18 Carbon Cycle Science in Support of Decision Making

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KEY FINDINGS

1. Co-production of knowledge via engagement and collaboration between stakeholder communities and scientific communities can improve the usefulness of scientific results by decision makers (*high confidence*).
2. Integrating data on human drivers of the carbon cycle into Earth system and ecosystem models improves representation of carbon-climate feedbacks and increases the usefulness of model output to decision makers (*high confidence*).
3. Attribution, accounting, and projections of carbon cycle fluxes increase the usefulness of carbon cycle science for decision-making purposes (*very high confidence*).
4. Developing stronger linkages among research disciplines for Earth system processes, carbon management, and carbon prediction, with a focus on consistent and scalable datasets as model inputs, will improve joint representation of natural and managed systems needed for decision making (*high confidence*).

18.1 Introduction

Recent decades have seen continually increased interest in how best to reduce net carbon emissions, including maintaining or augmenting natural and managed carbon stocks (Griscom et al., 2017) and decreasing anthropogenic carbon emissions. Decisions about carbon management extend from future energy production and technology planning to designs for urban infrastructure and refurbishment; transportation; and agriculture, forest, and natural resource management. Over this same time period, scientists have conducted extensive basic and applied research on biogeochemical cycles, land-cover change, watershed to Earth System Modeling, climate change, and energy efficiency, all of which inform the understanding of the efficacy of various carbon management options (CCSP 2007). However, the information needs of decision makers differ from the objectives that drive basic science to understand natural carbon cycling. Explicitly identifying the information that various decision makers will use, including the form in which they need it, is critical for taking carbon cycle science from laboratory to management action. While much progress has been made in understanding individual components of both fundamental and applied science contributing to decision-making frameworks (see Figure 18.1, p. 730), additional work is needed to connect these components to address existing research and policy questions.

Methods for connecting and integrating basic and applied carbon cycle research take a number of forms. For example, researchers can 1) simplify complex models to provide mean estimates for given activities (e.g., a complex nitrogen cycle model providing mean and uncertainty estimates for nitrous oxide [N_2O] emissions); 2) interpret biogeochemical model results to estimate net carbon flux associated with particular activities (e.g., natural disturbance contributions to global carbon fluxes versus net emissions associated with the management of natural disturbances); or 3) aggregate and analyze scientific data in a different manner to address specific questions (e.g., national emissions estimates versus attribution of net emissions associated with particular activities). These approaches to connect basic science and decision making have most often been employed post hoc, harvesting results from foundational research that already has been conducted to inform decisions, rather than designing and organizing large research programs around user-defined information needs (Lemos and Morehouse 2005). Post hoc methods often are used to synthesize, and sometimes simplify, fundamental research findings for common applications and

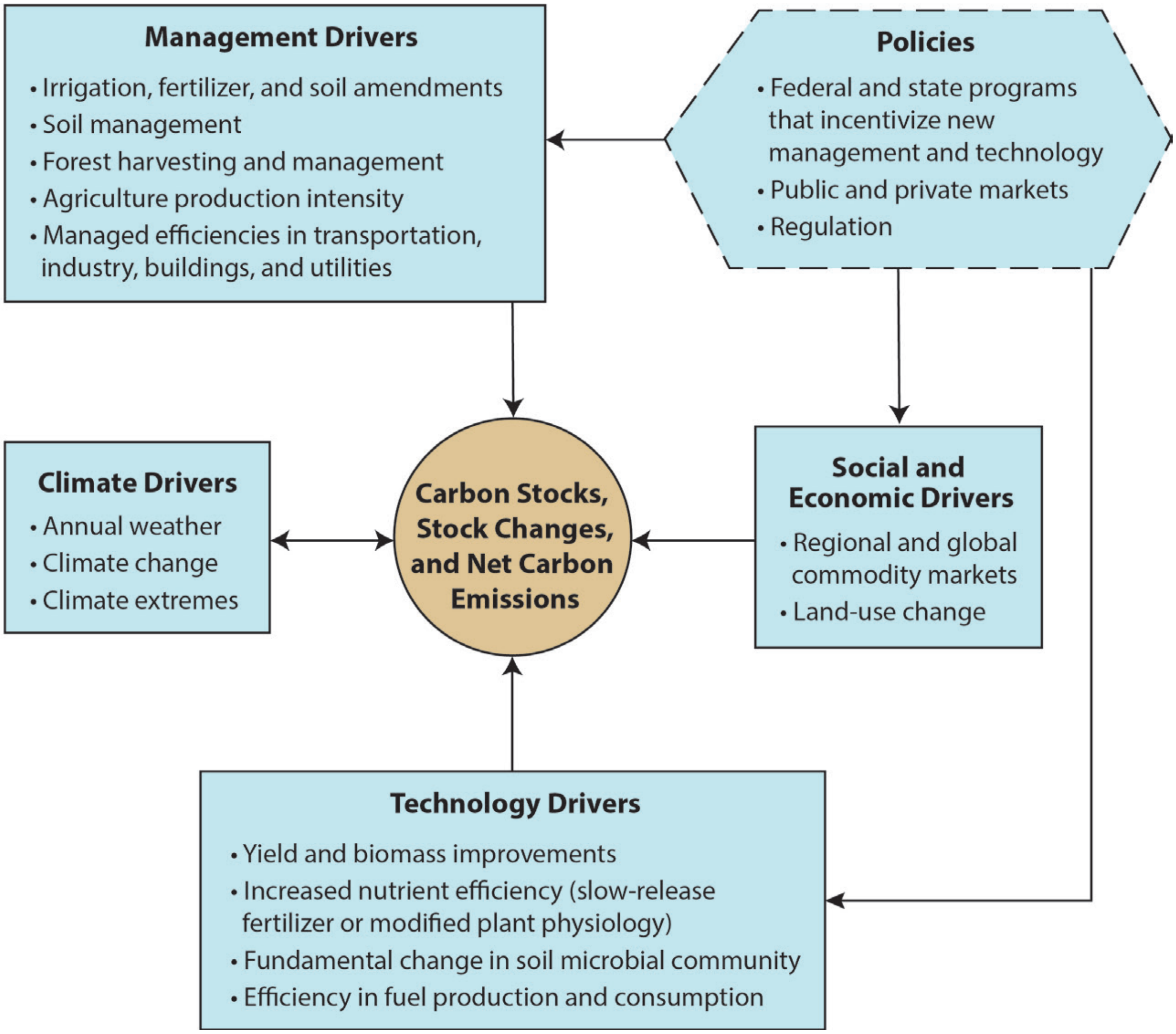

Figure 18.1. Primary Drivers of Carbon Stocks and Emissions. Carbon and carbon dioxide (CO_2) estimates can be generated using observations, models of differing complexity, or both. To understand and estimate future carbon stocks and emissions, drivers of carbon stock changes and carbon emissions must be considered and represented. This schematic illustrates examples of components needed to represent carbon stock changes prior to addressing policy drivers.

decision making, including in the Intergovernmental Panel on Climate Change's (IPCC) *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and the U.S. Department of Agriculture's (USDA) *Methods for Entity-Scale Inventory* (USDA 2014).

While organizations make decisions with whatever information they have available, multiple, competing interests are generally at play in setting priorities, so the quality and credibility of information can influence decisions about carbon management. Some decisions about carbon cycle management require only coarse-level estimates or discipline-specific knowledge, while others benefit from more nuanced analysis or multidisciplinary research. Multidisciplinary research is particularly

needed to inform economy-wide carbon management targets (e.g., to maintain atmospheric carbon dioxide [CO_2] within a safe operating space for humanity; Rockstrom et al., 2009) and to understand links among sectors (e.g., soil carbon in the land sector associated with biofuel production in the energy sector). Collaborations between scientists and practitioners increase the chances that information intended to inform decisions is actually needed and delivered in a highly useful manner. For decisions affecting multiple sectors, collaborations among scientists of many disciplines tend to produce knowledge that is more credible and practical in the eyes of multiple stakeholders compared to knowledge produced in more siloed environments (Weaver et al., 2014). Although collaborations have increased (Mooney et al., 2013), there remain lost opportunities for effective carbon cycle management that could be captured via more integration.

Federal, state, and local policymakers; company executives; energy managers; urban designers; natural resource managers; families; and individuals make short- and long-term decisions that can influence the carbon cycle. These entities require adequate information from science-based analyses to inform their choices and to understand how management, technologies, or behavioral decisions can affect net carbon emissions or carbon stock changes. Meanwhile, scientists are developing more sophisticated monitoring, data interpretation, and modeling methods that could be relevant to these decision makers, providing more refined understanding. An important but challenging part of carbon cycle science is ensuring that scientists have sufficient understanding of decision makers' needs to produce information that actually is usable by decision makers and that funding organizations place sufficient priority on actionable science. To facilitate strategic, effective use of carbon cycle science in carbon management, as well as to provide insights about the opportunities and constraints that shape the availability of user-driven carbon cycle science now and in the future, this chapter provides information on national and international needs for carbon cycle information, current status of research to inform carbon cycle and greenhouse gas (GHG) management, and future needs. It also focuses on the sectors of agriculture, forestry, and other land uses (AFOLU) and discusses energy and associated carbon sources in the context of integrated carbon cycle systems.

18.2 User Demand for Carbon Cycle Science

Diverse institutions demand information about the carbon cycle that enables them to meet their particular objectives and interests. For example, stakeholders wishing to prioritize actions for reducing emissions need to know the distribution among sectors (e.g., transportation, infrastructure, buildings, power generation, and land management), as well as the technical, economic, and behavioral potential for reducing these emissions in different sectors and locations. Illustrative questions that stakeholders including decision makers ask include:

1. How much can emissions be reduced from transportation versus power generation versus building sectors, and at what costs?
2. What actions are consumers likely to take, and which kinds of technologies (e.g., smart meters) and campaigns (e.g., foot-in-the-door models) are likely to result in behavioral change (Scott 1977; Mogles et al., 2017)?
3. How much methane (CH_4) leaks into the atmosphere from natural gas wells and pipelines, and how does that leakage influence the attractiveness of natural gas as a "bridge" fuel (Miller et al., 2013)?
4. How can carbon be managed from procurement through production and inventory management (Benjaafar et al., 2013)?
5. How fast will different agricultural practices build soil carbon or reduce CH_4 emissions from cattle, and how will these rates vary geographically (Olander et al., 2014)?

6. How will the consequences of different sets of agricultural and forest management practices on a single tract of land add up?

18.2.1 Variety in Types of Users and Their Needs

Users of carbon cycle science to reduce emissions include 1) carbon registries and protocol developers (Gonzalez 2014; Climate Action Reserve 2018), 2) businesses that have made voluntary commitments to reducing GHG emissions from their supply chains (Christopher 2011; Tseng and Hung 2014; CISCO 2017; Walmart 2017), 3) utilities developing strategies for reducing their GHG footprints (Consolidated Edison 2016), 4) state and municipal governments committed to reducing GHG emissions in their public and private sectors (Carbon Neutral Cities Alliance 2018; Elizondo et al., 2017), and 5) non-governmental organizations and research institutes producing roadmaps to achieve different atmospheric CO_2 targets (UCS 2009). In addition, national governments and international organizations rely on carbon cycle science combined with policy and management practices to identify the primary socioeconomic drivers of carbon emissions (e.g., Fricko et al., 2017; Rogelj et al., 2018) and to understand how well science-based recommendations for carbon budgets align with global commitments for carbon management (Fricko et al., 2017; Burke et al., 2018; Rogelj et al., 2018). These users vary in the types of decisions they make about carbon cycle management; their capacity to support research or engage with research institutions; their maturity in defining their information needs; and their potential to impact regional, national, or global carbon pools. Mapping these capacities with an eye toward producing information in formats that align with standard business practices would be a valuable contribution for social science research.

18.2.2 Institutional Arrangements for Meeting User Demand

Despite having identified numerous users of carbon cycle science and the deep knowledgebase summarized within this report, tailoring and synthesizing carbon cycle science to make it truly useful to specific institutions continue to present a challenge. In carbon management, as in numerous other realms of decision making that benefit from technical input, the traditional science supply paradigm for producing usable or socially robust knowledge (i.e., provide the research results, and somebody will eventually use them) remains problematic and usually ineffective. The disconnect between knowledge production and consumption is particularly apparent when applying cross-disciplinary research to societies (Dilling 2007). In contrast, various initiatives have demonstrated that beginning research by identifying user information demands, subsequently working intensively with users to understand those needs in detail, ultimately leads to science products that are actually used (Zell et al., 2012). User-driven science, however, thrives when institutions shift their priorities to meet user needs and set reward structures accordingly.

Co-Production of Knowledge

The hybrid approach that has enabled user demand to take advantage of carbon cycle science within the confines of existing institutional structures has been referred to as the co-production of knowledge by scientists and the user community (Cash et al., 2006; Dilling and Lemos 2011). This coordination entails establishing a shared vision that a decision-making process requires, and ensuring that the decision makers receive information in a usable format and at an appropriate time (Brown and Escobar 2013). In addition to engaging stakeholders, co-production of knowledge also emphasizes collaboration across scientific disciplines. Although cross-disciplinary research has received considerable discussion over the past few decades, institutional cultures within a number of large organizations that have especially robust research capacity continue to impede collaborations in the absence of strong direction and leadership to do otherwise (Mooney et al., 2013; Weaver et al., 2014). Overcoming barriers between the sciences (see McGreavy et al., 2015) remains a challenge to producing information that effectively influences decision making.

Examples of co-production and user-driven research in which carbon cycle science has informed management action include development of the Southeast Florida Regional Climate Change Compact (Georgetown Climate Center 2017), the Maryland Carbon Monitoring System (University of Maryland 2016), and methods for reducing emissions from deforestation and forest degradation plus (REDD+; see Section 18.3.2, p. 736) accounting in Mexico (Birdsey et al., 2013).

Boundary Organizations

Boundary organizations facilitate interactions between science producers and users by helping to structure the flow of information from basic and applied research to decision making, enabling improved engagement and stronger relationships across disciplines (Kirchhoff et al., 2013; see Figure 18.2, this page). They focus on activities that engage all carbon cycle science disciplines and promote opportunities to foster interdisciplinary and intramural collaboration (Clark et al., 2016). Diverse non-governmental organizations have played a strong role engaging with carbon cycle research activities to understand and apply the science. A primary objective of these organizations is to support and present science in ways that enable local and individual action that links science to decision making at a variety of scales.

The North American Carbon Program (NACP) is an example of a boundary program that supports scientists' efforts to engage in social, economic, and policy-relevant research to improve how carbon cycle science is conducted and ensure policy-relevant findings (NACP; Michalak et al., 2011). A co-authorship network analysis using data from publications of core NACP members indicates that the structure and collaborative pathways within the NACP community created an effective boundary organization (Brown et al., 2016). Results illustrate that the NACP community expanded its research on human and social impacts on the carbon cycle, contributing to a better understanding of how human and physical processes interact with one another. NACP has formed a tightly connected community with many social pathways through which knowledge may flow, and it has expanded its network of institutions involved in carbon cycle research over the past several years (Brown et al., 2016). Further coordination of research in social science, economics, business management, and carbon cycle science should enable decision makers to understand the motivations for people's actions that either directly or indirectly affect the carbon cycle (see Ch. 6: Social Science Perspectives on Carbon, p. 264) and the situations in which refined understanding of the biophysical carbon cycle can

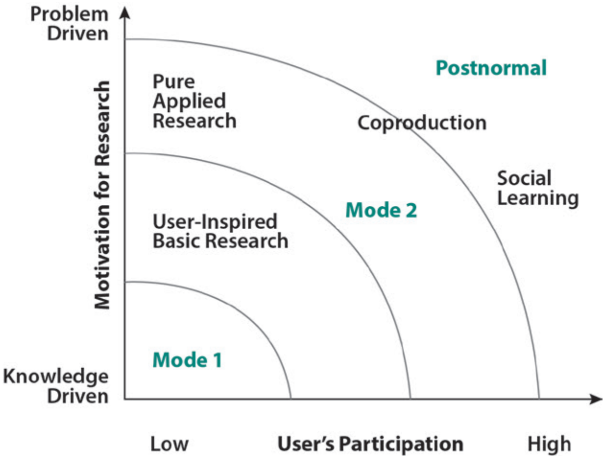

Figure 18.2. Evolution in the Complexity of Knowledge Production and User Participation. On the vertical axis, the complexity of knowledge production increases from low (where production is predominately focused on increasing fundamental knowledge) to high (where production aims to help solve societal problems). On the horizontal axis, the complexity of user participation changes from low to high as users become increasingly active in the knowledge-creation process. **Mode 1** represents the concept that societal benefits accrue because of the separation of science from society, where science is separated from society to maintain objectivity and credibility. **Mode 2** organizes science production at increasing levels of interaction and integration across disciplines (from multidisciplinary to transdisciplinary) and across the science-society divide. In **postnormal science**, scientific knowledge alone is not enough to solve societal problems; therefore, interaction between producers and users of science across the science-society interface entails specific involvement of stakeholders throughout the process. [Figure source: Redrawn from Kirchhoff et al., 2013, copyright Annual Reviews (www.annualreviews.org), used with permission.]

influence business decisions such as supplier selection for creating low-carbon supply chains (Hsu et al., 2013).

18.3 Carbon Cycle Science Used for Decision Making

Carbon cycle science supports decisions in a number of national and international contexts. For example, decisions about managing ecosystems such as national or state forests require integrating stakeholder perspectives with scientific input on the consequences or alternative policy approaches for ecosystems, emissions, and climate (BLM 2016). At the international level, as countries establish goals to stabilize carbon and GHG concentrations in the atmosphere, the scientific community should play an important role in assessing carbon budgets and developing the technologies, methods, and practices for reducing net GHG emissions and managing carbon stocks. Global efforts to slow deforestation, improve human health, and decrease global GHG emissions will be aided by substantial input from the international scientific community and respective national agencies. In all of these examples, and many others, improvements in the quality and process of scientific input can help inform sound decision making. Recent research on CH_4 emissions provides a notable example of fundamental carbon cycle science used in decision making. Reducing anthropogenic CH_4 emissions has become a high priority for policymakers, given the potential for near-term climate benefits and the relative tractability[1] of monitoring and mitigating emissions from many sectors. Concerted effort to develop relationships among scientists and decision makers has enabled progress in identifying information needs, developing technology to provide needed information, and establishing science questions that evaluate existing knowledge. With respect to policy drivers, new laws and rules have been enacted to mitigate and measure CH_4 emissions in California and other key regions and sectors in the United States (Federal Register 2016a, 2016b). Atmospheric or "top-down" scientific methods for detecting, quantifying, and attributing CH_4 fluxes have dramatically improved. For example, satellite observations have enabled scientists to identify concentrated regions of CH_4 emissions, information relevant to policy and management that previously had not been well known or understood (Kort et al., 2014). Recent field studies have revealed evidence of a long-tail statistical distribution of emissions sources in the U.S. natural gas supply chain, where a relatively small number of superemitters dominate key regions and sectors (Brandt et al., 2014; Zavala-Araiza et al., 2015; Zimmerle et al., 2015). Some stakeholders (e.g., California Air Resources Board) already have applied the atmospheric and field research findings to make corrections to CH_4 inventory estimates. Additionally, recent advances in remote sensing of CH_4 point sources (Frankenberg et al., 2016; Thompson et al., 2016) demonstrate the potential to efficiently detect leaks from point sources.

Because the demand for tailored knowledge is often urgent, specific, and only weakly aligned with incentives that drive fundamental research, consulting firms and non-governmental organizations (NGOs) have often met this demand. These institutions have generated a great deal of user-driven science over the decades. For example, the World Wildlife Fund (WWF) and the Carbon Disclosure Project (CDP) partnered with multiple, large, U.S.-based corporations to produce *The 3% Solution*, an analysis of the business case for businesses to achieve net savings of up to $190 billion by 2020 through measures to reduce carbon emissions (WWF and CDP 2013). Woods Hole Research Center, in collaboration with the U.S. Agency for International Development (USAID), produced a map of aboveground carbon stocks in Mexico. The map built on information already assembled by Mexico's government for its

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[1] Mitigation of methane (CH_4) emissions—particularly point sources from the energy, waste, and some agricultural sectors—has strong near-term tractability because it involves detecting and repairing local fugitive emissions rather than economy-wide shifts in energy and transportation infrastructure associated with fossil fuel carbon dioxide (CO_2) mitigation. Monitoring anthropogenic CH_4 fluxes is generally more tractable (with existing technology) than monitoring CO_2 fluxes, since the latter includes large, confounding fluxes from the biosphere. However, area sources of CH_4 such as wetlands and some agricultural fluxes (e.g., rice and enteric livestock emissions) continue to present a challenge.

National Forest Inventory and met a clear need to advance the estimates of Mexico's forest carbon stocks at both national and municipal levels (Cartus et al., 2014; WHRC 2014). As these examples illustrate, contract-driven science is sometimes made publicly available, such as when governmental agencies provide funding to support projects in the public interest or when private-sector entities and NGOs partner to develop analyses of common interest. However, the private contract model has limitations. Many products of contract research remain outside the public domain, and users without the resources to purchase these goods cannot easily access tailored information for their decision-making needs. User institutions that lack these resources are typically smaller and also have less influence than their larger counterparts in a variety of forums. This imbalance in access to information has profound implications because, as many chapters in this report demonstrate, carbon management has consequences for all of society, not only the entity making a particular decision. Because user-driven science that does not enter the public domain is difficult to access, further characterization of its contributions or extent are not included in this chapter. In spite of this, significant effort should be placed on accessing relevant science that is outside the public domain in order to determine whether this science has sufficient value to impact the decision-making process.

18.3.1. Use of Carbon Cycle Science for Land Management

The carbon research community performed a great deal of work in the past decade with the aim of improving decision making in agriculture, energy production and consumption, building infrastructure design and maintenance, transportation, and many other sectors that consume fossil fuels or generate land-based emissions. This research filled knowledge gaps that helped decision makers understand multiple impacts of land-management decisions. Research foci included, for example, ecosystem disturbance (e.g., fire and pest outbreaks), human health and risk, indirect land-use change, efficient production throughout commodity supply chains, full life cycle energy and emissions impacts of ecosystems and production systems, and how these analyses change under alternative land-management scenarios. Federal guidance to U.S. agencies documents how full GHG accounting has been incorporated into environmental impact analyses under current and alternative scenarios (Federal Register 2016b). Briefly illustrated here is the potential impact of scientific input on land management through examples of land-use policy and of terrestrial management on the carbon cycle.

The use of carbon cycle science for decisions on carbon emissions reductions in agriculture is relevant for a wide suite of societal and policy questions relating to the direct impacts of land-use decisions on energy, emissions, health, and ecosystems (see Ch. 5: Agriculture, p. 229). For example, carbon cycle science from multiple disciplines informs dialogue and decisions about the role biofuels can play in the energy economy. Biofuels can include dedicated energy crops, agricultural wastes and residues, and CH_4 from agricultural wastes. The use of biofuels can decrease GHG emissions, depending on net changes in biomass growth stocks across the landscape (e.g., harvest rates, deforestation, and indirect land-use change) and on the net efficiency of converting biomass to energy (see Ch. 3: Energy Systems, p. 110). Biofuel policy options have complex and highly variable implications for carbon emissions that are a function of energy expended in production, processing, and use of biofuels; indirect land-use change; and ecological and economic costs and benefits of biofuels (Paustian et al., 2001). In seeking solutions to energy, environmental, and food challenges, biofuels can either contribute positively or negatively to existing societal issues (Tilman et al., 2009). Full carbon cycle analysis and modeling are key to ensuring that policies and resulting actions actually lower carbon emissions instead of raising them. Such analyses continue to be used to ascertain the benefit of biomass to reduce net emissions, including biomass burning (Cherubini et al., 2011; Johnson 2009; Khanna and Crago 2012; Miner et al., 2014; Mitchell et al., 2012; Tian et al., 2018) and forest thinning to reduce

wildfire risks (Campbell et al., 2012; Mitchell et al., 2009). Analyses at different spatial scales (e.g., plot, national, and global) and temporal scales (e.g., years, decades, and centuries) can yield different conclusions for land-related carbon issues, indicating the need to synthesize or integrate approaches used across scales (i.e., plant growth models, land-use change models, integrated assessment models (IAMs), and natural resource supply models).

18.3.2 Carbon Management Strategies

While some carbon management strategies are still being debated within the science community, a number of strategies have been well documented and quantified. Some of them are summarized from results in preceding chapters of this report (see Table 18.1, p. 737). Many land-based strategies are associated with changes in management. Humans have a long history of altering the landscape and associated carbon stocks around the world since initial settlement and population expansion (Sanderman et al., 2017; Köhl et al., 2015). People have changed forests to agricultural areas and vice versa; changed management of soils, forests, grasslands, and other ecosystems; and developed urban and suburban areas. There is a robust literature of observations and carbon stock comparisons under different land uses and management regimes that provides guidance for managing natural resources, fossil resources, and renewables with regard to carbon. Potential sequestration rates have been estimated by aggregating data from hundreds of paired plots, and the data have been used for national scale estimates (U.S. EPA 2016) and global default values for numerous management practices across land, energy, and transportation sectors (IPCC 2006). Research has moved beyond estimating the influence of management changes within a sector, to evaluating how change in one land or energy sector causes changes in other land or energy sectors.

The many land-management options available to reduce net GHG emissions or increase removal of GHGs from the atmosphere (see Table 18.1), taken together, could reduce net emissions by 100 to 500 teragrams of carbon (Tg C) per year, with co-effects becoming highly significant in the high end of this range. Therefore, decisions about land-management policies must take into account the co-effects, which may be positive or negative, along with the potential benefits in terms of reducing GHGs. One of the most significant negative impacts of altering land management to increase carbon storage is a potential reduction in land area devoted to food production if the amount of additional land required exceeds the area of "marginal" (i.e., not productive for crops) land available. On the other hand, positive co-effects may result from management practices that increase soil fertility along with carbon storage, or those that increase protection of water quality or damage from storms and floods.

Although traditionally considered the province of biophysical science, the demand for actionable results has increasingly drawn attention to the need for research from sociology, psychology, and human behavior to inform carbon management. Research in these fields has identified obstacles to effective carbon management, and the approaches to overcome them, at individual to institutional scales (Ross et al., 2016). In researching the interests and understandings held by different actors in Mexico's program for monitoring, reporting, and verifying (MRV) REDD+, Deschamps Ramírez and Larson (2017) found tension arising from poor understanding of international reporting requirements and the roles and responsibilities of subnational institutions. Weaknesses in understanding and social relations among key institutions limit the effectiveness of carbon management even when decision makers possess and understand strong biophysical analyses (Deschamps Ramírez and Larson 2017). Individuals respond strongly to default options and associated social norms, as demonstrated in comparisons of decisions about whether or not to participate in organ donor programs among different countries. Default settings on furnaces and other appliances to conserve energy, with the option for owners or users to change that setting, could produce widespread behavior shifts and associated changes in carbon emissions (Ross et al., 2016). Efforts to support the capacity of businesses to manage carbon involves research but

Table 18.1. Summary of Options, Capacity, and Co-Effects for Reducing Greenhouse Gases (GHGs) in North America[a]

Activity	Impact on GHGs	Potential Reduction[b]	Co-Effects
Afforestation and improved forest management (Ch. 9, 12)[c]	Increase in net removals from the atmosphere. Reduction in emissions by avoiding the conversion of forests and grasslands to other cover types. Increase in carbon removals from the atmosphere by promoting the conversion of other land covers to forests or grasslands.	30 to 330 teragrams of carbon (Tg C) per year (U.S. only)	Potential impacts on food production, biodiversity, net forest resources, and counter harvesting elsewhere (i.e., leakage), resulting from increased forestland area.
Managing grasslands (Ch. 10)[c]	Increase in net removals from the atmosphere and in biomass and soil carbon storage by improving grazing practices and grasslands management.	Tens of Tg C per year (U.S. only)	Shifts in species composition.
Reducing methane (CH_4) emissions from livestock (Ch. 5)[c]	Reduction in net agriculture emissions by controlling livestock CH_4 emissions.	13 to 19 Tg C per year	Potential co-benefits such as improved feed efficiency or productivity in livestock.
Cropland management practices (Ch. 5, 12)[c]	Increase in organic residue inputs and soil carbon stocks by reducing tillage and summer fallow, implementing cover cropping, or managing nutrients to increase plant production. Reduction in CH_4 and nitrous oxide (N_2O) emissions by optimizing nitrogen fertilization and water management.	Soil carbon stock increases of up to 3 megagrams of carbon per hectare; up to 80% reduction in CH_4 (especially rice) and N_2O, depending on crop, environment, and combination of practices.	Potential co-benefits such as improved soil productivity and lower costs for nitrogen fertilizers. Increased organic carbon for improved buffering capacity, water holding capacity, soil fertility, and tilth. Reduced water use (especially rice).
Reducing wetland and coastal ecosystem loss (Ch. 13, 15)[c]	Reduction in emissions by avoiding the loss of wetlands and coastal estuaries. Increase in carbon sequestration by restoring drained wetlands, though possibly increasing CH_4 emissions.	Based on the amount of wetlands converted to other land uses in Canada and the United States, restoring all wetland acreage, leading to a gross but highly unrealistic estimate of 43 Tg C per year.	Potential impacts on coastal zone development. Increased protection of property from storms. Reduced export of nutrients to the ocean. Restored wetlands via improved flood abatement and water quality, but with only about 21% functional compared to functionality of undisturbed sites.

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Table 18.1. Summary of Options, Capacity, and Co-Effects for Reducing Greenhouse Gases (GHGs) in North America[a]

Activity	Impact on GHGs	Potential Reduction[b]	Co-Effects
Urban mitigation (Ch. 4)[c]	Reduction in city carbon emissions by implementing or improving urban development pathways, building codes, transportation planning, electricity supply, or biotic planning (e.g., tree planting). Reduction in CH_4 leakage, for example, by upgrading infrastructure.	Data unavailable for a comprehensive assessment of mitigation potential.	Implications for air quality, urban heat island, and human health, among the many co-effects and priorities for consideration.
Increasing bioenergy (Ch. 3)[c]	Possible reduction or increase in net GHG emissions by substituting biofuel for fossil fuel. Impacts dependent on fuel source and effects on production and consumption cycles.	Estimates of mitigation potential based on life cycle analysis unavailable, though biofuel supply is potentially large.	Increased agricultural commodity prices and land-use changes in other regions, dependent on extent of land supplying the biofuel. Increased forest harvesting in response to higher demands for forest biomass, possibly followed by forest area expansion.

Notes

a) Table includes GHG emissions reductions, carbon stock increases, and avoidance of carbon losses.

b) Potential reductions are in addition to baseline.

c) Chapter titles—3: Energy Systems, p. 110; 4: Understanding Urban Carbon Fluxes, p. 189; 5: Agriculture, p. 229; 9: Forests, p. 365; 10: Grasslands, p. 399; 12: Soils, p. 469; 13: Terrestrial Wetlands, p. 507; 15: Tidal Wetlands and Estuaries, p. 596.

can fall outside traditional academic frameworks. For example, the Sustainable Purchasing Leadership Council (SPLC) evaluated third-party tools for estimating supplier sustainability across an entire supply base (SPLC 2018). Although these tools focus more broadly than carbon, SPLC's work summarizing and evaluating them demonstrates the type of collaboration that spurs user-driven science and produces actionable recommendations.

18.4 Technical Capabilities and Challenges for Supporting Decision Making

Assuming adequate organization, communication, and funding is in place, there are a number of scientific and technical challenges associated with better connecting basic and applied science for decision-making purposes. This section discusses current capabilities and needs for data, modeling, accounting, and broad system approaches for carbon management.

18.4.1 Data Collection, Synthesis, and Analysis

Data for basic carbon research and decision making are often similar, although they typically are used independently instead of informing one another. For example, global climate models rely on national and global datasets on human activities and land management. Conversely, models of natural resource ecosystems and economics that inform land

management require input on global changes in total land resources, commodity markets, and climate. A revised assessment of existing data, across disciplines, could help basic and use-inspired research on carbon and also address interrelated climate and carbon research issues.

Inventory data on fossil fuel emissions and land emissions and sinks are estimated nationally (e.g., U.S. EPA 2016) and reported internationally under the United Nations Framework Convention on Climate Change (UNFCCC). Advances in carbon cycle science are reflected in carbon modeling and accounting used to produce the inventory data. For example, field experiments that collect data on fertilizer application methods and timing, livestock and manure management, soil management, and other activities can be incorporated into models that estimate GHG emissions, thereby refining the national carbon budget.

Inventory data provide information on emissions sources and sinks and how net emissions change with land management or fuel supplies. To be most useful for local and regional planning, these data often require spatial distribution (West et al., 2014) or additional information on land-cover, land-use, and ecosystem characteristics that may be provided by satellite remote-sensing or economic survey data. Integrating inventory and remote-sensing data can provide new data products to understand local and regional carbon dynamics (Huang et al., 2015) and to inform land-management and policy decisions. Using integrated data on land use and management in climate modeling activities may become increasingly important (Hurtt et al., 2011) to facilitate consideration of climate feedbacks in local and regional decision making.

Although inventory data often serve as the basis for understanding human-induced impacts on the carbon cycle and subsequent decision making on carbon mitigation strategies, other datasets can provide additional or complementary estimates. For example, fossil fuel emissions can be estimated by the production of fossil fuels (U.S. EPA 2016) or by the consumption of fossil fuels (Patarasuk et al., 2016). The same is true for land-based emissions, which can be estimated using ground-level survey data from the Forest Inventory Analysis or the National Agricultural Statistics Service (West et al., 2011) or using atmospheric concentration data and modeled with atmospheric transport and inversion models (Schuh et al., 2013). The survey or inventory data represent "bottom-up" estimates while the atmospheric data represent a "top-down" approach. Reconciling data and approaches benefits both basic and applied science. Earth System Models (ESMs) require accurate base-level data and also need multiple ways to evaluate results. Similarly, inventory data used in models for decision making could benefit from alternative estimation approaches that evaluate existing inventory estimates (Jacob et al., 2016). Also needed are continued development and reconciling of data collection and modeling approaches to estimate carbon stocks and fluxes, requiring coordination among researchers, decision makers, and funding sources (see Box 18.1, Key Data Needs for Decision Making on Terrestrial Carbon, p. 740).

18.4.2 Decision Support Tools for Carbon and Greenhouse Gas Management

Research models and decision support tools that can forecast future changes, as well as integrate and analyze current and past conditions, can provide solutions to challenges presented by climate change. At the broadest level, capabilities include assessment and decision-making tools that analyze feedbacks between human activities and the global carbon cycle. These capabilities can enable decision makers to 1) assess how changes in the carbon cycle will affect human activities and the ecosystems on which they depend and 2) evaluate how human activities—past, present, and future—impact the carbon cycle.

National GHG Inventories Critical for Modeling

For national-scale planning and in international agreements and negotiations, national GHG inventories have consistently been recognized as essential parts of the model-data system. Policy developments of the past few years have reinforced the global

Box 18.1. Key Data Needs for Decision Making on Terrestrial Carbon

- Collect and analyze inventory data that observe and represent changes in carbon stocks associated with human drivers.
- Integrate inventory and remote-sensing data for inclusion in Earth System Models.
- Reconcile different carbon emissions and sink estimates to further improve independent and combined estimates.
- Explore and develop plausible scenarios for the influences of different demographic, social, and geopolitical trends and developments in other sectors (e.g., energy) on terrestrial carbon.
- Refine and decrease uncertainty of estimates for land-based carbon emissions and stock changes.

recognition of the need for high-quality and regularly reported GHG inventories. Increasing numbers of developing (i.e., UNFCCC non-Annex 1) countries produce annual GHG inventories and submit them to the UNFCCC using an extensive set of guidelines for national GHG reporting based on IPCC GHG inventory reporting guidelines (IPCC 1996, 2003, 2006). Deforestation and forest degradation constitute a major source of carbon emissions in many developing countries; the Global Forest Observations Initiative (GFOI) has developed guidance for using remotely sensed and ground-based data for forest monitoring and reporting of reduced emissions from deforestation, forest degradation, and associated activities produced in cooperation with UN-REDD and Forest Carbon Partnership Facility (FCPF) initiatives (http://www.gfoi.org/methods-guidance).

Most GHG inventories rest on estimates of the emissions associated with a particular activity (e.g., amount of CO_2 emitted per amount of fuel combusted). The factors that relate activities to emissions are called emissions factors. For sectors dominated by fossil fuels (e.g., power generation, transportation, and manufacturing), emissions factors are well constrained (IPCC 2006). Therefore, the major limitation to estimating emissions accurately is the ability to collect, organize, and verify the activity data (e.g., numbers of transformers upgraded, hectares of perennial plants established for bioenergy, and number of cattle raised on forage known to reduce CH_4 production). For biogenic-driven GHG emissions, such as those associated with agriculture and forestry, there is much greater variability in the emissions rate per unit of activity (e.g., N_2O emissions per unit of fertilizer added) because of heterogeneity in climate and soil conditions and in management practices. Dynamic process-based models offer an alternative approach that can account for this heterogeneity (Del Grosso et al., 2002; Li 2007), but using these models requires sufficient capacity (e.g., trained staff, functioning institutions).

GHG inventories that use activity data and emissions factors (or activity-specific process modeling) are referred to as bottom-up approaches (see Section 18.4.1, p. 738). All national GHG inventories use this approach, which, by definition, attributes emissions sources and sinks to identifiable entities and activities and lends itself to policy applications to reduce emissions and incentivize sinks. Examples of spatially explicit, high-resolution model-data systems for major source categories include fossil fuel emissions (Gurney et al., 2012; Gurney et al., 2009), forest dynamics (USDA 2015), biofuels (Frank et al., 2011), and land-use change (Sleeter et al., 2012; Woodall et al., 2015). These data combine knowledge of biophysical processes with data on human activities and economics that can help municipalities or geopolitical regions understand and quantify carbon emissions and sinks, thereby informing decision making. Challenges to these bottom-up approaches, aside from improving data quality on both activities and emissions factors to

reduce uncertainties, include ensuring completeness and avoiding double-counting of sources.

Land-Use Emissions Projections and Examples of Sector-Specific Tools

In addition to inventories, the carbon cycle science community develops projections that scale from local mitigation options to global impacts and, conversely, from global economic forces to local strategies. Many countries incorporate land-use emissions into their overall climate targets in some way, and these projections inform national and international strategies to address CO_2 emissions, carbon management options, and other sustainability goals. These estimates of future land-use sources and sinks are useful for decision making because they stem from a reliable, scientifically sound, and transparent process (U.S. Department of State 2016). Because this work reflects the development and use of new approaches in carbon cycle science, further work is widely acknowledged as being helpful to increasing the usefulness of land-use emissions projections.

Models and decision tools have also been designed to help industry, business, or other entities (e.g., universities, land-management agencies, farmers, and ranchers) assess their emissions and develop mitigation strategies. In a regulatory environment where emissions are in some way limited by law, models and decision tools are essential for planning, forecasting, and monitoring emissions reductions. These tools also are widely used in voluntary carbon accounting and reporting to generate and sell carbon credits from a variety of activities (CARB 2018).

Models and decision support tools for inventory and forecasting in the AFOLU sector at the scale of the farm, woodlot, or business have been developed and are increasingly deployed as tools to guide implementation of government-sponsored conservation programs. These tools can help inform decisions to reduce the GHG footprint of agricultural commodities through supply-chain management by agricultural industries and to support agricultural offsets in carbon cap-and-trade systems (see examples below).

- COMET-Farm (cometfarm.nrel.colostate.edu; Paustian et al., 2018)—Helps farmers and other landowners estimate carbon benefits associated with implementing practices supported by conservation programs of the USDA Natural Resources Conservation Service (Eve et al., 2014).

- Cool-Farm Tool (CFT; www.coolfarmtool.org/CoolFarmTool; Hillier et al., 2011)—A product of the Cool Farm Alliance, CFT is designed for use by farmers and is intended to support the Alliance's global mission of enabling millions of growers to make more informed on-farm decisions that reduce their environmental impact.

- DNDC (Denitrification-Decomposition) process-based biogeochemical model (Li 2007)—Used by institutions like the California Air Resources Board to support CH_4 reductions from rice farming as an agricultural GHG offset in California's GHG emissions reduction program (Haya et al., 2016).

- ExACT (Ex-Ante Carbon balance Tool; www.fao.org/tc/exact/ex-act-home/en)—Estimates CO_2 equivalent (CO_2e)[2] emissions based on a project's implementation as compared to a "business-as-usual" scenario. Project designers can use ExACT as a planning tool to help prioritize mitigation-activity terms.

- ALU (Agriculture and Land Use; www.nrel.colostate.edu/projects/ALUsoftware) national GHG inventory software—Assists countries in completing their national inventories. This tool was developed to meet a U.S. governmental priority of increasing the number of countries developing robust GHG inventories to create transparent, evidence-based understanding of global GHG emissions.

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[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

- Climate Change, Agriculture, and Food Security–Mitigation Options Tool (CCAFS–MOT; ccafs.cgiar.org/mitigation-option-tool-agriculture)—Identifies practices in Africa, Asia, and Latin America that can reduce emissions and sequester carbon on agricultural lands. MOT prioritizes effective mitigation options for many different crops according to mitigation potential, considering current management practices, climate, and soil characteristics.

- National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index (toolkit.climate.gov/tool/annual-greenhouse-gas-index-aggi)—Compares the total combined warming effects of GHGs (including CO_2, CH_4, N_2O, and chlorofluorocarbons) to their 1990 baseline levels.

- Bioenergy Atlas (toolkit.climate.gov/tool/biofuels-atlas)—Includes maps enabling the comparison of biomass feedstocks, biopower, and biofuels data from the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), and USDA. (Software hosted by DOE's National Renewable Energy Laboratory.)

- Global Carbon Atlas (www.globalcarbonatlas.org)—Aggregates global carbon data to explore, visualize, and interpret global and regional carbon information and changes from both human activities and natural processes. (Supported by the Global Carbon Project, www.globalcarbonproject.org; and BNP Paribas.)

Comparable decision support tools for carbon management have been developed for other sectors. For example, USAID's Clean Energy Emissions Reduction (CLEER) tool, based on internationally accepted methodologies, enables users to calculate changes in GHG emissions resulting from adoption of geothermal; wind; hydroelectric and solar energy generation; upgrades of transmission and distribution systems; increases in building energy efficiency; heating, ventilation, and air conditioning system efficiency improvements; fuel switching; capture of stranded natural gas by flaring; use of biomass for energy; and use of anaerobic digesters to capture CH_4 from livestock manure (USAID 2018).

Complex, Multisector Modeling

Integrated Assessment Models merit particular attention because they constitute a distinct field of research and serve a unique role in decision support. Among decision support tools for carbon management, IAMs are unique in estimating economy-wide responses, including GHG emissions, to different management and policy options. The objective of these models is to capture the primary interactions and interdependencies between natural and human systems (e.g., economic sectors) through a series of scenarios that represent plausible policy interventions (Weyent 2017). These models can help understand feedbacks among carbon sources and sinks at national and global scales (see Figure 18.3, p. 743), given specified emissions targets or implementation of carbon strategies (Grassi et al., 2017; Iyer et al., 2015). Integrative modeling frameworks that include land sector, energy sector, transportation, and other interconnected carbon sources and sinks have continued to develop more detailed model structures and higher-resolution data input (Kyle et al., 2011; Wise et al., 2014).

IAMs, designed to answer questions about carbon management, include 1) social and economic factors that drive GHG emissions as well as a representation of biogeochemical cycles that determine the fate of those emissions and 2) the effects on climate and human welfare. The dynamic interactions among sectors in these models mean that they can reveal nonintuitive outcomes. Actions in one sector or geography can influence those in another, and a common goal of carbon management policy is to limit the accumulation of CO_2 in the atmosphere. Therefore, understanding the economy-wide influences of policy choices is critical both to assess the actual consequences of a single policy on carbon accumulation in the atmosphere and to have a realistic idea of the level of atmospheric CO_2 that could be achieved with multiple countries and multiple policies.

Continued efforts to integrate IAMs, ESMs, carbon accounting, and national-scale resource modeling will help develop consistency in data input across these modeling platforms. The combination of global IAMs, national and subnational natural resource economic models, carbon accounting methods, land-use change models, energy technology, and market analyses are all needed to estimate carbon management strategies in a comprehensive manner from the local to global scale (see Box 18.2, Carbon Modeling Needs for Decision Making, p. 744). As one example, a process using IAMs, global and national natural resource (i.e., timber) models, and inventory data (i.e., field surveys) was conducted in the development of the *United States Mid-Century Strategy for Deep Decarbonization* (White House 2016).

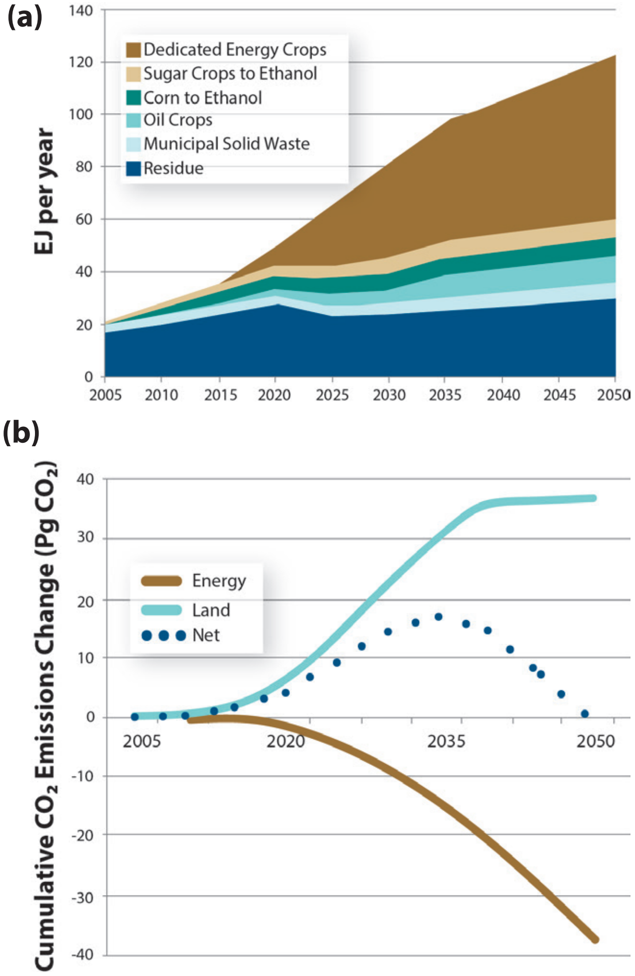

Figure 18.3. Example of Results from a Global Integrated Assessment Model. The illustration considers **(a)** economic market dynamics, land-use change, land resources, and impacts on the carbon cycle that are associated with a high-biofuels mandate scenario. **(b)** Net change in cumulative emissions of carbon dioxide (CO_2) from land-use change and energy systems in high-biofuels scenarios is shown in comparison to the baseline. Key: EJ, exajoules; Pg, petagrams. [Figure source: Redrawn from Wise et al., 2014, copyright Elsevier, used with permission.]

18.4.3 Carbon and Greenhouse Gas Accounting

Data and models that estimate changes in carbon flux often were not initially developed for estimating direct and indirect net carbon changes associated with given activities. This is true for country-level inventory data reported by sector (U.S. EPA 2016), biogeochemical cycle models (Del Grosso et al., 2002), and integrated climate models (Wise et al., 2009). In many cases, incorporating the influence of particular activities on upstream or downstream energy, land use, and associated GHG emissions significantly changes estimates of the realized carbon savings. Full GHG accounting of all emissions related to a given activity can significantly augment or reduce reported emissions compared to partial or incomplete accounting.

Accounting of carbon fluxes and stock changes in ecosystems or industrial systems dates back to early work on energy input and output models and systems modeling (Odum 1994) and has evolved rapidly since then. A systems analysis can be developed to understand and quantify net carbon exchange associated with specific management activities (Schlamadinger and Marland 1996). Such analyses, for example, consider disturbance (e.g., widespread tree mortality and erosion from hurricanes or ice storms), forest regrowth over time, landscape area boundary, and forest growth trends over time in the absence of disturbance (Lippke et al., 2011; Lippke et al., 2012). Fossil fuel offsets associated with harvested wood and wood products are also included in these system-scale carbon budgets. These types of analyses often are conducted to illustrate the methods and provide an averaged national answer. To be

Box 18.2. Carbon Modeling Needs for Decision Making

- Link Integrated Assessment Models, natural resource management models, and socioeconomic models for predictive capabilities such that regional scale analysis can be conducted while being informed and constrained by global economic market dynamics.
- Improve projections for national land-use emissions in the United States and other countries.
- Increase understanding of drivers of land-use change in different global regions.
- Evaluate model predictions through hindcasting, model diagnostics, and multimodel intercomparisons.
- Evaluate how scenario results change depending on the time step used (i.e., subannual to decadal), spatial resolution of model input data, and spatial extent of output.
- Assess and further develop uncertainty quantification methods for carbon-related modeling activities.

useful for decision making, full carbon accounting would need to be conducted for regions that have obvious differences in ecosystem attributes, climate regimes, and social and economic drivers (see Box 18.3, Carbon Accounting Needs for Informing Decision Making, this page).

Past development of carbon accounting methods suggests a number of basic carbon accounting guidelines. Properly defining time and space boundaries of the system or activity of interest is an essential first step, and highlighted below are additional guidelines.

Box 18.3. Carbon Accounting Needs for Informing Decision Making

- Elicit user needs for carbon accounting through a two-way dialogue, and socialize the resulting needs and understanding in the carbon cycle science community.
- Conduct regionally specific carbon accounting for dominant activities in land management and fossil fuel management.
- Quantitatively understand how activities affect entire supply chains.
- Perform landscape-scale life cycle analysis that capture regional differences.

Stock Changes Are Less Prone to Error than Adding up All Biological Fluxes and Uptakes. This finding is currently guiding analyses by EPA's Science Advisory Board Panel on Biogenic Emissions from Stationary Sources on net carbon emissions from the use of biomass for energy production (U.S. EPA 2014). The stock change approach also has been the chosen method for estimating net emissions from forests and agricultural soils (U.S. EPA 2016). Trying to simulate all fluxes in and out of a system is useful for understanding ecosystem processes and climate feedbacks, but the increased complexity may introduce additional error and uncertainty. In contrast, changes in carbon stocks inherently combine the net result of multiple fluxes into and out of a given stock entity. Differences in complex models and stock change methods are exemplified in an analysis by Hayes et al. (2012).

Accounting for Energy and Emissions One-Level Upstream and Downstream Is Often Sufficient to Capture Adequately the Total Flux Associated with an Activity of Interest. When estimating emissions associated with changes in fertilizer application rates, for example, the fuels used to process

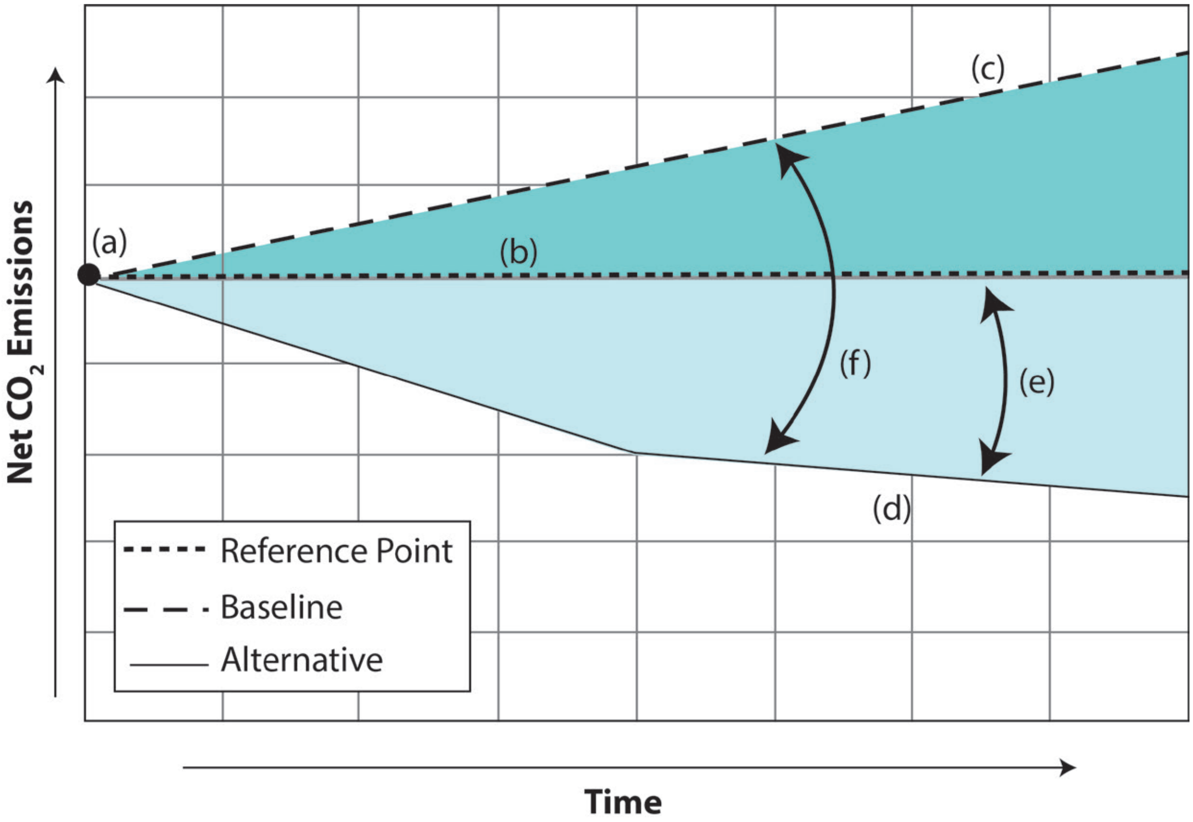

Figure 18.4. Illustration of Basic Hypothetical Carbon Accounting Scenario. Accounting begins at **(a)** the reference point and continues through time with the **(b)** reference line or the **(c)** estimated baseline, and the **(d)** observed or estimated impact of alternative management. Depending on the use of a reference line or baseline, the carbon savings in this hypothetical scenario would be comparatively **(e)** less or **(f)** greater, respectively.

the fertilizer (e.g., natural gas) should be considered (i.e., Level 1 upstream), but the energy used to mine the fuel (e.g., natural gas; Level 2 upstream) is often statistically insignificant (West and Marland 2002). Although exceptions should always be considered, accounting for emissions of both Level 1 upstream and downstream (e.g., transporting the fuel) of the activity of interest remains a good general rule.

Establishing the Proper Reference Point (System that Exists Prior to Changes in Management) Is Essential. The reference point is the current system, prior to a change in activity (see Figure 18.4, this page). The reference point should not be chosen at a time prior to the current activity (e.g., based on historical trends), nor should it be arbitrarily chosen before or after activities associated with the new or alternative management. This issue is currently debated in regard to some forest management techniques (Campbell et al., 2012; Hurteau and North 2009).

A Baseline Trajectory May Be Conceptually More Comprehensive Than a Reference Point But May Have More Uncertainty. Models that project changes in land use, fossil fuel combustion, or other GHG emissions can be particularly useful for understanding future scenarios. However, the trend line for the future trajectory can be uncertain, and using baselines to compare new or alternative systems should only be done with caution (Buchholz et al., 2014). The use of a reference point or baseline should be decided based on the certainty associated with baseline projections (see Figure

18.4). For example, a baseline of forest growth (e.g., increased growth until forest maturation) is well established in forest growth curves, whereas future changes in land use based on commodity markets is less certain. There may also be policy considerations that influence whether baselines or reference points are more appropriate for a given context.

18.4.4 Systems Approach for Decision Making

Combining several of the aforementioned capabilities (e.g., data collection, modeling, and accounting) can help facilitate the use of research products for both decision making and the next generation of new relevant scientific analyses (West et al., 2013). Data assimilation systems have been under development to bring together inventory-based datasets, atmospheric modeling, global land models, and accounting procedures. Integrating these research areas using data assimilation, where appropriate, can help researchers explore data similarities and differences, reconcile data differences, and potentially integrate datasets to attain enhanced data products or model results with reduced bias, reduced uncertainty, and improved agreement with observations. Past efforts include 1) a project in the midwestern United States (Ogle et al., 2006), 2) a North American continental analysis (Hayes et al., 2012; Huntzinger et al., 2012), and 3) similar analyses in Europe (Le Quéré et al., 2015). Of these analyses, those for the midwestern United States and Europe resulted in little to no statistical difference between bottom-up and top-down emissions estimates, indicating promising capability in using one method to constrain another and in integrating methods for a more comprehensive and potentially more accurate estimate. There also is an indication that atmospheric inversion model estimates (i.e., top-down estimates) can be useful in smaller regions, but they are potentially less informative or accurate at continental or global scales (Lauvaux et al., 2012). Accounting issues also were identified and resolved between atmospheric estimates and terrestrial-based estimates so that the two methods could be compared and contrasted, contributing to a new lexicon that helped define land-based fluxes in a manner consistent with fluxes observed from atmospheric measurements (Chapin et al., 2006; Hayes and Turner 2012).

Box 18.4. Research Needs for Integrative Observation and Monitoring Systems

- Couple life cycle analysis models with Integrated Assessment Models to understand carbon impacts associated with specific activities.
- Use inventory-based land-cover and land-use data in Earth System Models, so that global and regional outputs from carbon-climate models are more useful for decision making.
- Continue research efforts on different methods of observing and modeling carbon sinks and emissions so that existing inventory estimates can be improved and more complete.

Although reconciling bottom-up and top-down estimates can help build confidence in existing estimates, thereby forming a stronger foundation for decision making, other existing modeling systems could be combined to improve national and global decision making about carbon. Largely independent efforts continue for climate modeling, land-use modeling, global and regional economic modeling, and energy modeling. Coordinating these modeling activities so that, at a minimum, output from one model can be used as input for other models would help in coordinating decisions that inherently affect or are affected by climate, land use, and energy production and consumption (see Figure 18.1, p. 730). This effort would require high-level coordination among research organizations that support modeling in different research fields covering fundamental, applied, and social sciences (see Box 18.4, Research Needs for Integrative Observation and Monitoring Systems, this page).

18.5 Pathways for Science to Support Decision Making

Carbon cycle science to date has made significant advancements in understanding carbon dynamics and feedbacks between global carbon and climate. For these advances to be more useful in decision making, increased understanding and quantification are needed regarding how individual activities affect carbon sinks and emissions, both directly and indirectly. This information would aid accounting of energy consumption, fossil fuel combustion, as well as land-related emissions and sinks (see Table 18.2, this page). Science-based estimates of net emissions associated with activities, complete with statistical uncertainty, may then be scaled up using relatively high resolution data on environmental conditions and human activities. This information then can be used to better understand how decisions under consideration by public and private entities may impact carbon sources and sinks.

Many land-management decisions at the U.S. Federal and state level (i.e., conservation programs) over the past decade could not have been made without the previous generation of work on carbon cycle science and efforts that supported basic research, fostered co-production of knowledge, and linked scientific inputs with the needs for inventories, assessments, projections, and decision making. Yet, with the evolving interests of communities and policymakers, as well as new policy requirements for implementing and setting national goals, new needs have emerged that emphasize input from the scientific community at the international, national, and subnational levels. Establishing strong partnerships among scientists, stakeholders, and funding sources may be essential for making effective use of carbon-related research over the coming years.

Table 18.2. Research to Support Carbon Cycle Decision Making

Decision-Making Goal	Information Gap	Research Activity Need
Prioritize activities and geographic regions for soil carbon sequestration and net greenhouse gas (GHG) emissions reductions.	Predict changes in soil carbon based on regional changes in land-management practices.	Calibrate existing soil models with field data and develop multivariate meta-analyses of field data.
Consider carbon stock changes in private and public forest management plans.	Understand net carbon stock changes associated with land-management strategies.	Assess forest carbon stocks and net changes in stocks at the regional and landscape levels associated with fire, regrowth, harvesting, thinning, and wildfire management.
Consider carbon stock changes in land-use planning and in legislation and policies that affect national and global land use.	Understand the connections between direct and indirect land-use change and national and global changes in population, diet, affluence, technology, energy, and water use.	Integrate science-based carbon stock and flux estimates, including uncertainty estimates, with global and regional socioeconomic models.
Increase the use of bioenergy, bioproducts, and renewable energy.	Compare net emissions of alternative technologies to existing technologies and capture regional differences, if warranted.	Conduct life cycle analyses (LCAs) for all proposed bioenergy, bioproducts, and renewable technologies and compare these analyses with LCAs for fossil fuel technologies.

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Table 18.2. Research to Support Carbon Cycle Decision Making

Decision-Making Goal	Information Gap	Research Activity Need
Incentivize sustainable bioenergy.	Develop accurate bioenergy emissions accounting at individual facilities.	Calibrate existing forestry models to accurately reflect forest owner planting responses to market signals.
Protect vulnerable high-carbon landscapes.	Identify land areas at high risk of settlement conversion.	Project trends in urban development and land-management choices.
Maximize carbon mitigation on lands at risk of natural disturbance.	Project natural disturbances and their carbon impacts.	Develop region-specific carbon accounting protocols and management guidance.
Optimize national gross domestic production (GDP), its factors, and GHG emissions.	Understand factors of GDP and emissions and how those factors can be used to decrease emissions while positively affecting GDP.	Include GHG emissions in analyses of GDP and national economic growth.
Optimize energy production and consumption for reduced carbon emissions.	Understand fuel mixes, substitutes, combustion efficiencies, energy intensity, and carbon intensity associated with energy production and use.	Develop and integrate models that investigate carbon intensity of fuel use at local to national scales, with feedbacks to other related sectors (e.g., land resources and bioenergy).

SUPPORTING EVIDENCE

KEY FINDING 1

Co-production of knowledge via engagement and collaboration between stakeholder communities and scientific communities can improve the usefulness of scientific results by decision makers (*high confidence*).

Description of evidence base

Understanding what is useful for decision making can help guide development of science more effectively (Lemos and Morehouse 2005; Moser 2009). In many cases, this development requires little extra time or funding and can be as simple as understanding the formatting of information. For example, experimental data on carbon emissions may be generated daily and at a local level, but information on an annual timescale and at the geopolitical level often is needed to inform decisions. In other cases, matching model results with existing decision-making processes will take time and changes to models and processes. Stakeholder engagement has resulted in the use of science results to support decision making for a number of activities, including 1) new modeling capabilities to estimate national forest carbon and attribution of carbon stock changes (Woodall et al., 2015), 2) methods for estimating methane (CH_4) emissions (Turner et al., 2016), and 3) policy-relevant soil management (Paustian et al., 2016). Boundary organizations that bring together a cross-section of disciplines have been successful in promoting fundamental science that is useful to decision makers (Brown et al., 2016). Inherent in the communication and coordination of science and decision makers regarding Key Finding 1 will be the need to revisit, understand, and define the boundaries among science, policy, and management, as well as fundamental science, use-inspired science, and applied science (Moser 2009). Defining these boundaries will help guide and support the co-production of knowledge.

Major uncertainties

The co-production of knowledge is limited by the success and effectiveness of communication, and the certainty of success depends on the process of engagement.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Communicating information and data formatting needs for carbon stock changes, estimates of net emissions associated with specific activities, and projections of carbon stock and net emissions with uncertainty estimates has helped guide field work, observations, and modeling to meet these needs.

Summary sentence or paragraph that integrates the above information

Carbon-related research that is co-produced by scientists and decision makers helps ensure that science results address questions posed by decision makers. The result for Key Finding 1 is robust science that is useful for addressing societal issues. The likelihood of success is high, based on past successes, and the effectiveness is often determined by the level of participation.

KEY FINDING 2

Integrating data on human drivers of the carbon cycle into Earth system and ecosystem models improves representation of carbon-climate feedbacks and increases the usefulness of model output to decision makers (*high confidence*).

Description of evidence base

For Key Finding 2, the impacts of human management activities on carbon stocks have been analyzed and documented for entity-scale greenhouse gas estimation of agricultural activities (Eve et al., 2014). This information is being integrated into models for use by agricultural land managers. For U.S. forests, attribution of human and natural influences (e.g., harvesting, natural disturbance, and forest age) has been successfully disaggregated using field data and models (Woodall et al., 2015) to help inform decision makers. Finally, to better represent human drivers on climate, carbon stocks, and commodity production and consumption at the global scale, human drivers representing land management are being integrated into Earth System Models (ESMs); Drewniak et al., 2013), and the management of land, energy, and fossil fuels is included in Integrated Assessment Models (IAMs; Chaturvedi et al., 2013; Le Page et al., 2016). As human drivers continue to be included in scientific research models, these models will continue to better represent actual local and global dynamics, thereby becoming more useful for decision making.

Major uncertainties

While inclusion of human drivers in estimates of carbon cycle fluxes and stock changes often results in more useful information for decision making, it also can result in a higher number of model parameters, which can increase statistical uncertainty and variability of model results. However, this increased statistical uncertainty does not necessarily reduce the usefulness of findings for decision making, particularly if the uncertainty is a uniform bias or a broader confidence interval surrounding a stable trend.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Continued inclusion of human drivers within ecosystem models and ESMs will better represent the influence of human activities on the carbon cycle, thereby improving the usefulness of results to decision makers.

Summary sentence or paragraph that integrates the above information

Inclusion of human drivers in carbon cycle models increases the accuracy of models and generates model output that is more useful for decision making. For Key Finding 2, statistical uncertainty may increase or decrease based on the change in model complexity.

KEY FINDING 3

Attribution, accounting, and projections of carbon cycle fluxes increase the usefulness of carbon cycle science for decision-making purposes (*very high confidence*).

Description of evidence base

Carbon cycle fluxes by themselves, both observed and estimated, are useful to understand carbon cycle processes but not particularly useful for decision making. Changes in net emissions associated with changes in human activities in the past, present, and future are particularly useful.

Placing emissions in the context of a baseline or business-as-usual scenario, compared to alternative or new management, is necessary. For Key Finding 3, it is the relative change in carbon stocks and emissions associated with activities, along with tracing these activities to their functions in human well-being, that is most needed by decision makers (see Ch. 6: Social Science Perspectives on Carbon, p. 264). This information often is embedded in science-based models, but to be useful it must be aggregated or synthesized using established carbon accounting protocols.

Carbon accounting of direct and indirect impacts of bioenergy production and consumption has been analyzed (Adler et al., 2007) and included in energy and natural resource economic models (Frank et al., 2011; Mu et al., 2015). While carbon accounting in forestry has a long history of development (Schlamadinger and Marland 1996), there remain issues and debate around the effects of wildfire management on net emissions (Campbell et al., 2012; Hurteau and North 2009) and the use of wood products to offset emissions (Lippke et al., 2011; McKinley et al., 2011). Much of the debate surrounds a relatively new finding that conducting carbon accounting and life cycle analysis at the landscape scale is more representative of the net impact of policies and practices on carbon stocks than doing so at a field or plot scale (Galik and Abt 2012; Johnson 2009). Skog et al. (2014) provides a recent summary of practices that are most effective for reducing net emissions. Developing consistency in accounting and projections across the energy and land sector, along with the tools needed to represent upstream, downstream, and landscape-scale impacts, would be useful for decision making.

Major uncertainties

Representation of net carbon fluxes will become more accurate with the inclusion of established carbon accounting methods. This is evident in the science publication record that illustrates convergence of net emissions estimates associated with changes in management.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Estimating net carbon emissions using established and state-of-the-art carbon accounting methods will increase the usefulness of carbon cycle science results for decision makers. Conducting more research in this area, particularly among researchers involved in carbon accounting and basic carbon cycle science, will be essential to generating science-based findings useful for decision making.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Improvements in projection capabilities very likely will help guide decisions associated with energy, land use, and the carbon cycle. Increased use and development of accounting and attribution methods also are highly likely to improve the understanding of changes in carbon stocks and emissions and the application of this understanding to decision making.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, different methods of carbon accounting result in different estimates of carbon stocks and emissions, thereby resulting in inconsistent science results. Use of established carbon accounting methods by researchers in carbon cycle science research will increase consistency in carbon emissions estimates associated with given activities, thereby providing more useful information to decision makers and more useful metrics for comparison within the research community.

KEY FINDING 4

Developing stronger linkages among research disciplines for Earth system processes, carbon management, and carbon prediction, with a focus on consistent and scalable datasets as model inputs, will improve joint representation of natural and managed systems needed for decision making (*high confidence*).

Description of evidence base

Integration and coordination among global climate models, land models, and IAMs are occurring. National land management models and natural resource economic models also are becoming increasingly integrated. However, there remains a gap between global climate and IAMs and national land-use and economic models. The latter are used more often for decision making, but the former are critical in understanding global feedbacks among carbon, climate, economics, and land-use change. For Key Finding 4, increased communication and links between global drivers and subnational dynamics that impact carbon (Beach et al., 2015; de Vries et al., 2013; Kraucunas et al., 2014; Verburg et al., 2009) could help develop comprehensive science-based systems to better inform decision making. Efforts like this will depend on cross-sectoral and cross-scale research to better understand how to integrate or link needed components and scales.

Major uncertainties

Uncertainties exist in successful development of models across scales (e.g., local, regional, continental, and global).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

A more complete picture of carbon dynamics across scales, using more realistic representation of actual stocks and emissions, will increase the accuracy of carbon models and their use by decision makers.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The likelihood of impacts is high, although developing links between national- and global-scale data and models can be challenging, and success is less certain.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, connections between global biogeochemistry and climate models with subnational land management models will be useful to understand the feedbacks between global carbon cycles and carbon management activities. Linking models or model output and input is often challenging and includes a level of inherent uncertainty.

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