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THE ROLE OF CARBON CYCLE OBSERVATIONS AND KNOWLEDGE IN CARBON MANAGEMENT

Lisa Dilling,[1] Scott C. Doney,[2] Jae Edmonds,[3]
Kevin R. Gurney,[4] Robert Harriss,[1] David Schimel,[5]
Britton Stephens,[6] and Gerald Stokes[3]
[1]Environmental and Societal Impacts Group, National Center for Atmospheric Research, P.O. Box 3000, Boulder Colorado 80307; email: ldilling@ucar.edu, harriss@ucar.edu
[2]Marine Chemistry and Geochemistry, 360 Woods Hole Road, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543; email: sdoney@whoi.edu
[3]Pacific Northwest National Laboratory/Joint Global Change Research Institute at the University of Maryland, 8400 Baltimore Ave. Suite 201 College Park, Maryland 20740; email: jae@pnl.gov, stokes@pnl.gov
[4]Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado 80523; email: keving@atmos.colostate.edu
[5]Climate and Global Dynamics Division, National Center for Atmospheric Research, P.O. Box 3000, Boulder, Colorado 80307; email: schimel@ucar.edu
[6]Atmospheric Technology Division, National Center for Atmospheric Research, P.O. Box 3000, Boulder, Colorado 80307; email: stephens@ucar.edu

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■ **Abstract** Agriculture and industrial development have led to inadvertent changes in the natural carbon cycle. As a consequence, concentrations of carbon dioxide and other greenhouse gases have increased in the atmosphere and may lead to changes in climate. The current challenge facing society is to develop options for future management of the carbon cycle. A variety of approaches has been suggested: direct reduction of emissions, deliberate manipulation of the natural carbon cycle to enhance sequestration, and capture and isolation of carbon from fossil fuel use. Policy development to date has laid out some of the general principles to which carbon management should adhere. These are summarized as: how much carbon is stored, by what means, and for how long. To successfully manage carbon for climate purposes requires increased understanding of carbon cycle dynamics and improvement in the scientific capabilities available for measurement as well as for policy needs. The specific needs for scientific information to underpin carbon cycle management decisions are not yet broadly known. A stronger dialogue between decision makers and scientists must be developed to foster improved application of scientific knowledge to decisions. This review focuses on the current knowledge of the carbon cycle, carbon measurement capabilities (with an emphasis on the continental scale) and the relevance of carbon cycle science to carbon sequestration goals.

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INTRODUCTION

Human combustion of fossil fuels and conversion of natural landscapes are commonly accepted to be the primary cause of the observed long-term increase in concentrations of atmospheric carbon dioxide (1). Carbon dioxide in the atmosphere acts as a greenhouse gas (GHG), and the human-induced increase from 280 to 370 ppm (parts per million) over the past 140 years is thought to have contributed to an average global temperature increase of $0.6 \pm 0.2^\circ$C as well as other changes in climate (2). Increasing concern that these changes might pose an unacceptable risk to human societies and the environment has prompted the international community, corporations, and local communities to consider options to mitigate further increases in atmospheric carbon dioxide (CO_2). Future atmospheric CO_2 trajectories can be slowed, and eventually reversed, in one of two ways: decreasing emissions due to fossil fuel combustion and land-use change or disposing and/or sequestering CO_2 to prevent it from accumulating in the atmosphere. Many of the latter approaches depend on successful manipulation of natural or managed systems that already are part of the active cycle of carbon exchanging throughout the earth system. Knowledge of the carbon cycle is therefore essential for successful application of deliberate carbon management strategies whether on land or in the ocean. Furthermore, quantification for policy verification and support may require advanced carbon cycle measurement capabilities, the details of which will depend on policy frameworks and protocols.

This review focuses on carbon cycle scientific knowledge and measurement capability for supporting carbon sequestration and disposal, only one aspect of carbon management. Other options for managing future atmospheric CO_2 increases, such as changes in energy systems, are equally critical and well described by Hoffert et al. and other reviews in this series (3, 4). As reviewed in the U.S. Department of Energy (DOE) "11-lab study," energy production and use can be managed to reduce carbon emissions by changing either the energy intensity or the carbon intensity of fuel used (5–7). Changing energy intensity involves improving the effectiveness of energy use in delivering gross domestic product (GDP) through end-use efficiency (fuel economy) or structural changes in the economy, and changing carbon intensity involves changing fuel to a less carbon intensive option (5, 7). Although the specification of a mitigation strategy can in principle be any mixture of effective technology, there is a preference for the strategy to be economically practical as well. The most comprehensive economic approaches are the economically efficient path approaches, first introduced by Wigley et al. (8). It is only when there is a cost for carbon that technologies, such as sequestration, capture and disposal, or perhaps even nonfossil derived hydrogen fuels, become an economically viable part of the mix. Economic drivers and cost incentives for climate and carbon management are being studied extensively and are not reviewed here [but see (9)].

Carbon sequestration and disposal have been seriously discussed as GHG management options for about a decade (10). Carbon sequestration and disposal remove carbon from the atmosphere by increasing the amount of carbon stored in biomass on land, in the ocean, or in geologic reservoirs. In order for these techniques to successfully meet climate policy goals, they must result in long-term, sustained net removal of CO_2 from the atmosphere through environmentally and economically acceptable means. Furthermore, the amount of carbon sequestered, environmental impact, and other parameters must be quantifiable in order for policy frameworks to be effective.

Development and application of policy in this area have relied on a number of carbon management principles, whose definition continues to be the subject of intense policy negotiations. The development and use of these principles imply an underpinning of a sophisticated understanding and application of carbon cycle science, which include observations, modeling, and fundamental knowledge. Here we evaluate the current capabilities and knowledge available from carbon cycle science to support the carbon management principles of quantification, additionality, separation, permanence, and environmental acceptability for the area of carbon sequestration and disposal. Additional steps will be needed to determine precisely what information policy makers need, if it is available and if it can be properly used.

In this review, we briefly describe the development of climate policy relevant to carbon management and outline the principles that have emerged from that process. We then describe several of the common sequestration and disposal approaches. The body of the review focuses on currently available scientific capabilities and knowledge as they apply to management principles for carbon sequestration and disposal.

Carbon cycle science provides only a part of the potential foundation necessary to the development of carbon management; technology, social science, economics, and political feasibility all play substantial roles as well. Nonetheless, we suggest that many assumptions of carbon management principles for sequestration depend on carbon cycle observations and knowledge and that these two areas of endeavor must therefore engage one another rigorously in the coming decade.

CARBON MANAGEMENT POLICY PRINCIPLES

The development of policy relevant to carbon cycle management has occurred primarily, but not exclusively, at the international level with the United Nations Framework Convention on Climate Change (UNFCCC) and its legally-binding instrument, the Kyoto Protocol (11). The Kyoto Protocol, constructed in 1997, has now been ratified (at which time, they become parties to the Protocol) by 101 nations, whose emissions are equivalent to 43.9% of the global emissions of quantified GHG in 1990. When the represented emissions reach the 55% mark, the Protocol will enter into force and thereby achieve its legally binding status for those nations that ratified it.

Because the Kyoto Protocol laid out relatively general guidance concerning how binding emission reductions were to be achieved, intense international negotiations occurred between 1997 and 2002. These resulted in the Marrakesh Accords, which contain far more detail on the broad issues outlined in the original Protocol and include description of emissions trading, funding, compliance, and carbon exchange with the biosphere (12). This last category of activity is referred within the negotiation process as land use, land-use change, and forestry (LULUCF), and later it included crop and rangeland management to emphasize the fact that carbon exchange with the biosphere includes both emissions and uptake. The biotic exchange reported must have occurred since 1990 and must be human induced. When biospheric or physical carbon uptake into the land or ocean from the atmosphere is greater than release over a region, it is defined as a “carbon sink.” Other types of carbon sequestration activities beyond those defined as LULUCF are not included in the Kyoto framework but will be discussed in this review.

The introduction of carbon sinks as a climate mitigation tool during the Kyoto policy process has been controversial for a number of reasons. Some parties argued that nations should meet their targets by reducing fossil fuel emissions or else risk that the efforts would result in no appreciable change in overall GHG concentrations. Others argued that the policy benefited some nations over others, depending on the existing land-use characteristics and land-use history. But these arguments notwithstanding, the introduction of carbon sinks into the negotiating picture likely made it possible for the Kyoto Protocol to come into existence. Flexibility in implementation is often a key feature of international agreements, and the Kyoto Protocol was no exception (13).

Although the international Kyoto Protocol is certainly the most visible and extensive framework, numerous decision processes relevant to carbon management are underway at a variety of governmental scales and within private entities on a voluntary basis. For example, over 560 local municipal governments worldwide have passed resolutions to implement emission reductions measures through a variety of mechanisms suitable for their region (14). Multinational corporations, such as British Petroleum, have implemented their own internal emissions trading policies to gain experience in emissions trading and to help meet their internal emissions reduction goals (15). Privately- and publicly-funded field experiments, such as the International Energy Agency (IEA) Weyburn CO_2 Monitoring and Storage Project at the Weyburn oilfield in western Canada, are proceeding in anticipation of eventual international agreements on emissions reductions. These examples suggest that carbon management principles and policies are of much broader relevance than solely at the international negotiation level.

As currently framed, policies for carbon management depend on assigning credit for activities such as carbon sequestration or emissions reduction. The subtleties and criteria discussed for determining the value of carbon credits can be reduced to three main attributes: how much carbon is stored (or emissions prevented), by what mechanism, and for how long.

The following terms have emerged from consideration of LULUCF activities under the Kyoto framework but also have relevance for broader carbon management options. They provide an important set of carbon management principles because they have been guiding policy framing and activity implementation. Scientific knowledge and capability to underpin a subset of these principles in the implementation of carbon management will be elaborated in the analysis that follows. These principles will be defined for discussion purposes as:

Quantification refers to the ability to measure a parameter at the required scale, within the level of uncertainty to adequately meet policy goals.

Additionality is the carbon exchange through carbon management that must be in addition to what would have occurred in the absence of deliberate carbon management policy.

Separation means the carbon management activities due to planned direct, human-induced activity and distinguishable from natural occurrences. Therefore, biospheric carbon exchange due to mechanisms, such as CO_2 fertilization, unintentional nitrogen fertilization, and climate change, must be accounted for before credit is calculated.

Leakage refers to activities aimed at sequestering carbon but that fail because they simply displace biospheric emissions to a land area not included in the national accounting. For example, a project aimed at afforestation of a tropical pasture may result in deforestation elsewhere and negate the carbon gains within the project boundary. Leakage is not unique to LULUCF activities but can arise if industries shift GHG emitting production to parties that do not have emission limits.

Permanence has two distinct aspects; one relates to physical permanence and the other to institutional longevity. The first aspect acknowledges that carbon storage and exchange is a reversible process. Thus carbon sequestered during a commitment period may be emitted at a later time due to natural or human-induced processes. Similarly difficult is the notion of institutional permanence. Any accounting system will require an institutional longevity on the scale of biospheric timescales: decades to centuries.

Perverse incentive is one that rewards action that is actually detrimental to reducing emissions while perhaps fitting within the letter of the law. One example drawn from the current interpretation of the Kyoto Protocol is the possibility that parties using joint activity mechanisms may remove forest cover after 1990 but before the beginning of the first commitment period in 2008 followed by reforestation or afforestation activities. This would allow for the accrual of credits that are not true carbon removals when integrated over years prior to, and including, the first commitment period.

Transparency refers to the need for the activity accounting to be easily amenable to examination, verification, and validation. Much work has been performed in this regard by the Intergovernmental Panel on Climate Change (IPCC) and is embodied in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (16) and subsequent work currently underway (17).

Verification refers to procedures that can be followed to establish the reliability of carbon exchange data. This will require independent estimation of the reported carbon exchange and implies two different methods.

SEQUESTRATION AND DISPOSAL OPTIONS

Several techniques for carbon sequestration and disposal are being considered, generally grouped by the part of the earth system that must be managed (3). For current purposes, the essential difference between sequestration and disposal is that *sequestration* enhances the uptake of carbon by the nonatmospheric components of the natural carbon cycle, and *disposal* places carbon or CO_2 in a location or state that prevents it from becoming part of the active carbon cycle. It should be noted that there is some debate about the specific nomenclature to be used, specifically disposal is sometimes referred to as storage. For policy purposes, capture and disposal is thought of as an emissions reduction strategy but sequestration is not; both strategies do ultimately lessen the atmospheric CO_2 content.

Terrestrial Sequestration

Much carbon is stored in natural and managed ecosystems on land. Terrestrial sequestration refers to the process of increasing carbon retained in soils or in standing biomass on a particular plot of land. Early estimates of the technical potential for global biospheric carbon sequestration commonly fall within a range of 1–2 GtC/year (18). In some regions, opportunities for land conversion, land restoration, and improved management could result in potential sequestration in specific agroecosystems (19–23). Potentially cost-effective activities for carbon sequestration in the forestry sector include increasing the area and productivity of forest lands, increasing agroforestry, and increasing the use of harvested materials in durable wood products or in biomass energy generation. It is clear from these and many other studies that the sequestration of carbon in forests, croplands, and rangelands should be seriously considered in the design of climate change mitigation strategies.

Terrestrial sequestration was the first sequestration method to be examined carefully as a carbon management option because of its inclusion in the Kyoto Protocol. Additionality, permanence, and other principles as they relate to terrestrial sequestration are discussed in detail below. Although not a part of the eventual Kyoto Protocol, maintenance of existing forests was intensely debated. It was rejected as a strategy in the current policy framing because it does not result in a net reduction of atmospheric CO_2. A role for maintenance of existing forests is still experimented with in voluntary carbon management strategies, such as those coordinated by environmental nonprofit groups.

Terrestrial sequestration has been suggested as a strategy for buying time to allow other, more permanent options to be implemented (24). Terrestrial sequestration is available for implementation immediately, for example, while development and implementation of carbon-free energy technologies is a longer-term enterprise. This suggests that near-term investment in biospheric carbon sequestration projects is not a substitute for significant attention to the development and implementation of carbon-free energy technologies but merely a complementary strategy (3). The U.S. Department of Energy sponsors an Internet resource on selected current research on carbon sequestration in terrestrial ecosystems at http://csite.esd.ornl.gov/.

Ocean Sequestration

The oceans are a large natural sink for excess CO_2. CO_2 exchanges at the air-sea interface, becomes dissolved, and then is transported in seawater through the thermohaline circulation. Carbon is also transported to depth by the sinking of phytoplankton and other organic material through the biological pump. Deliberate carbon sequestration has been conceived through two mechanisms that attempt to simulate these natural processes in the ocean. One method involves injecting CO_2 directly into the deep ocean, bypassing the mixed layer (25). The second is to add nutrients to the surface ocean to increase the rate of the biological pump. Opportunities for crediting carbon sequestered in the ocean are not yet available, but it is widely discussed as an option by researchers and entrepreneurs.

Deep-ocean injection would involve the transmission of a stream of liquid or gaseous CO_2 through a fixed or towed piping system down to depths in the ocean at which the CO_2 forms clathrates, semisolid substances. The clathrates would then slowly dissolve into the surrounding seawater and rapidly increase the local concentration for a period of time until stabilization occurs at a new higher dissolved concentration in a broader region. Pilot-scale experiments have been conducted to demonstrate the feasibility of this method (25). Long-term environmental effects have not yet been determined (26).

Ocean fertilization would involve adding a nutrient that is currently in short supply to the surface ocean, such as iron, to stimulate phytoplankton growth and thereby take up more CO_2 from the surrounding seawater into biomass (27). The approach then supposes that the excess biomass will sink out of the mixed layer of the ocean to the deep sea and effectively transfer the carbon from the atmosphere to the ocean. Field experiments have demonstrated that adding iron to the surface ocean in regions where it is lacking, such as the Equatorial Pacific and Southern Ocean, will indeed stimulate growth (27, 28). The fate of the stimulated biomass growth, that is whether it actually sinks out of the mixed layer to the deep ocean, has not yet been determined. This method has been criticized both for potential negative ecosystem effects and for concerns about its effectiveness (29, 30), although research is still underway to explore these issues (31).

Geologic Disposal

Geologic disposal is the process of placing CO_2 in a geological medium with the intent of retention for sufficiently long periods of time to assist in the stabilization of atmospheric concentrations (32). There are two different scenarios for disposal of carbon; one injects a dissolved gaseous form or a supercritical fluid into a confined geological medium, and the other reacts CO_2 with a mineral to form a new stable mineral form. The new mineral form is either created in situ, or the mineral reaction is used as a capture mechanism, and the resulting mineral is buried or used for some other purpose. In addition to a great deal of work conducted in DOE laboratories, academic institutions, private corporations, and two large academic-private partnerships have formed to research carbon sequestration and disposal and new energy technologies (33, 34).

SCIENTIFIC CAPABILITY FOR INFORMING CARBON SEQUESTRATION AND DISPOSAL POLICIES

All of the methods for carbon sequestration and disposal will need to adhere to the carbon management principles defined above in order to be successful, in particular: how much carbon is stored—quantification; by what means—additionality and separation; and for how long—permanence. In addition, any strategy will need to address environmental acceptability and economic feasibility. The scientific and social uncertainty underpinning future targets for atmospheric CO_2 levels discussed here is relevant to policy debates as well. Addressing the issues determining economic feasibility would require more space than we have in this review and are deferred to other reviews.

Quantification

Because carbon sequestration policy has thus far developed around the concept of meeting specific targets, quantification of carbon sequestration and emissions is of paramount concern. Whether to meet an absolute target set by a project, nation, or corporation or to ensure the value of traded carbon credits, methods must be established that are accepted and transparent. From a scientific point of view, the measurement system could be designed with attention to several attributes: quantity to be measured, accuracy and precision desired, cost, required spatial and temporal scales, targeted longevity of system, ease of use, and transparency to others. These requirements may change in relative importance when viewed from the policy maker's perspective.

CURRENT METHODS AND SCALING The current capability to quantify the amount of carbon stored or released from land or ocean depends on the scale at which the measurement is needed (both spatial and temporal). Often the quantity measured can only give information about carbon exchange or sequestration on a specific spatial scale, whether hundreds of kilometers or a few meters squared. Reconciling information gained at different scales is of intense interest in the scientific community, as elaborated below. Techniques do not easily scale up to extrapolate larger patterns or scale down to explain mechanisms at the local scale. This has implications for applying measurement techniques to specific policy needs.

For decision making purposes, information on carbon exchange will likely be needed at a variety of scales, from the global and national level to regional, state, and local levels, including the private sector. An enhanced dialogue between scientists and decision makers could aid in developing a mutual understanding of measurement capabilities and decision makers' constraints.

Global and continental scales For decades, observations at relatively few remote locations established the rate of the global average increase of CO_2 in the atmosphere (35–37). These observations provided the scientific confirmation that CO_2 was indeed increasing above the level expected by normal variability and spurred contemplation of policy measures. The continued operation, improvement, and expansion of these networks is critical for improving our understanding of the global carbon cycle and ensuring that the intended consequence of reducing the growth rate of atmospheric CO_2 is indeed happening (38).

Not all of the CO_2 released by human activity stays in the atmosphere. Approximately half of the excess CO_2 is absorbed by the land and ocean. On a global scale, determination of net carbon fluxes is challenging because they typically represent small differences between large gross fluxes. For example, the annual terrestrial and oceanic uptake of fossil fuel CO_2 emissions, presently on the order of 3.5 billion tons of carbon per year (PgCyr^{-1}), is small compared to the natural seasonal exchanges of roughly 60 PgCyr^{-1} between the atmosphere and terrestrial biosphere and 90 PgCyr^{-1} between the atmosphere and oceans (39). The causes of these natural cycles, biological growth and decay, seasonal ocean heating and cooling, and large-scale ocean circulation, tend to be in approximate global balance such that the anthropogenic perturbation only becomes distinguishable on annual and longer timescales. Carbon cycle measurements are further complicated by large interannual variability in these natural processes, as shown in Figure 1.

The atmosphere also provides a way to measure integrated carbon exchange in the aggregate at very large scales, such as that of broad latitudinal zones. Spatial gradients in atmospheric CO_2 concentrations can be used to infer in a top-down sense the location of surface carbon sources and sinks using inverse modeling techniques (40, 41). Atmospheric inverse modeling maps the sum of anthropogenic uptake and any net pre-industrial carbon fluxes, such as those driven by the ocean thermohaline circulation and biological pump. Large-scale model estimates of broad latitudinal patterns are in general agreement in indicating a large sink ($\sim$3 PgCyr^{-1}) in northern midlatitudes, a moderate source ($\sim$1.5 PgCyr^{-1}) in the tropics, and a small sink ($\sim$1 PgCyr^{-1}) in the extratropical southern latitudes. (40, 42). Atmospheric ^{13}C and O_2/N_2 isotopic ratios and land and ocean constraints provide evidence that the northern midlatitude sink is primarily terrestrial in origin and that the tropical source is a mix of tropical ocean outgassing and biomass burning (42–46).

Recent expansion of the global atmospheric network has allowed a rich exploration of continental patterns of carbon sources and sinks using inversion techniques (41, 42, 45, 48–54). However, this move toward higher spatial resolution generally requires specification of additional information or “priors,” and data and atmospheric model limitations prevent robust estimates on smaller scales. These limitations include sparse data, spatial and temporal mismatch between high-resolution measurements and coarse models, and systematic model errors. The largest model uncertainties are associated with representing seasonal covariation of atmospheric transport and biospheric carbon exchange (42, 55). To date, the attempts to differentiate surface carbon fluxes on a continental scale, such as Eurasia from North America or North America from the North Atlantic, have been somewhat consistent in similar time periods but have large uncertainties (for one regional example, see Table 1). To examine the causes of differences in atmospheric inversion results, a recent international model intercomparison (Transcom 3) divided the globe into 22 regions, compared 16 different transport models inverted using common data, and assumed prior fluxes and errors (42). The authors found uncertainties from ± 0.25 to ± 1.25 PgCyr^{-1}, depending on the region, resulting from differences in the transport models, model coarseness, and limited observational data in the tropics and over continents.

Additional challenges arise when applying atmospheric inverse techniques on smaller scales using continental data that is highly variable due to intense local sources and sinks. Although the amount of data is a major limitation, transport models typically employed in recent inverse studies are too coarse to use all of the available data, particularly that collected at high time resolution or over continents

TABLE 1 An example of continental and subcontinental carbon sink estimates: the carbon balance of either temperate North America or the United States (excluding fossil fuel emissions)

Method	Regional area	Time period	Magnitude (PgC/yr) (negative = uptake from atmosphere)	References
Atmospheric inverse				
(Fluxes estimated for all components and processes in a given region as viewed from the atmosphere)				
	United States (coterminous)	1981–1986	−0.2 ± 0.3	(51)
	United States (coterminous)	1980–1989	−0.4 to −1.5 ± 0.25	(53)
	North America (>15N; <70N)	1985–1995	−0.5 ± 0.6	(49)
	North America (>15N; <70N)	1985–1995	−0.7 ± 0.7	(50)
	North America (>15N)	1988–1992	−1.7 ± 0.5	(48)
	North America	1990–1995	−1.0 ± 1.2	(52)
	North America	1990–1994	−0.8 ± 0.6	(54)
	Temperate North America	1992–1996	−0.8 to −1.2 ± 0.4	(42)
Bottom-up				
(Fluxes estimated from individual components of terrestrial systems)				
Forests	United States (all 50)	na	−0.1	(70)
Forests	United States (coterminous)	na	−0.08	(72)
Forests	United States (coterminous)	1952–1992	−0.3	(77)
Agricultural soils	United States (all 50)	1980s	−0.1	(124)
Expanded inventory	United States (coterminous)	1980–1989	−0.3 to –0.6	(53)
Process-based				
(Contribution to total flux from various processes as estimated by models)				
Land-use change	United States (all 50)	1980s	−0.35	(124)
CO_2 and climate	United States (coterminous)	1980–1995	−0.08	(138)

where concentrations are more variable. Recent modeling work has shown that there is information about sources and sinks in such records (56). With considerably more data and significant improvements in transport models, one might expect inverse methods to be able to distinguish annual source and sink regions over land at the continental scales to within ±0.2–0.5 $PgCyr^{-1}$ (57).

Local to regional scales Towers instrumented with eddy covariance instruments are very well suited for characterizing local exchange of trace gases including CO_2 between the atmosphere and biosphere over a range of timescales from diurnal to interannual (58). The growing network of eddy-flux towers provides key information on the response of the terrestrial biosphere across a multitude of biomes to meteorological and climate variability (59, 60). These instruments, however, are generally deployed on towers only a few meters above canopy height and thus provide fluxes from relatively small footprints ($\sim$1 km^2). The heterogeneity between sites and the small spatial scale makes aggregation of data to quantify larger patterns of uptake or release difficult (61). In addition, complexities in the airflow patterns during low flux periods or nighttime flow, for example, have increased the uncertainty of calculating long-term uptake, especially in complex terrain (61, 62). A more troubling issue has to do with the potential for biased or unrepresentative site locations. For example, flux towers are rarely located in regions of active disturbance or complex terrain.

Several tall towers have also been instrumented for flux and concentration measurements at heights up to 500 meters above the ground (63). A number of ongoing studies highlight the ability of the tall-tower concentration measurements to constrain regional scale CO_2 fluxes (64). Methods are also being developed to combine surface concentration and flux measurements from shorter towers with boundary layer models to create so-called virtual tall towers (65).

Aircraft sampling can also bridge the spatial scale gap between eddy correlation flux towers and global atmospheric gas measurements. Weekly flask profiles for CO_2 and other gases, collected from light aircraft, extend the sampling above the boundary layer into the free troposphere and are now being made at over 20 sites worldwide. These measurements provide valuable additional data for inversion studies and strong tests for the representation of vertical mixing in transport models. Intensive airborne sampling campaigns from research aircraft have been carried out, and it is clear that such measurements can provide short-term estimates of regional scale CO_2 fluxes and high-resolution data for planning routine measurements (66–69).

Early attempts at direct estimation of terrestrial carbon budgets through biomass inventories focused on forests (70–73). All of the countries of Annex I (a set of nations that includes members of the European Community, the Russian Federation, eastern European countries, the United States, the United Kingdom, Australia, New Zealand, Japan, and Canada) of the Kyoto Protocol maintain continuous forest inventories (18). These inventories, generally conducted for timber and resource assessment purposes, can be used to infer changes in carbon stocks in timber over the time period of study. In general, forest inventories measure aboveground woody biomass, known as the stem wood volume, through either direct in situ observations or remote sensing. Wood volume is converted into equivalents of carbon specific to the forest type [e.g., (72)]. Carbon present in soils, leaf litter, and woody debris, as well as carbon in forest types not included in the definition of forests are not counted in most national forest inventories. Differences in how timberland is defined can also affect stock estimates. In addition, nations differ in how they assess their forests and in how all forests on private and public land are counted. Finally, most national forest inventories are conducted on a 10-year, or in rare cases 5-year, rotation cycle and therefore cannot assess changes on a shorter temporal scale than a decade. Some of the limitations of forest inventories have been pointed out in previous reviews in this series (74, 75). These methods remain somewhat uncertain, and efforts are increasing in many nations to improve capacity for full carbon accounting.

Agricultural lands, rangelands, grasslands, and lands in suburban mixed use are also not included as part of the forest inventories, although the U.S. Department of Agriculture maintains a separate crop yield and residue database. Wood products produced from harvested timber as well as agricultural products removed from a region for consumption elsewhere must also be counted in order to obtain a full carbon budget. Separate estimates have been conducted for many of these lands and biomass types in the United States and other nations in order to estimate a full carbon budget for continental regions (76, 77). As with forest inventories, inventories of other stocks and fluxes are subject to uncertainties and limitations to the ability to measure shorter-term intervals.

Ideally, aggregated data at the smaller scale should be consistent with independent estimates gathered with methods at the larger scale. It has been difficult to reconcile inventory-derived estimates showing little carbon uptake in temperate northern latitudes with atmospheric constraints suggesting large uptake (Table 1). One study recently attempted to reconcile atmospheric inversion-based estimates and land-based inventory approaches (53). Within the large uncertainty estimates for each approach, estimates for carbon uptake for the coterminous United States for the period of 1980–1989 were found to be consistent in the range of 0.3–0.58 PgC/yr. The study demonstrated the importance of vegetation processes other than forests as contributors to the U.S. carbon sink; a full 50% of fluxes were found to result from vegetation outside the forest sector, such as woody encroachment, which is primarily the expansion of scrubland. Several components of the land-based analysis are highly uncertain, as are the atmospheric inversion results. Also, not all of the terrestrial carbon storage estimated by atmospheric inversion studies is likely due to ecosystem processes. Fluxes from additional processes such as burial of carbon in reservoirs and sediments and export of carbon by rivers are included in atmospheric inversions, because the atmosphere integrates the results of all flux processes in the domain (78, 79).

Ocean measurements Somewhat paradoxically, ocean measurements can be used to address continental uptake issues (48, 80). The better the ocean uptake is defined on interannual to decadal scales, the better we can estimate the land by difference from the known fossil fuel emissions and atmospheric inventories. At the global scale, a major advance has been the development of accurate and precise analytical techniques for measuring dissolved inorganic carbon (DIC) in seawater sufficient to detect the anthropogenic uptake against the large natural background (81–84). Regional patterns of ocean carbon fluxes can be estimated from air-sea CO_2 partial pressure (ΔpCO_2) fields (85, 86) together with empirical parameterizations of gas-exchange rate as a function of wind speed [e.g., (87)]. A recent compilation of close to 1 million underway surface ΔpCO_2 data points collected over the last 40 years from research vessels and merchant ships of opportunity provides a good picture of the climatological seasonal cycle and the role of physical and biological processes (86). The resulting CO_2 flux maps are both an essential input to the atmospheric inversion models and an important check on the estimated global sources and sinks [e.g., (42)]. The atmospheric and ocean approaches agree reasonably well except for the Southern Ocean, where there are substantial ocean data gaps, especially in winter, as well as potential errors in atmospheric and oceanic transport models

(39). The coastal ocean is extremely variable in both space and time, with high frequency variations in surface water ΔpCO_2 and air-sea flux. The implications for the atmospheric CO_2 signal and high resolution atmospheric inversions are unclear. Finally, the river runoff of particulate and dissolved carbon in both organic and inorganic form is not negligible at roughly 0.8 $PgCyr^{-1}$ (79). Comprehensive strategies for ocean carbon observations have been developed that would bring together volunteer observing ship surface pCO_2 transects, hydrographic surveys, moorings, remote sensing data, and time-series stations (88) and anticipate the ability to constrain basin-scale annual-mean CO_2 fluxes to within 0.1–0.2 $PgCyr^{-1}$ (57).

Emission and carbon sequestration inventory Emissions inventories are another key set of data, now reported at the national level, that might also be valuable for carbon management if reported at different scales, such as the state level or county level. Emission inventories for CO_2, methane, and other GHGs are available for most nations and some regions and cities. The IPCC, IEA, and a variety of other organizations publish global inventories of CO_2 and other GHG emissions that are updated at regular intervals (2, 89). The IPCC has established a set of GHG reporting protocols for the estimation of GHG emissions (16). The sources of data for the inventories are developed in two ways. First the reported emissions can come from direct monitoring at the source, (e.g., stack monitors on chemical plants). Alternatively, activity measures can be made in which the primary data collected is the level of a particular activity, such as the tonnage of chemical manufactured. Then the level of activity is multiplied by an emission factor determined by other means, and that represents the amount of emission associated with the activity, such as the amount of CO_2 released during aluminum smelting (16, 91).

National data on specific components of carbon sequestration are also required to be reported by the UNFCCC along with emissions inventories. For example, the U.S. Environmental Protection Agenct (EPA) estimated annual U.S. carbon sequestration for the year 2000 at 0.246 Pg carbon equivalent, a decline of approximately 17.7% from the estimated sequestration in 1990 (92). The EPA derives its estimates of carbon sequestration from changes in forest carbon stocks, changes in agricultural soil carbon stocks, changes in carbon stocks in urban trees, and changes in carbon stocks in landfilled yard trimmings. Many uncertainties remain in the accounting methodologies and conceptual framework for estimating carbon sequestration in vegetation, soils, and waste streams.

Remote sensing Remote sensing can provide high spatial and temporal coverage for some variables and thus can serve as a bridge between bottom-up local measurements and top-down atmospheric methods. Aboveground vegetation, ocean surface chlorophyll, and terrestrial and marine photosynthesis rates can be estimated using visible remote imagery combined with algorithms to convert remotely sensed parameters to biomass and carbon exchange (93, 94). In situ validation data is critical for developing and validating these algorithms. Satellite measurements cannot directly sense belowground biomass, a large component of carbon storage in terrestrial ecosystems, air-sea CO_2 fluxes, or key ocean properties, such as nutrients or DIC concentrations. In addition, carbon uptake is sensitive to a host of specific factors that cannot be easily detected from space; these include stand age, vegetation type, ecosystem health, plankton composition, and ocean circulation. Nevertheless, remote sensing is one of the few truly global tools available to characterize the carbon balance, and it has been used to document increased plant growth from observed climate variability (95–97). In addition, accurate measurements of atmospheric CO_2 concentrations from space would significantly advance our ability to constrain continental and regional CO_2 fluxes through inverse modeling (98). Existing satellite measurements of thermal emission can be used to estimate mid-troposphere CO_2 concentrations at a useful precision (99), and missions to measure total-column CO_2 from reflected near-IR are being planned (http://oco.jpl.nasa.gov/index.html).

Each of the techniques described above has unique advantages for yielding information on the carbon cycle, either for quantifying fluxes and budgets or elucidating process information. There is enormous power in combining these approaches by simultaneously assimilating all available information and measurements into a coherent, dynamically consistent picture of the carbon cycle (80, 100–102). Many regional field campaigns now being planned to focus on locating and quantifying carbon storage and determining mechanisms are following more integrated approaches (103–103e). The challenge remains to be able to effectively combine information from very different spatial and temporal scales in a rigorous and robust fashion. Data assimilation and multi-constraint analysis may offer a strategy for bridging scales and multiple data streams (104, 105).

MEASUREMENT FREQUENCY Simply documenting the amount of carbon present in a system at a given point in time is not equivalent to documenting the exchange of carbon with the atmosphere. The system must be monitored over time to measure changes at the timescale appropriate for the process. If the stocks change frequently on an annual basis, one must carefully consider when they are measured, so that short-term variations do not skew the reporting of a long-term trend. The same argument holds true for flux measurements. Flux measurements must be integrated over a long enough period such that variations in fluxes from the diurnal cycle, seasonal cycle, and episodic variability are considered. Ideally, the carbon balance of the land in question should be monitored for several annual cycles to ensure that variations in carbon uptake from year to year due to climate variability are taken into account. To reduce costs, some projects have taken the approach that only the pools of carbon that are likely to change much are monitored (18). However, this methodology may prove limiting in ecosystems that are less well known. Although much progress has been made on where carbon is stored within the components of managed and unmanaged ecosystems, it is still a subject of intense research (106). Techniques for nondestructive monitoring of some components such as soils are still needed.

CARBON ACCOUNTING Opportunities for measurement are available at a variety of scales, but policy language may in fact further constrain the possibilities by allowing only certain activities or components to be counted towards carbon credits. This could greatly limit the usefulness of various techniques if they are not specific to the requirements of the policy prescription. For example, although atmospheric methods are able to integrate information over a large spatial scale, they generally cannot discriminate among the causes for the observed atmospheric response to carbon uptake. If policies count only forest activities as meritorious of credit, then a system over a mixed forest/grassland would need to separate out only the creditable biomass. An inventory method might provide much greater specificity, but it would be more labor intensive, would need more sampling sites to overcome heterogeneity of point measurements, and would be less able to integrate the combined effect of the full ecosystem components that are difficult to measure such as belowground biomass.

The *IPCC Special Report on Land Use, Land-Use Change and Forestry* (18) has reviewed several types of projects to date. So far, most projects have adopted a two-step approach to developing a baseline. The approach is a combination of predicting the likely fate of ecosystems within the project boundary and then estimating the resulting changes in carbon stocks that would occur without additional management (18). This is often done by a simple logical argument—what would have happened in the absence of climate policy—or by land-use models. After the baseline is established, quantification of carbon stocks occurs by comparison to control plots or proxy areas or by modeling. One way forward is to focus accounting efforts on projects that can be clearly identified as additional, for example, replanting forests on denuded land. In such cases, the carbon stored in the project can be easily inventoried.

Land itself is stationary, and therefore can be monitored consistently to document storage. But the products derived from the land are not. Movement of goods and products from agriculture and timber from the area of production to the area of consumption is not insignificant and must be counted to estimate accurate fluxes (53). Similarly, nonproduct related terrestrial carbon may be transported to rivers and through river flows to the coastal ocean, where it may decompose and be released back to the atmosphere (79, 107).

Accounting for carbon storage in the ocean would pose unique challenges. Monitoring of direct injection into the ocean can take place either at aboveground facilities if the injection point is located at the coast, by shipboard observation, or through undersea monitoring. Quantification of the amount of carbon injected as well as tracking of the resulting plume are required. Because of water movement, carbon sequestered at one location may be released to the atmosphere at a different location in another part of the world. This poses a challenge both for monitoring and for assigning credit or debit for the action. The long-term effectiveness of sequestration and fate of excess carbon fixed during ocean fertilization is still unknown (27, 30). Ocean sequestration is an area of intense study as well as commercial interest (25).

A system designed to monitor carbon sequestration, either that caused by natural or deliberate means, may ultimately need to be a compromise among various goals demanded by scientific rigor and practical expediency. The level of accuracy and precision of measurements is an area of potential trade-off and depends on the measurement itself. Often, for example, there is a trade-off between cost and accuracy or precision, because instruments available for a lower cost on the mass market may have different design criteria than those that a scientist might require for specialized experiments. It is unclear in many cases whether a few really good measurements or many lower quality measurements would be more useful. The longevity of the system, ease of use and maintenance, and autonomous operation all are critical elements that may be demanded for a low cost, ubiquitous carbon monitoring system (108).

Currently, the scale, frequency, precision, and accuracy at which decision makers might need carbon cycle information is not known well in the scientific community. Decision makers at many levels are moving forward with carbon management policies that will likely require scientific support for quantification at levels not currently feasible. For example, if the Russian Federation decided to undergo forestry related LULUCF activities to sequester carbon at the maximum rate allowed under the Marrakesh Accords, 17.7 MtCyr^{-1} (12), their total sink would be a factor of 30 smaller than the current uncertainty on an atmospheric inversion at this scale (42). The details of which carbon stock and what measurement scale are important for successful policy outcomes. Because the cultures of scientific endeavor and policy decisions are intentionally separated from each other, deliberate and sensitive mechanisms must be found to foster a two-way exchange of information on an ongoing basis.

Additionality and Separation

Additionality and separation are closely linked. Additionality states that changes in carbon storage must be in addition to what would have occurred otherwise, and separation states that credit can only be given for storage caused by direct, human-induced activity. These concepts are important for ensuring the effectiveness of carbon management for climate policy, because they prevent participants from claiming credit for carbon sequestration that would have happened anyway and thereby results in no net reduction of CO_2 in the atmosphere. The complexity of the carbon cycle and our lack of full knowledge of the human and natural processes that govern carbon exchange currently limit the ability of science to underpin policy in these areas.

It is not possible to trace the mechanistic origin of CO_2 in a system by direct observation except in a few cases using isotopes (18). In the natural system, carbon actively cycles between the atmosphere, ocean, and land on timescales from seconds to centuries. Processes operating at the interfaces, such as air-sea exchange, fire and disturbance on land, ecosystem growth patterns, and human land use, all act to moderate the amount of CO_2 in the atmosphere. A molecule that arrives in a plant whether by CO_2 fertilization or normal growth will look the same. Additionality and separation cannot therefore be directly quantified by measuring the properties of CO_2 or carbon itself. This is in sharp contrast to other chemical species released by human activity such as freons (chemicals formerly used in refrigerants and aerosol propellants), which were the target of other international negotiations, namely the Montreal Protocol.

The approach that must be followed for additionality and separation, therefore, is to identify and quantify mechanisms that are sequestering or releasing carbon. These mechanisms must be identified by indirect methods, such as modeling, comparison, and extrapolation of experimental and field results.

One step toward determining additionality is to first establish a baseline to which changes can be compared. The baseline is an accepted view of what the normal trajectory of carbon sequestration or release would be in a given plot of land or ocean parcel. For terrestrial sequestration, it is important to understand the land-use history, vegetation type, climate interactions, and other factors regulating carbon exchange at a given site in order to estimate what its carbon storage might have been in the absence of deliberate activity. There are several possibilities for defining a baseline, and they include changes that would result from a business as usual projection of an arbitrary year of activity levels, lack of active management, or not meeting performance benchmarks (18). One can also monitor a separate plot of land that has not been subject to deliberate sequestration activities as has been done in some pilot projects (109). All of the potential baseline definitions, however, suffer from similar sources of uncertainty—they are based on assumptions about the potential trajectory of the carbon exchange of a particular area.

Quantifying carbon storage in a single year without accompanying mechanistic information is not enough to set a baseline, because carbon storage can vary from year to year and decade to decade due to external factors such as climate variability (58) (Figure 1). This information is available for sites in some cases, but in regions where records are lacking, it is difficult to reconstruct. Often, models are used to project baselines into the future, but these also require data to be successful and can still be poor predictors of specific local change, because of unexpected social or policy changes (18). Lack of data in developing countries is especially acute in many areas of rapid environmental change.

Documenting separation requires identification of the mechanism causing the sequestration and determining that it is via deliberate actions (such as changes in land-use practices or pumping of carbon to the deep ocean) rather than indirect effects (such as passive recovery from land-use change or disturbance, CO_2 fertilization, nitrogen deposition, and climate variability). Separating the causes of carbon storage is very challenging, although elegant methods have been developed to extract the influence of various mechanisms with existing datasets in some cases [e.g., (110)]. Scientific knowledge of the mechanisms that drive carbon exchange is essential to informing separation.

Land-use change is a major factor contributing to both carbon emissions and carbon sequestration. Observation and modeling of land-use change is therefore an important component to establishing both additionality and separation. Significant progress is being made on observational methods for quantifying land-cover change (biophysical attributes of the Earth's surface) and land use (human purpose or intent applied to these attributes); these methods characterize the importance of these changes for carbon cycle dynamics and derive the causes of land-use and land-cover change from case studies. A recent meta analysis of 152 subnational cases of tropical deforestation has significantly advanced understanding of the causes of land-cover and land-use changes (111). Simple explanatory relationships relating land-cover and land-use change to population, affluence, technology, and/or infrastructure rarely provide an adequate understanding of land change. Land markets and policies respond to the interaction of local, regional, and global economic and institutional dynamics (112). The increasing quality and quantity of satellite observations is accelerating progress on cross-scale understanding of the status and trends of changes in land use and land cover. For example, National Land-Cover Data and associated derivative products are being produced that elucidate temporal and spatial patterns of recent changes in the U.S. landscape (113–115). The U.S. Geological Survey is compiling an overview of the land-use history of North America that is available at http://bioloby.usgs.gov/luhna/index.html. An especially important component of land-use and land-cover change in the United States is suburban and exurban development (116).

Climate variability is another strong influence on carbon uptake patterns that must be taken into account when establishing additionality and separation. The atmospheric growth rate of CO_2 varies from year to year by as much as 100%, which indicates strong variability in terrestrial carbon sinks, with weaker variability in ocean sinks (45, 117–127) (Figure 1). Explanations for the variability in terrestrial sinks are still being explored, but causes are likely due to factors associated with large-scale climate variability such as the El Niño/Southern Oscillation, droughts, fires, and insect outbreaks (127–129). Interannual variability of carbon fluxes also varies between regions. During certain periods of time, carbon sinks can be much stronger in a given region than in other regions, and trends in uptake do not always correlate in time between regions (130). Trends in terrestrial carbon uptake can also vary over decades, possibly due to climate or long-term changes in land use on the decadal scale, and effects may be separated from initial causes for many years (time lags) (59, 122, 126, 129). Thus, carbon exchange can vary significantly from year to year regardless of deliberate human actions engendered by policy, and measurement and crediting systems must take this into account.

Natural disturbance can also affect uptake rates of CO_2 in terrestrial ecosystems. In general, natural disturbances lead to short-term release of CO_2 from the terrestrial biosphere to the atmosphere, usually as a result of oxidation of organic matter through combustion or rapid decomposition (131). As ecosystems recover from disturbances over the long term, they will take up CO_2 from the atmosphere. Examples of natural disturbance include forest fires, insect infestation, and wind-driven blow-over events. These processes may be local in scale, but their frequencies may be linked to larger scale climate and lead to greater impact on the regional or global carbon balance. Disturbance processes are also often linked to each other. For example, the water table in Indonesia had been artificially lowered in forested lands as part of forest and agricultural management, making the 1998 El Niño-related fires much worse than they might otherwise have been (132, 133). Forests weakened by insect infestations are more susceptible to fire, and carbon release can be higher from those forests subject to this linked effect (134). In addition, droughts brought on in tropical regions by climate fluctuations such as El Niño can lead to increased susceptibility to fire and multiple regions can be affected (133, 135). Fires in the boreal region also may account for a large percentage of carbon release to the atmosphere (136). Fire suppression policies in the United States and elsewhere have likely contributed to the trend of an increasing forest carbon sink, although these stocks are also now more vulnerable to extreme conflagrations (137).

Other processes thought to influence the uptake of carbon in terrestrial systems at the present time are CO_2 fertilization, nitrogen deposition, and climate change itself. These processes would need to be accounted for if separation is a requirement for policy frameworks. Increased CO_2 can lead to increased plant growth and therefore carbon uptake, but the effect is thought to be minor compared with the effects of land-use change (109, 138, 139). Nitrogen deposition, and consequent potential stimulation of growth through increased nutrients, is also thought to only play a small role (110, 139). Changes in temperature and precipitation patterns can affect carbon storage, although vegetation responses to these patterns are not uniform and vary with geographic region and vegetation type (129). For example, a recent study showed a trend of increasing terrestrial carbon uptake due to increased precipitation over North America (140).

Models can be quite useful in simulating the effects of different mechanisms on carbon storage. For example, Houghton and colleagues (124) estimated contributions to the U.S. carbon budget from land-use change, such as cultivation and abandonment of agricultural lands, woody encroachment, fuel wood harvests, wildfire, fire suppression, and other disturbances. Houghton has also estimated global fluxes of carbon to the atmosphere by land-use change (124). Schimel and colleagues (138), in contrast, estimated carbon uptake in the coterminous United States from climate and CO_2 fertilization effects. Both of these approaches rely on models to estimate the extent of processes over the potential land area affected. It now appears that much of the documented forest carbon sink in the coterminous United States is due to regrowth on agricultural land and in areas harvested 20–100 years ago and forest management practices (plantations and fire suppression) that increase carbon stocks, rather than climate enhancement or CO_2 fertilization (53, 110, 138).

If additionality and separation are key components of future policy measures, cooperation with the scientific community will be essential to establish what types of parameters are feasibly measured or modeled. As reviewed by Houghton (139), all of the methods used to estimate terrestrial sinks have weaknesses, whether in their inability to attribute mechanisms, poor geographic resolution, or lack of precision. Therefore, it is extremely difficult to definitively separate the amount of carbon stored by deliberate mechanisms versus indirect ones, except in certain cases. Actions undertaken to store carbon are likely more easily monitored, such as changes in tillage practices, management of forests, and pumping carbon to the deep ocean or to deep aquifers. If further research shows that indirect effects on land are minor compared with land-use change and land management, as Caspersen et al. (110) suggest, separation may be easier to demonstrate (139). Furthermore, the concept of additionality can potentially result in perverse incentives if it discourages land managers from taking positive land management actions in the near term in the hope of gaining credit for those same steps at a future time (141).

Permanence

Because carbon is exchanged between terrestrial ecosystems, the atmosphere, and the ocean, carbon stored in one reservoir may not be retained in that reservoir indefinitely. Projects that aim to deliberately sequester carbon must therefore grapple with the issue of how long carbon can stay sequestered.

In land-use change projects, for example, any carbon stored in biomass or soil through deliberate sequestration practices could be lost to the atmosphere if that land is then disturbed through harvest of vegetation, fire, or other human or natural events. For example, a forest planted as a carbon mitigation strategy will only keep carbon out of the atmosphere as long as it is standing, and new forests must be continually planted over time to maintain carbon sequestration rates. Some have argued that permanence of land-use sequestration is difficult and perhaps unnecessary to gain benefit towards mitigation of CO_2 (24). This argument suggests that there is value to delaying emissions, thereby allowing policy and technological options to develop a more permanent solution. Policy analysts have devised several options for dealing with the issue of permanence in a policy framework; these include delayed credits, carbon insurance, land reserves, and expiring credits (142). These less permanent approaches take into account the likelihood of long-term stewardship of land for carbon sequestration purposes and the sovereignty of developing nations, which may find it unpalatable to commit to uses of their land in perpetuity (143).

Ocean sequestration faces similar issues of permanence, albeit at different timescales than terrestrial sequestration. Ocean water masses are constantly in motion. Water parcels containing higher amounts of carbon from direct injection or stimulated biomass production will not remain stationary. Even though the water parcels begin at great depth, for climate purposes it is important to know when that parcel of water will next contact the atmosphere. The average mixing time of the ocean is 1000 years (144), but some parcels of water will emerge to the surface much sooner and some later. When a parcel of water with a higher carbon concentration contacts the atmosphere, it will equilibrate, thereby releasing the stored carbon back to the atmosphere. The placement of injection sites will help to determine how long injected carbon remains sequestered. Modeling studies are useful in this regard, but there are still uncertainties in mesoscale dynamics that should be taken into account. For ocean fertilization, much work still needs to be done to determine where the excess CO_2 gets remineralized (i.e., at what depth) and when that water with enhanced CO_2 might next contact the atmosphere (31).

Geologic disposal is regarded as perhaps the most permanent option currently under consideration (32). For mineralization approaches on the surface, the measurement systems must be in place to assure that the storage or use of the mineralized product does not result in the eventual venting of the CO_2 to the atmosphere. For CO_2 that is kept in its gaseous or liquid form in underground geologic reservoirs, measurement systems must monitor and assure the integrity of the confining geological structures. Because the integrity of these structures will be important during the injection of the gas and to assure ongoing integrity of the reservoir, separate measurement systems may need to be developed in the near and long term.

Unique monitoring needs are required to sustain projects designed to be permanent. A system must be designed with a long-term strategy in mind. Issues that are common to long-term observational systems include preserving calibration between technique transitions, long-term support for measurements, and archiving and accessibility of data (108). In addition, measurements must be transparent to others, with a commonly accepted protocol, to enable long-term verification of carbon sequestration. Finally, carbon sequestration projects must be monitored for the long term to document potential unexpected changes in carbon storage or release. If, for example, under climate change ecosystems experience warmer and wetter conditions, rates of photosynthesis, respiration, and decomposition may change and result in undetermined changes in carbon exchange with the atmosphere. The direction of these changes is highly uncertain under current understanding. However, all mechanisms currently used to explain the present terrestrial carbon sink predict a saturation of the terrestrial sink sometime during the twenty-first century (2). Ocean circulation is also predicted to change as a result of climate change. Carbon sinks created deliberately under carbon management may or may not saturate; this depends on the mechanism used to create the sink.

Environmental Effects and Linkages

If manipulation of the natural carbon cycle is being considered as an option for carbon management, it is imperative to understand and monitor its impacts on other components of the earth system. The area of carbon sequestration is fairly new, and long-term studies are not yet available on environmental effects and potential unintended consequences. There have been some suggestions of potential benefits as well as negative impacts. The structure of food webs, nutrient cycles, biodiversity, indigenous livelihoods, nutritional content of food, ecosystem health, water quality, air quality, and vulnerability to disease all may potentially be affected by artificial manipulation of the carbon cycle. Public acceptance of carbon sequestration will likely depend on a thorough understanding of the environmental consequences.

Certain agricultural practices, such as reduced tillage, have the potential to be win-win situations for both carbon sequestration and soil quality, because they reduce surface water runoff, wind erosion, and enhancing wildlife habitat (76, 145–147). Similarly, restoration of degraded lands or use of degraded lands for carbon sequestration projects may have positive overall benefits. Reduced tillage may also have downsides with respect to environmental objectives, such as increased need for pesticide use (147). Emissions of other GHGs must be taken into account when estimating the climate effectiveness of tillage practices and other carbon sequestration options. For example, no-till systems do have a potential for slightly higher N_2O emissions than other systems, although no-till systems may have the lowest overall greenhouse warming potential (148). It has also been suggested that increasing forest cover may decrease albedo and result in a warming (149).

Potential cautions for carbon sequestration as a management option have been raised for environmental reasons, in particular biodiversity and ecosystem effects. Climate policy framing has explicitly stated that environmental sustainability is to be considered in climate mitigation solutions. In some cases, biodiversity can be improved through careful management of degraded lands (150). Caution must be exercised, however, that the maximization of carbon sequestration does not result in reduction of biodiversity, whether by expanding low diversity, mono-culture crops or by converting low biomass regions with high diversity, such as grasslands, to high biomass regions with low diversity, such as plantation forests.

Parallel cautions have been raised in the area of ocean sequestration. Concerns have been raised that large-scale manipulation of the ocean to store carbon through ocean fertilization may change ocean food webs, nutrient availability, and patterns of primary productivity (30). Research on environmental effects of ocean sequestration is only just beginning, and so unintended consequences on ocean systems are unknown at this time (25, 26). Some have suggested that the precautionary principle should be exercised in the management of the ocean for human needs, although this principle has not yet been extended to ocean sequestration (151). Use of the ocean poses additional legal and ethical issues, because there are vast regions that are not controlled by any state, and water masses move around the globe over time (152). This suggests that actions taken in one region of the ocean may well have impacts in other regions at later times.

It is clear that because the carbon cycle is linked to many other aspects of the earth system and human activity, decisions to manage the carbon cycle cannot be made in isolation. Carbon cycle information must therefore be considered as only one component of a broader, integrated discussion of carbon management in society.

Predicting Future Atmospheric CO_2 Levels

Some formulations of carbon policy depend partly on knowing what future levels of CO_2 might be under different scenarios. The ultimate goal of the UNFCCC, for example, is to “stabiliz[e] greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (4; Article 2). What constitutes "dangerous anthropogenic interference" is still being defined (153). Equally important to the success of these policy formulations is the ability to anticipate future atmospheric CO_2 concentrations. There is considerable uncertainty in discerning the natural and human-driven mechanisms that might control future CO_2 levels, and thus gauging the potential trajectory of atmospheric CO_2 is quite difficult. Knowledge of mechanisms not only informs how much carbon will be removed from the atmosphere but also provides insight into the potential success of carbon sequestration or emission reduction strategies. Surprises in the carbon cycle also have the potential to rapidly change carbon cycle exchange between the land, ocean, and atmosphere and therefore should be taken into account when considering policy options.

The methods used to generate scenarios of future CO_2 concentrations in the IPCC thus far have assumed a very simplistic concept of the natural carbon cycle and its interactions with human activity. CO_2 increases are projected without coupling between earth system responses and climate change. Climate model projections are done using even simpler conceptions of the carbon cycle in which, typically, monotonic concentration increases are used to project climate change (2). This simplification likely underestimates the sensitivity of the carbon cycle to climate change and human activity. The inclusion of nonlinear processes and feedbacks in models of the carbon cycle and/or climate system is a significant mathematical challenge. Yet, geological and historical records document phenomena in both natural and social systems that cannot be reproduced by existing models (154). Recent experiments have coupled active carbon cycle models to general circulation models and simulated impressive nonlinear feedbacks between the carbon cycle and climate. An experiment using the Hadley Centre model simulated a large pulse of CO_2 entering the atmosphere in the mid-twenty-first century, due to a dieback of tropical forests, but a similar simulation using a different model showed a much smaller effect (155, 156).

Currently, half of the CO_2 emitted by fossil fuel combustion and land-use change is taken up by the ocean and land (see Figure 1). It is unknown whether these mechanisms will continue to operate in the future at the same level. The types of mechanisms parameterized in models have a large impact on the sensitivity of the modeled future carbon cycle to climate change. For example, if the mechanism driving the current terrestrial carbon sink is recovery of forests from previous land use, it will have a different implication for future CO_2 levels than if the mechanism is CO_2 fertilization (157).

Climate model projections for this century suggest an ocean with warmer, more stratified surface waters and slower thermohaline circulation. All of this will contribute to reduced anthropogenic carbon uptake from the atmosphere, with the Southern Ocean being particularly sensitive. The response and feedbacks of ocean biology to climate and other global change perturbations is potentially large but not well understood in detail (158–160). In addition to the changes in ocean physics already mentioned, environmental factors such as aeolian deposition of trace metals via dust, cloud cover and solar and UV irradiance, riverine and atmospheric nutrient deposition to the coastal ocean, and ocean carbonate chemistry are all sensitive to global change. Another carbon cycle surprise may await under the sea floor: geological data suggest that stocks of carbon in methane clathrates might have been released episodically in response to past climate warming (161, 162).

Emissions due to fossil fuel consumption are projected to play the dominant role in controlling atmospheric CO_2 in the twenty-first century (2). Indeed, "carbon cycle projections are more sensitive to uncertainties about carbon emissions than to uncertainties about the natural science of the carbon cycle" (163). Although several plausible scenarios have been developed as part of the IPCC process, predicting the evolution of society's relationship with energy and consumption of fossil fuel is highly uncertain. Increasing global anthropogenic CO_2 emissions throughout the twentieth century largely reflect the unprecedented rise of fossil fuel energy use by industrial nations (4). Historical variations in CO_2 emissions have been significantly influenced by political and institutional factors that changed short-term market behavior and long-term fuel choices (4). Projections of long-term future demand for fossil fuels have been unreliable (164). Econometric models typically rely on extrapolations from past experience and cannot anticipate surprises like the socially and politically driven oil price variations experienced over the past three decades (165).

Several examples of social phenomena that are poorly characterized in most emission scenarios are: (*a*) changes in the structure of production and work, (*b*) substitution of services for products, (*c*) changes in household composition and lifestyles, and (*d*) changes in nonenvironmental policies (166). The roles of population dynamics and technology as factors in CO_2 emissions have received the most attention to date. The dramatic reductions in fertility and the aging of populations taking place in many countries of the world could influence consumption patterns, political choices related to environmental issues, and the potential for the diffusion of innovative technologies. The impact of widespread adoption of information technology in business and society on CO_2 emissions is a recognized, albeit controversial, issue and an important research topic (167).

Urban planning and design has important implications for CO_2 emissions. For example, urban sprawl is closely associated with the growth in CO_2 emissions associated with the transportation sector. Cross-national studies have documented an inverse correlation between gasoline consumption and urban population densities. The DOE has supported the development of planning support materials that encourage mitigation of CO_2 emissions as a design objective for land-use planning and urban infrastructure development (168). Energy use is also influenced by a variety of other lifestyle characteristics (166). An enhanced program of research on how social, cultural, economic, and political factors influence consumer consumption patterns and emission dynamics will be crucial to improvements in scenario development and forecast methodologies for future carbon emissions.

There is significant uncertainty about the future trajectory of CO_2 levels in the atmosphere, in both the natural and human factors and policy responses that might be adopted. If policy measures are formulated to aim for a specific level of CO_2 in the atmosphere, it will be important to know how uncertain future predictions are and where knowledge on mechanisms and interactions might make a difference to policy choices.

AN EXAMPLE OF CARBON MANAGEMENT POLICY—LAND USE, LAND-USE CHANGE, AND FORESTRY IN THE KYOTO PROTOCOL

Land Use, Land-Use Change, and Forestry Provisions

The key provisions within the Marrakesh Accords that define the categories and amounts allowed for Land Use, Land-Use Change, and Forestry (LULUCF) activities include four main elements (12):

- A set of principles to govern LULUCF activities
- A list of eligible LULUCF activities
- Common definitions necessary to define and employ the allowed LULUCF activities
- Methodological rules and guidelines that include a system of caps limiting the carbon credits available via LULUCF activities.

The principles reflect concerns that the use of LULUCF activities should not undermine the environmental integrity of the Protocol. They include, for example, the need for sound science and consistent methodologies, as well as the importance of conserving biodiversity. They also specify that naturally-occurring carbon uptake, which includes uptake as a consequence of indirect anthropogenic effects, should be excluded from the carbon accounting system and that any subsequent release of GHGs (both CO_2 and non-CO_2 such as methane, N_2O) must be promptly counted. The Subsidiary Body for Scientific and Technical Advice is the primarily conduit for official communication, such as scientific assessments and analyses of specific issues between the national negotiating bodies and the scientific community.

The list of eligible LULUCF activities is: afforestation, deforestation, reforestation, revegetation, forest management, cropland management, and grazing land management. Definitions for each of these allowed sequestration activities are provided in the Accords in addition to a single definition of a “forest.” The forest definition allows for flexibility in terms of the minimum area of land considered, percent cover, and height at maturity. However, once chosen, a party must employ that definition for all LULUCF accounting in the first commitment period (2008 to 2012).

The amount of credit one can gain from the forest-related categories (afforestation, reforestation, deforestation, and forest management) is capped at an amount specified for those parties working under a GHG reduction target. Each party has some flexibility in how they use the forest-related cap through joint activities with other parties, through domestic action, or as an offset to domestic deforestation activities. The amount of LULUCF activity in the cropland management, grazing land management, and revegetation categories are unbounded.

For example, consider the emissions reduction target and a sequestration estimate for Canada. Canada has agreed to lower their emissions 6% below their base year amount of 167 Mt C eq/year (11). This implies that the average Canadian emissions during the first commitment period must come to roughly 157 Mt C eq/year or a reduction of about 10 Mt C eq/year. Emission projections in light of recent trends suggest that the business as usual Canadian emissions in the year 2010 would rise to roughly 197 Mt C eq/year. This suggests that were Canada to continue recent trends, their necessary reduction would be, at the most, 40 Mt C eq/year. Of course, the actual reduction will depend on their future emissions trajectory.

Estimates of Canadian sequestration potential combined with the negotiated caps for LULUCF activities suggest that Canada could accrue roughly 14 Mt C eq/year of credit through these mechanisms (K. Gurney, unpublished information). Relative to their negotiated target, these activities have the potential to meet or exceed their reduction. Relative to their likely emissions trajectory, these activities could make a substantial contribution.

This example highlights the first of a few challenges facing both the scientific and policy communities. Assuming one wanted to measure sequestration with an error of 50%, this would imply measurements that were accurate to less than 0.01 Gt C eq/year. This level of accuracy is well outside the anticipated capability of most current carbon accounting methods at the national or regional scale. Such accuracy is possible at the plot level, but the current disagreement between the various methods when aggregating to regional scales remains a barrier to confidence.

The example also emphasizes the need to both account for the politically eligible carbon credits and the complete carbon exchange. Separation can only be attempted at the plot or local scale, but consistency with regional scale estimates, where separation is not possible, is essential to build confidence in accounting estimates.

A further accounting distinction between the crop, grazing, and revegetation activities versus the forest-related activities is the time at which accounting is initiated (setting a baseline). For crop, grazing, and revegetation activities, the carbon credit or debit measured is the difference between total net emissions in the first commitment period (integral of 2008 to 2012) minus five times the net emissions in the base year (1990 for most parties). For forest-related activities, the carbon credit or debit is the difference in carbon stock between the end and beginning of the first commitment period, provided the activity for which one is accounting was begun on or after January 1, 1990.

A few other important details further guide the LULUCF accounting. First, once a land parcel is accounted for, it must remain in the accounting system indefinitely to address the issue of permanence. Accounting on a given land area begins at the onset of the activity or the beginning of the commitment period, whichever comes last. Finally, it is important to note in the context of measurement requirements and capabilities that the LULUCF accounting system specified in the Marrakesh Accords is not necessarily going to be utilized in future commitment periods. Given the ad hoc nature of the capped amounts on forest-related activities, future accounting may be substantially different.

The Marrakesh Accords represent significant progress in elaborating how and which LULUCF activities are to be included in the national carbon accounting under the Kyoto Protocol. However, difficult issues remain; many of which intersect current measurement and knowledge frontiers facing carbon cycle science. The challenge is to translate the various spatial and temporal scales represented in the scientific community's investigation of the carbon cycle into meaningful boundaries for specific LULUCF activities as defined above.

CONCLUSIONS

Knowledge of the carbon cycle has direct relevance to the success of carbon management policy as currently framed (169). The functioning of the carbon cycle must, therefore, be taken into account when designing and implementing policy to achieve the goal of reducing CO_2 and other GHGs to mitigate climate change. However, it has not yet been shown that the scientific process in carbon cycle research takes into account the specific needs of policy makers. As in other arenas where science is relevant to policy, some portion of the scientific portfolio must be posed in a framework that is policy relevant. Lessons from past interactions between science and policy have demonstrated that in the absence of a clearly established process with frequent feedbacks, scientific results may not be usable to answer the policy questions for which they are needed (170).

Measurement tools for carbon management are sophisticated but tend to be aimed at scientific objectives rather than policy implementation. For example, the atmospheric observing network has been designed to quantify global trends with precision; flux networks are focused on quantifying differences between different eco-climatic conditions, and inventory plots are designed to monitor economic potential and forest health. Linking these scale-specific approaches requires new, integrative experimental designs and analysis models. Costs of monitoring are currently high, because most techniques exist mainly in the research realm and do not enjoy economies of scale. Measurement and modeling uncertainties still limit progress in most components of the carbon cycle.

There may be a significant scale mismatch between currently available direct measurements and the needs of managers and policy makers. Direct measurements provide the strongest constraints at global to continental scales (atmospheric network), and at the plot scale (flux and process studies). Carbon flux estimates at intermediate scales (landscapes to the national scale) today must be converted and extrapolated using inventory methods and emission models. Many of the needs of decision makers for information on carbon management may fall within this intermediate scale. Systematic efforts to improve direct regional-scale measurement techniques, such as through tall tower and aircraft flux techniques, and also to evaluate sample designs, measurement approaches, and the validation of extrapolation techniques would aid in bridging this gap. Focused research efforts to understand the needs of decision makers and possible uses of carbon cycle science are also needed. One of the initial areas of focus may be to understand the scaling needs of decision makers at both the national and regional level. Attempts to upscale and downscale information may then be able to inform policy needs and aid in formulating realistic prescriptions.

Options to mitigate increasing CO_2 concentrations in the atmosphere are varied and wide-ranging. Those options that involve alteration of natural and managed ecosystems on land, or the ocean system, need to carefully consider the functioning of the carbon cycle in the coupled earth system, which includes human societies. Observed features of the carbon cycle, such as vulnerability of carbon stocks to exchange with other reservoirs, interannual and decadal variability, economic and environmental controls, and potential feedbacks with climate change, all affect the success of a carbon sequestration strategy.

Decisions on how to manage carbon will likely always be made to some degree under uncertainty. Even if the scientific uncertainty is reduced, the intended and unintended consequences will still be somewhat unpredictable. Research and understanding of decision making under uncertainty and decision making involving multiple stresses are critical to improving outcomes of decisions made to manage carbon in the environment.

This review focused on the connection between available carbon cycle science and implied needs from carbon sequestration principles. However, some of the greatest opportunities for mitigation of atmospheric CO_2 may lie in tackling the energy intensity and carbon intensity portions of the equation. Over the course of the twenty-first century, fossil fuel emissions are expected to be the dominant cause of increases in the atmospheric concentration of CO_2. Although major uncertainties exist in the functioning of the terrestrial and oceanic sinks, especially in the area of potential feedbacks, even these large uncertainties are smaller than the uncertainty of the future trajectory of fossil fuel and biomass burning (2). The human dimensions of the carbon cycle (i.e., energy supply and demand, consumption patterns, population growth, future development path of human societies, ability and willingness to adapt to change, and tolerance for risk) are extraordinarily difficult to predict.

Policy for carbon management must therefore be informed by carbon cycle science, and vice versa. Each endeavor has much to learn from the other. The challenge for this generation of policy negotiators and carbon cycle scientists is to forge an environment of communication in order to best implement rational policy that reaches the desired outcome without unacceptable negative consequences.

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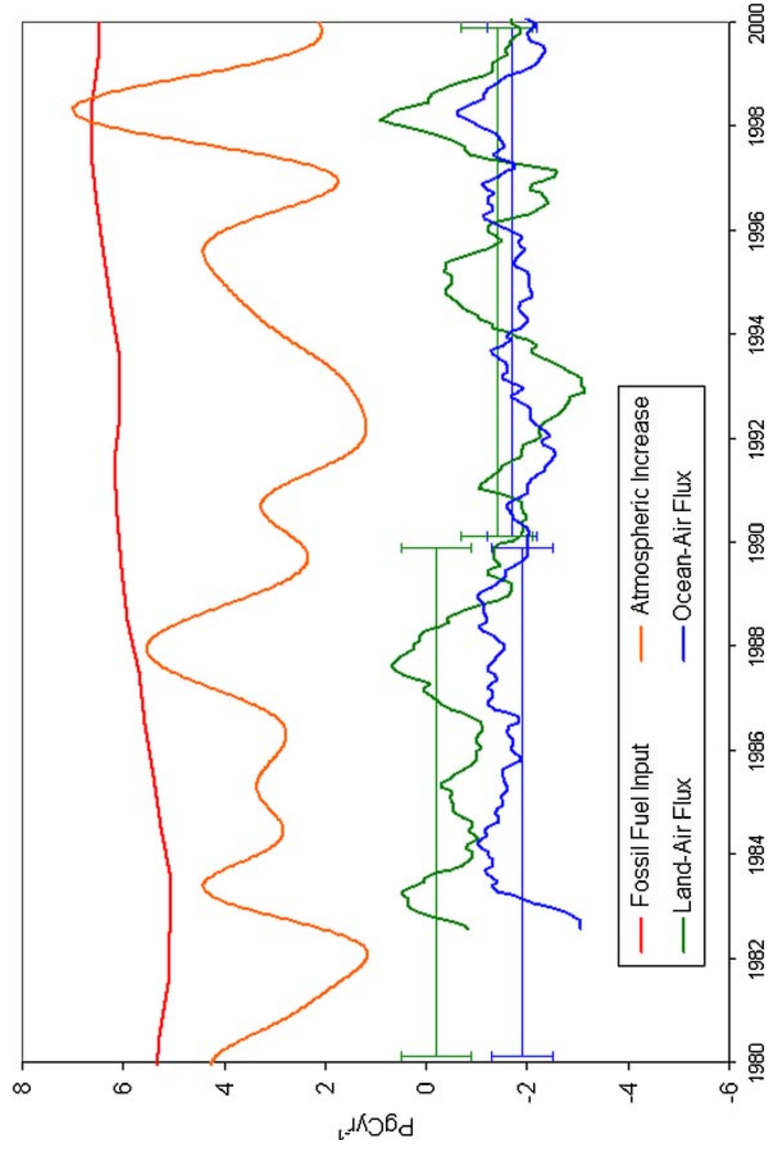

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Figure 1 Interannual variations in global carbon fluxes for the past two decades. The upper red curve represents annual CO_2 inputs to the atmosphere from fossil-fuel combustion (91). The more variable orange curve represents the globally averaged atmospheric CO_2 growth rate (171) after deseasonalizing and applying a 1-year running mean. The difference between these two curves represents the amount of CO_2 taken up by the land and ocean. The lower two curves are an estimate of the partitioning between these two fluxes, based on atmospheric ^{13}C and O_2 measurements from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [update to (45) provided by R. Francey, personal communication]. The green curve represents CO_2 fluxes from the terrestrial biosphere to the air, and the blue curve represents CO_2 fluxes from the ocean to the air. The long-term average net flux information comes from O_2 measurements; the shorter-term variations come from ^{13}C measurements. Graphically, the sum of the red, blue, and green curves should approximately total the orange curve. The decadal average land and ocean fluxes from the IPCC budget, also calculated from atmospheric O_2 measurements, are indicated by the green and blue bars.