are highlighted by comparing the reliability of the CO_2 assessment between the intensely sampled North Atlantic Ocean and the sparsely sampled Southern Ocean, which is thought to account for more than half of the oceanic sink [14]. The proximity of scientifically advanced countries to the North Atlantic basin, and the density of shipping lanes between Europe and North America, has allowed the uncertainty in the oceanic flux in this basin to be reduced to 15%. The uncertainty in the sub-Antarctic zone sink of the Southern Oceans exceeds 50% [14].

On land, one of the most globally significant and least-constrained quantities is the carbon emission from deforestation. The measurements of forest cover, deforestation and forest degradation are of poor accuracy [21]. Consistent and harmonised observations of global land cover which change at an annual timescale remain absent, yet are critical for the terrestrial carbon balance and attribution. Likewise, the soil hosts the largest terrestrial carbon pools, some of them very vulnerable to change [17], yet the global soil carbon stock remains very uncertain. The single global basis for area extrapolation of soil attributes remains the Soil Map of the World, first published in 1974 by the UN Food and Agriculture Organization, but in many areas based on field mapping undertaken long before that date. A recently published improved soil database for the northern circumpolar permafrost region illustrates the problem: it estimated a carbon content in the first meter of soil about double of that reported in previous analyses [22].

The reliance on observations funded out of research budgets works against achieving a stable long-term global observing system. The emphasis on precision, continuity and long-term measurements that characterises operational observation systems makes them unattractive to research funding agencies oriented toward innovation and quick returns [1]. ‘Monitoring’ that delivers products, even if based in excellent science, is often seen as pedestrian science, and contribution to global data sets is not rewarded in terms of academic prestige.

Satellite-based remote sensing plays an indispensable role in both land and ocean observations. Dense estimates of atmospheric CO_2 profiles from space, coupled with other remotely sensed observations, will improve the spatial resolution of land and ocean carbon fluxes in the future, provided enough validation with ground observations is available. However, up to now, Earth observations from space have to a large degree hitched a ride on other space agendas, including the development of launch capacity, platforms and sensors for reasons of national security and pride. After a brief flirtation with the commercialisation of Earth observations, it seems that there is no viable business model for Earth observations as a ‘private good’ at any level approaching full cost recovery. The continuity of key carbon cycle observations, such as synthetic aperture radar for observing forest cover through the clouds that often blanket the tropics, or highly accurate ocean color observations at moderate resolution, are not assured. These data are currently provided by research missions, not operational programmes.

There is no designated unified repository of global carbon cycle data. The Carbon Dioxide Information and Analysis Center located at Oak Ridge, TN, USA, hosts many of the key data sets and makes them freely available, but provision of the data to the center remains voluntary. Some parties might be suspicious of a data centre so closely associated with one national government. Furthermore, although observations remain so dependent on individual research groups, there is a reluctance to make the data publicly available until its publication value has been exhausted.

Toward an adequate system

The theoretical tools for designing an optimal carbon observation system exist. One could design an adequate system by first solving the level of precision required to address a prioritised set of questions, and then using modelling and observation-based estimates of the variability of the system to calculate the type, number and disposition of the observations that would be required to reduce the uncertainty to be within those bounds [23]. This approach has been successfully applied to estimate how many climate observations, profiling ocean floats and atmospheric CO_2 measurements are required to achieve a certain level of accuracy. The analyses also revealed how critical the spatial distribution of those measurements is.

The final investment level for a global carbon observatory should be consistent with the size of the societal benefits it provides. Current climate mitigation efforts are already of the order of hundreds of billions of dollars annually. A carbon observatory costing a small fraction of this amount could verify that the investments result in the intended emission reductions or enhancement of uptake.

In our view, an adequate system would constrain the uncertainty level of major carbon fluxes globally and regionally to no worse than 10% of the mean. This is not achievable through the present short-term, national science programme funded system. It requires a globally managed carbon observatory, sustained throughout the 21st century. This calls for new institutional and funding arrangements.

The responsibility for obtaining, verifying, compiling, archiving and making available the key data sets essential for the management of the shared biosphere ought to be vested in an autonomous organisation, and backed up by treaties that ensure reasonable access to data for sample locations within national territories. Virtually all the international environmental treaties already contain such provisions, but they are seldom as energetically invoked as, for instance, the treaties on nuclear nonproliferation. The threat of nuclear warfare is clearly perceived by the community of nations to be sufficient to override concerns of national sovereignty: why is the equally plausible threat of multiple environmental crises taken less seriously?

The Group on Earth Observation (GEO) and its proposed Global Earth Observation System of Systems (GEOSS) represents a step in the direction of global coordination, but in its current form lacks any executive powers or an operational budget. A global carbon observatory could be functionally associated with an existing international entity such as the World Meteorological Organization, but needs its own mandate, operational goals, governance system, reporting lines and budget if it is to maintain its focus and continuity in the face of many other competing demands, some of which are very compelling in the short term. A global carbon observation system would deliver annual carbon flux assessments in the ocean, atmosphere and terrestrial domains at an agreed spatial resolution, and be judged in terms of its ability to meet the accuracy specifications set for it in a cost-effective manner. The outputs would be used in international policy and national economic and energy planning.

A perceived danger of long-term commitment to observations is the risk that the monitoring system outlives its societal value or fails to keep current with the science. This emphasises the need for the observatory to remain closely coupled to research programmes, but not simply as a happenstance consequence of their activities. International carbon networks are developing increasingly effective mechanisms of global scale coordination, for instance through the Earth System Science Partnership's Global Carbon Project (GCP), the UNESCO- and IOC-based International Ocean Carbon Coordination Project (IOCCP) and its VOS, GO-SHIP and TS initiatives, the EU-based CarboOcean Project and Carina assessments, and the Fluxnet network. These networks will carry on playing an invaluable role in providing an understanding of the drivers of CO_2 flux variability and their links to the long-term global observatory proposed here. Thus, a global carbon observation system can be built on a solid scientific base and existing relationships; but reliance solely on the organic evolution of the patchwork system we have today is insufficient for the challenges ahead. The importance and political implications of the observations argues for an approach less vulnerable to the whims of national research budgets and agendas.

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