21 Climate Change and Terrestrial Ecosystem Management: Knowledge Gaps and Research Needs

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21.1 INTRODUCTION

Atmospheric concentrations of greenhouse gases (GHGs) are increasing as a result of human activities (Chapters 2 and 4). This trend began with settled agriculture, and conversion of natural ecosystems to cropland, rice paddies, and pasture has resulted in measurable increases of CO_2 and CH_4 over the past 8000 and 5000 years, respectively.[1] With the beginning of the industrial revolution, release of CO_2 from the burning of fossil fuel has added a new dimension to this phenomenon, and rates of change have continually increased through the 19th and 20th centuries. Current atmospheric levels of CO_2 are higher than any documented within the past 400,000 years and, without effective mitigation, are projected to reach twice pre-industrial levels by the end of the 21st century (Chapters 2 and 3).

Although it is hard to separate direct effects of climate change from other global change impacts, there is mounting evidence that effects of GHG-related warming can already be detected (Chapters 3 and 4). Increases in the frequency of fire in Canadian forests over recent decades, for example, may be in part attributable to climate warming, and there have been significant regional and continental-scale trends in budding, leaf emergence, and flowering — all phenological events directly controlled by temperature (Chapter 3). The warming expected to accompany future increases in atmospheric GHGs will further accelerate such changes, and agronomic impacts alone have significant implications for global food security, especially given an expected 50% increase in human populations between 2000 and 2050.[2] Other projected effects of climate change include a rapid displacement of major biomes (Chapters 9 and 10) and increased frequency and severity of natural disasters, with serious impacts on human lives and economic systems (Chapters 2 and 3). Given these challenges, understanding of climate-change mechanisms and their effect on biological systems is an important research priority, with land managers and policy makers needing information from scientists to develop effective strategies for adaptation (Chapters 2 and 5) and mitigation (e.g., Chapters 9, 11, 12, 13, 15, and 16).

Much of the human-induced increase in atmospheric GHGs is due to perturbations of the global carbon (C) cycle, with fossil-fuel burning and land-use change (deforestation) as the primary mechanisms (Chapters 4 and 9). So far, therefore, human alterations of the biosphere have been part of the problem, contributing ~25% of all anthropogenic C emissions in the 1990s (Chapter 9). Future cycling of C in the biosphere will be affected by both human land use and climate change, and the complexity of climate-biosphere interactions makes net effects hard to predict (e.g., Chapters 2, 4, 5, and 9). However, human control over global C cycle processes could also make the biosphere part of a climate solution, if changes in land use or management can prevent or offset GHG emissions (Chapters 5, 9, 11, 12, 16).

Drawing on information presented throughout this book, this chapter identifies key knowledge gaps relating to climate and climate-change effects on agriculture, forestry, and wetlands. It further points toward research needed to make management of these ecosystems part of a solution, by identifying gaps in the current understanding of biosphere-based adaptation or mitigation strategies. The list presented here is only concerned with climate change — biosphere interactions, and with questions of land use or management where they intersect with this topic. It cannot tackle the much larger subject of "global change," or strategies for GHG mitigation that are not biosphere based. Further, it focuses on science needed to support economic or policy decision, without making reference to specific market or legislative tools. It also makes no attempt to include knowledge gaps relating to the development of economic or policy mechanisms needed to make biosphere-based GHG mitigation a functional and attractive option. For an introduction to this field, the reader is referred to Chapter 19.

21.2 KNOWLEDGE GAPS AND RESEARCH PRIORITIES

Three overall questions should guide a holistic approach to research into sustainable resource management in a climate change context:

1. Can terrestrial ecosystems, which have helped to moderate the globally coupled C-cycle–climate system within a reasonably narrow domain of CO_2 and climate for at least 420 million years (Chapters 2, 4, and 9), be managed so as to return the system to its previous narrow domain of co-variation?
2. Should such mitigation efforts fail, what will be the new C-cycle–climate domain, and how will terrestrial ecosystems respond? How will agricultural and forest resources be altered, and how will continued increases in fossil fuel emissions affect active C-pools and C-fluxes?
3. If mitigation is feasible (in the sense of question 1), how can agricultural, forest, and peatland ecosystems be managed to best provide a net sink for atmospheric CO_2, provide the needed food and fiber resources, and be a part of the solution for overall improvement of the global environment?

The following sections summarize key research needs to address these overall questions, including different components of the climate system as well as our understanding of current ecological conditions, climate change impacts, and adaptation or mitigation strategies.

21.2.1 The Climate System

1. *What are the processes that determine the role of the biosphere in the climate system, and how can they be represented in global and regional circulation models?* Climate-biosphere interactions are often nonlinear, involving complex interactions between energy, biogeochemical, and H_2O cycles (Chapter 2). The newest generation of GCMs attempt to incorporate biospheric feedbacks by including explicit (although simplified) representations of these processes, but significant challenges remain. These include especially the scaling of exchange processes that occur over short time- (hours and days) and small spatial (plant and stand-level) scales up to the longer (decades and greater) and larger ones (regional and continental) that effect global patterns. In such scaling, responses that cause significant changes in ecosystem physiology (plants and soils) or distribution must be included.
2. *What is the relative importance of different forcing factors in driving observed "recent" changes in temperature?* As discussed in Chapter 2, different climatic forcing factors (solar activity; GHGs; aerosols) vary

independently, and some (e.g., sulfate aerosols from volcanic eruptions) can have a net cooling effect. Disentangling the relative contribution of these forcing mechanisms to past climatic changes — and projections of their likely future variability — are critical to accurate climate projections and associated estimates of uncertainty.

3. *Are trends in means related to the frequency and severity of extreme events, and if so how?* Ecological and societal impacts of climate change depend both on long-term trends in means (i.e., climate), and on changes in daily, intra-annual, and inter-annual patterns of extremes (i.e., extreme weather). Projected increases in the frequency and severity of drought for example (Chapters 2, 3, and 5) may limit agricultural productivity in some regions, while outbreaks of insect pests such as mountain pine beetle (Chapters 3 and 17) may spread beyond their present range with a warming of minimum winter temperatures. Ability to project future trends in extremes as well as trends in means is key to the development of appropriate risk scenarios, especially at regional and local scales (see next point).
4. *How will climatic parameters (especially precipitation and extreme weather conditions) change at regional and subregional scales?* Although most current climate models agree on the expected direction of global trends, projected changes especially in precipitation tend to vary at regional levels (Chapter 2). Moreover, weather patterns (including extreme events) may shift in space and time, even if large-scale regional means remain unchanged. Climate-change impacts such as drought, wild fires, ice storms, and floods are often associated with locally extreme weather, and management is carried out at local scales. To develop adaptation strategies that tailor to biotic and economic realities of specific regions, improved projections (and error estimates) are needed at regional and subregional scales.
5, *Will there be changes in intra-annual climatic patterns?* Intra-annual climatic patterns such as the timing of rainfall and length of growing season affect crop survival and harvesting schedules, with strong implications for the productivity of both agricultural and forest systems (Chapters 3, 5, and 17). Significant changes in the timing of phenological events in recent decades (Chapters 3 and 17) indicate that changes are already occurring, and the ability to forecast intra-annual patterns of climate events and their effects on plant phenology and life cycles is important in developing adaptation strategies (Chapter 3).
6. *How will anthropogenic emissions and atmospheric concentrations of GHGs change over time?* GHG emission scenarios are a key element of uncertainty in climate change projections (Chapter 2). Apart from highlighting the potential range of future climatic trends, emission scenarios are an important component of decision tools, as they allow for a weighing of likely costs and benefits of specific policy decisions. Realistic emissions scenarios have to account for biosphere feedbacks as well as human effects, the latter influenced by both overall population growth and attitudes to land use and fossil-fuel use. Human behavior is complex and

hard to predict, but the ability to do so is critical to emission scenarios and the forecasting of future resource use.

7. *How will current buffering capacities (e.g., oceanic, biotic, pedologic) be altered by changes in climate and further emissions of CO_2 and other GHGs?* As discussed in Chapters 2, 4, and 9, only 40 to 50% of the CO_2 emitted from fossil fuels and land-use change currently remains in the atmosphere. The rest is returned to terrestrial and oceanic sinks, providing an important buffering effect against GHG-related climate effects. The permanence of C taken up by biotic sinks in particular is currently poorly understood, and the potential for further ecosystem C sequestration is likely to decrease with increased temperatures (Chapter 4). Understanding of mechanisms that control the ability of natural systems to buffer anthropogenic emissions is needed to predict future GHG trajectories.

21.2.2 Current Stocks and Fluxes

Determining baseline data for terrestrial ecosystem C stocks and fluxes is an essential first step to evaluating climate- or human-induced changes. As discussed in preceding chapters, fundamental gaps in understanding for all sectors still limit our ability to predict the consequences of different management actions on C fluxes in a changing environment. A comprehensive understanding of processes that control terrestrial ecosystem C dynamics and their interactions with the biosphere and hydrosphere is needed to develop recommendations for land managers. Important research domains and questions include the following:

21.2.2.1 C Dynamics of Different Ecosystem Types

1. *What are current ecosystem distributions and their associated C stocks?* Data of this type are needed for most managed and natural ecosystem types, including agricultural land, pastures, woodlots/plantations, forests, and wetlands. Although data exist for some regions and sectors, these are not complete (see, e.g., Chapter 18), and their accuracy is usually not well characterized (Chapters 16 and 17). Without basic data on current ecosystem distributions and extent, C-stock assessments will be inaccurate and projections of change unreliable.
2. *What is the current source/sink status of different ecosystem types, and what are rates of C sequestration under natural conditions (or current management)?* While data on C accumulation and sequestration rates are increasingly available for some ecosystem types and components, sparse data networks and high interannual variability confound the calculation of averages and comparisons between ecosystem types or regions. Comprehensive data on all component C fluxes are known only for a few intensively studied research areas, and are rarely available at the landscape level. In addition to more data collection, there is an urgent need to develop reliable spatial and temporal scaling techniques in order to maximize the usefulness of existing data sets.

3. *What are the factors that control C sequestration in managed and natural ecosystems?* Even in cases where rates of C sequestration are documented, causative factors needed to evaluate the vulnerability of these indicators are often poorly understood, and existing data tend to be inadequate for future change predictions. Dependence of C sequestration on nutrient (N, P, S) and hydrological cycles (Chapter 4) limits our ability to predict effects of climate change on agricultural ecosystems (Chapter 3), and the combined effects of temperature and moisture-related variables on the C-sequestration capacity of peatlands are poorly quantified (Chapter 10).
4. *How sensitive are different ecosystem components to climatic variability, and how can information on total-ecosystem C flux be partitioned into component processes?* Whole-ecosystem measurements of CO_2 exchange (e.g., from eddy-covariance flux towers) examine the net C balance of a site under a given set of climatic and environmental conditions, and are the most direct way to assess the short-term C source/sink status (Chapter 17). However, the response of different ecosystem components to environmental variability is often nonlinear, and understanding of climate-change effects over longer times requires a partitioning of net response into different component processes (e.g., gross and net primary productivity, autotrophic and heterotrophic respiration). Methodologies or models that can partition observed responses and "bridge the gap" between functional levels of ecosystem C cycling are necessary to understand current ecosystem behavior, and to predict future responses.
5. *How important are belowground processes in net ecosystem C exchange?* Belowground processes are hard to observe or measure and have often been neglected in studies of ecosystem C dynamics (e.g., Chapter 5). Few reliable estimates of belowground productivity are available for most ecosystem types, and factors such as the importance of fine-root dynamics or mycorrhizal associations in soil organic matter (SOM) turnover (Chapter 17) or the sensitivity of soil microbial communities to temperature and moisture conditions (Chapter 5) are poorly understood. Belowground processes control rates of ecosystem C and nutrient cycling and are a key component of biosphere-climate interactions.
6. *How do different disturbance events (harvesting, fire and insect defoliation) affect C dynamics?* Ecosystem disturbance leads to biomass C losses that can be minor (e.g., from a low-level insect attack) or severe (e.g., from clear-cut harvesting or stand-replacing wildfire) (Chapters 4 and 9). Beyond immediate C losses, however, disturbance influences many aspects of C and nutrient cycling, and future trajectories can depend on factors such as the fate of dead biomass that remains on-site (Chapters 4 and 9). To fully evaluate the importance of disturbance to ecosystem C dynamics, data are needed on the short- and long-term effects of specific disturbance types on different aspects of C and nutrient cycling (e.g., effects of fire on above- and belowground C allocation, N cycling, or fine root dynamics).

21.2.2.2 Major Non-CO_2 Greenhouse Gases

1. *How are N_2O emissions from agricultural systems related to hydrology, soil environment, and nutrient cycling?* Nitrous oxide emissions from soils are dependent on hydrology as well as N availability (Chapter 12), and the relative importance of these variables in driving emissions is often poorly understood. More data are needed, for example, on the effect of landscape structure and management practices on N_2O emissions, on relationships between fertilization or N-fixation and N_2O production, and on the importance of C/N relationships in controlling N_2O emissions (Chapter 16). Information of this type is critical to evaluate the full GHG impact of alternative management options, and for the development of mitigation strategies.
2. *What are the factors that control CH_4 emissions from wetlands and soils?* Methane is a powerful GHG that is released during anaerobic decomposition in waterlogged soils and wetland systems, with the net flux of CH_4 dependent on factors such as temperature, nutrient status, oxygen availability, and water-table depth.[3] Although effects of some of these factors are well documented for some wetland types and systems, their interactions are often poorly understood, and potential trade-offs between lower CH_4 and higher CO_2 emissions from peatlands under an altered climate (Chapter 3) cannot be adequately quantified.
3. *How are CH_4 emissions from ruminant livestock related to dietary composition and genotype?* Although manure can be an important source of CH_4 especially in intensive livestock systems, most livestock CH_4 emissions are due to microbial digestion of cellulose by either fore- or hindgut fermentation. Many studies have shown clear effects of feed or pasture composition on CH_4 production (Chapters 12, 13, and 15), but the influence of different dietary compounds is often hard to separate, and mechanisms that control observed responses are largely unknown (Chapter 12). The same is true for genetic and physiological factors that control differences in CH_4 production between individual animals or breeds (Chapters 12 and 13), and all these are basic knowledge gaps that hinder the development of mitigation strategies.

21.2.3 Future Importance of Disturbance

Disturbance and subsequent cultivation or succession are important drivers of landscape patterns of C sources and sinks. In managed terrestrial ecosystems, for example, the current spatial distribution of CO_2 sinks may largely reflect historic patterns of land-use change, and areas that act as strong sinks may be recovering from recent anthropogenic or natural disturbance (Chapter 9). Types of disturbance with potentially significant impact on future C emissions include fire (Chapters 3, 9, 10, and 17), pests and diseases (Chapters 3, 5, 9, and 17), extreme climatic events (Chapters 2, 3, and 5), permafrost collapse (Chapters 3 and 10), and human land use/land-use change (Chapters 4 and 9). Key questions relate to the future frequency and severity of different disturbance events, and to their potential interactions and cumulative effects.

1. *What will be the effect of climate change on the frequency and severity of natural disturbance events?* One of the projected effects of climate change is a change in the frequency and severity of natural disturbance events such as pest outbreaks and fire (Chapters 3 and 17). However, the occurrence of such events is highly stochastic and hard to predict accurately in space or time (Chapter 17). To generate appropriate risk scenarios, more data are needed about the role of climate and specific local conditions in influencing the likelihood and severity of different disturbance events (Chapter 5). Resulting probability functions have to be validated wherever possible, and should be incorporated into stochastic models for risk analysis.
2. *How will patterns of anthropogenic disturbance change with increasing population pressure and changes in management strategies?* Humans have already affected many aspects of the C cycle-climate system, and human land use (agriculture/forestry) and land-use change (e.g., deforestation) are strong forcing mechanisms of biosphere GHG dynamics and C stocks (Chapter 4). Effects of anthropogenic disturbance are likely to increase with increasing population pressure, and their accurate forecasting is an important component of future climate projections (Chapter 2) and biosphere C stocks (Chapter 4).
3. *Will there be interactions between disturbance types, and what are the likely cumulative impacts?* Little is known about interactions or cumulative effects of different disturbance types. More data are needed, for example, on effects of management or land-use patterns on the population dynamics of pests, or on interactions between forest susceptibility to disease and fire (Chapter 17). Cumulative effects of multiple disturbances can severely impact C sink potentials of entire ecosystem types (Chapter 10), and strategies to maximize terrestrial C sequestration should be based on a firm understanding of relevant processes and mitigation options.

21.2.4 Ecosystem Response to Projected Changes

Ability to predict changes in ecosystem behavior resulting from future climate change is crucial to the planning of appropriate adaptation and mitigation strategies. While overall questions are the same for all ecosystem types, there are differences between managed (agriculture and many forests) and unmanaged (most wetlands) systems in both current knowledge and the potential to enhance C-sink capacities through active management. Consequently, key research gaps differ between these sectors.

21.2.4.1 Agriculture and Forestry

Climate change and increasing human populations are combined stressors that challenge policy makers and land managers to ensure food security, especially in developing countries. To support decision processes, improved knowledge is needed of the impacts of climate change in agroecosystems, especially in areas of soil quality

(Chapter 4) and agronomic productivity (Chapter 5). Forests supply human populations with building materials, food, and fuel, and are thought to play an important role in buffering anthropogenic emissions (Chapter 9). At the same time, both the distribution and productivity of these forests will be altered by climate change, a fact that has to be considered in developing adaptation or mitigation strategies. Important knowledge gaps in understanding climate change impacts on agricultural and forest systems are the following:

1. *What are the effects of elevated temperature and precipitation changes on plant growth, life cycles, and productivity?* Variation is a key feature of biological systems, and different species or cultivars differ in overall productive potential, tolerance to temperature and moisture stress, and many life history traits that may be important in a climate change context. Effects of climatic parameters on productivity and life cycles are an important knowledge gap, since they affect the selection of appropriate species/cultivars to maintain productivity under an altered climate (Chapters 3 and 5).
2. *How will these factors impact soil processes such as nutrient dynamics and the structure and functioning of decomposer communities?* Faster rates of nutrient cycling and C mineralization under a warming climate may offset the effect of increased plant production, leading to a net decrease in ecosystem (especially soil) C storage (Chapter 4). Effects of temperature changes have rarely been traced through full biogeochemical cycles, and impacts on decomposer and microbial communities are not well known. All these factors are important in trying to predict effects of future warming on GHG trajectories, or the potential for active management to enhance biosphere C stocks.
3. *How are climate-change effects exacerbated (or mediated) by specific local conditions such as nutrient (N, P, S) limitation, high nighttime temperatures, drought stress, and degraded soils?* At the present time, little is known about interactions between climate change-related variables (temperature, CO_2) and other environmental stressors such as radiation (UV-B), soil degradation, or nutrient limitation (Chapters 3 and 4). Information of this type is needed in order to predict effects of climate change on ecosystem functioning especially at local or regional levels, and to develop risk scenarios and adaptation strategies.
4. *What is the magnitude of the CO_2 fertilization effect, and will it change over time?* As discussed in Chapters 4, 5, and 17, plant responses to enhanced CO_2 differ between species and environmental conditions, and whole-ecosystem studies into CO_2 fertilization have only just begun. To assess whether CO_2 fertilization can partially offset anthropogenic GHG emissions, long-term data are needed to examine the sustainability of increased plant production, possible interactions between CO_2 and temperature effects, and the potential for management to enhance the magnitude and duration of CO_2 fertilization. To obtain such data, current ecosystem-scale studies should be continued wherever possible.

5. *How important are extreme events in controlling the response of agricultural and forest systems to climate change?* Environmental extremes (especially flooding or drought) can destroy entire harvests, and they may limit the potential of some areas to support certain crops (Chapter 5). Data on the sensitivity and resilience of different species to extreme climatic events are needed, for example, to select suitable species for food production or for afforestation (Chapter 9), and to anticipate management costs required to support bioenergy crops in a given region.
6. *How will the geographic distribution of different forest types change under a new climate, and how fast will these changes occur?* As discussed in Chapter 9, the distribution of major forest biomes is expected to shift northwards under a changing climate, but rates of change are hard to predict from current data. To determine (and manage) future forest C-stock or bioenergy potentials, information is needed on the climatic sensitivity of different species and life history stages, on the importance of disturbance in driving range shifts, and on likely response times and natural capacities for dispersal.

21.2.4.2 Wetlands

Northern wetlands (especially peatlands) contain a disproportionate amount of C compared to other ecosystem types and are an active sink for atmospheric CO_2 but a source of CH_4.[4] As discussed in Chapters 10 and 18, C cycling in wetland is intricately linked to hydrological processes, making these ecosystems inherently sensitive to climate change. Unlike agricultural systems and many forests, the large northern wetland areas of Canada and Siberia are mostly unmanaged, and even basic information on their C stocks and dynamics is often lacking. Key knowledge gaps in relation to climate change impacts on the C stocks and GHG source/sink relationships of wetlands are the following:

1. *How will climate change affect wetland hydrology?* Many climate-change projections suggest a drying especially of mid-continental regions (Chapters 2 and 3), i.e., in areas that currently support extensive wetland systems. Direct effects of drying climates on wetland water tables are poorly quantified, and areas where climate scenarios predict extreme future warming and drought tend to be those where human impacts on wetlands have been highest in the past (Chapter 18). The cumulative effects of climate change and human land use on wetland hydrology are important for development of wetland sensitivity ratings and regional assessments.
2. *What will be the effects of increased temperatures and often lowered water tables on productivity and C mineralization in peatlands?* As discussed in Chapter 10, interactions between temperature and water tables and their net effect on plant production and decay in peatlands are poorly quantified. Information of this type is urgently needed to predict C source/sink relationships of peatlands under a changing climate.

3. *How will climate change affect peatland distribution and botanical composition, and what are the consequences of these changes for C cycling?* Changes in peatland distribution and community composition expected under a changing climate have marked implications for future C cycling (Chapters 10 and 18). However, little is known about the potential for plant-driven or hydrological buffering effects, and rates of change (especially C loss from existing deep peat deposits) are impossible to predict from current data. Major knowledge gaps include species response rates, the effect of community change on short- and long-term GHG balances, and the importance of local factors in peatland establishment and disappearance.
4. *How will climate-induced changes in permafrost regimes affect the future GHG balance of peatlands?* Permafrost melt is a widespread phenomenon in peatlands of boreal western Canada (Chapters 10 and 17) and expected to increase in the 21st century (Chapter 3). Localized permafrost melt has been shown to increase C sequestration in peatlands (Chapter 10), but net long-term effects on C storage and GHG dynamics are far from understood. Major knowledge gaps include effects of widespread permafrost melt on peatland hydrology, long-term trajectories of organic matter production and decay at the ecosystem level, and net GHG effects resulting from differential responses of CH_4 and CO_2 to permafrost degradation.

21.2.5 Strategies/Technologies for Adaptation or Mitigation

In spite of uncertainties regarding the magnitude and effects of climate-related changes, scientists and policy makers are faced with the need to develop adaptation and mitigation strategies. Adaptation attempts to limit impacts of climate change through anticipatory or reactive management, for example, by implementing mechanisms that maintain the productivity of forest or agronomic systems (Chapters 3, 5, and 9). Biosphere-based mitigation involves the adoption of management strategies that prevent or offset GHG emissions (Chapters 5, 9, 11, 12, and 16), making the biosphere part of a strategy to prevent further atmospheric GHG increases. The identification of effective technologies for mitigation or adaptation is an important researchable issue.

21.2.5.1 Agricultural and Forest Ecosystems

1. *Development of varieties adapted to specific local conditions.* The development of high-yielding, high-temperature crop varieties is important especially in the tropics, where adaptation to climate change is complicated by added stressors such as soil degradation and increasing population pressure (Chapter 4). In many other regions, adaptation can be achieved by selection from existing cultivars (Chapter 5), but mechanisms are needed to facilitate technology and information transfer to local farmers.

2. *Development of effective technologies for the reduction of CH_4 from livestock.* Altered diets, vaccination/defaunation and development of stock with naturally low CH_4 production are all potential mechanisms to decrease CH_4 emissions from livestock. The relative effectiveness of these different methods needs to be investigated for different livestock systems (e.g., pasture vs. feedlots; Chapters 12, 13, 16), and easy, affordable implementations have to be made available to livestock managers.
3. *Methods of livestock/pasture management that reduce N_2O emissions.* Mitigation options to reduce N_2O emissions from rangeland and pasture systems include dietary manipulation to decrease nitrogen excretion (especially in urine), nitrification inhibitors, soil drainage or removal of stock from wet pasture, and fertilizer management/liming (Chapter 12). The relative efficacy of different methods needs to be investigated for different management systems, and positive side effects (e.g., increased animal efficiency with dietary augmentation; Chapters 12 and 15) need to be fully investigated.
4. *Methods of manure management that minimize GHG impacts.* Animal manure can be a significant source of GHGs, especially in intensive livestock systems. The mitigation benefits of different manure treatment options (application, on-farm treatment systems, composting, or storage) need to be investigated (Chapter 16), including GHG benefits from the use of manure as an on-farm energy source (Chapter 15).
5. *Potential for C sequestration in agricultural and forest soils.* Agricultural and forestry practices that maximize soil C sequestration and retention often have positive effects on both GHG emissions and plant productivity, but their relative effectiveness can differ widely between regions (Chapter 19). Short- and long-term C benefits of management options such as no-till systems (Chapters 4, 5, and 16), various crop rotations (Chapter 16), different harvesting/site preparation methods (Chapters 4 and 9) or conversion of cropland to grassland or forest (Chapters 5, 8, and 9) should be investigated under different climatic and environmental conditions, and any positive side effects (e.g., increased nutrient retention) more fully evaluated.
6. *Strategies to minimize GHG emissions through the entire cycle of production.* Efficient techniques are needed to help trace GHG effects through the entire life cycle of a product or commodity. By identifying "hidden costs," such methods can evaluate the full GHG impact of different building materials (Chapter 9) or land-management practices (Chapter 4), and they can help to avoid unnecessary emissions. In the context of GHG accounting, these methods are needed to do complete cost/benefit analysis and evaluate economic potentials of mitigation options such as biofuels (Chapter 11), on-farm energy production (Chapter 16), or increased use of forest products (Chapters 9 and 19).
7. *Potential for C sequestration in forests and forest products.* Forests are a major biosphere C pool and play a key role in potential strategies to increase terrestrial C sequestration (Chapter 9). Research is needed into the feasibility

and C-sink potential of afforestation projects in different regions, and into mechanisms to reduce deforestation. The potential for increased use of forest products to increase the residence time of sequestered C and avoid fossil fuel emissions during the production of alternative materials (e.g., cement) needs to be more fully evaluated (Chapters 9 and 19).

8. *Potential for bioenergy production.* Use of bioenergy from agricultural or forest systems avoids fossil-fuel emissions and has strong potential as a strategy for GHG mitigation. Research is needed into technologies for the production and processing of bioenergy sources, and into ways to optimally integrate bioenergy with existing fossil-fuel energy (Chapter 11). Analysis of both large-scale (e.g., forest management for biofuels) and small-scale (use of mill/farm waste or livestock CH_4 as an on-site energy source; Chapters 15 and 16) projects is needed to determine the GHG and economic benefits of bioenergy solutions.
9. *What is the permanence of C sequestered in different GHG mitigation strategies?* The permanence of sequestered C is an important consideration in evaluating the effectiveness of mitigation strategies, and is an issue that complicates the handling of offset credits in current trading markets (Chapter 19). Carbon fixed in biomass stocks is quickly returned to the atmosphere when a crop is harvested, unless it is transferred to a longer-lived pool such as forest products. However, forest product C fluxes are hard to trace in space and time, and credit for them is the subject of ongoing negotiation (Chapters 9 and 19). Carbon fixed in soils and wetland sediments has high potential permanence (Chapters 10, 16, and 18), but actual turnover rates are often poorly quantified, and information is needed on the effects of management on long-term retention (e.g., Chapter 19).

21.2.5.2 Wetlands/Peatlands

1. *How can the vulnerability of C in wetlands and peatlands be minimized?* As discussed in Chapters 10 and 18, C cycling in wetlands is intricately linked to hydrological processes, and information is needed on potential mitigation options to limit hydrological impacts of climate change. This is especially true for wetlands already affected by human land use such as agriculture or large-scale industrial activity (e.g., the oil sands development in northern Alberta). Even if such wetlands are not destroyed directly by human activities, cumulative effects may occur from lowered water levels and factors such as increased nutrient input or soil erosion.
2. *How can the C-accumulation potential of drying peatlands be maximized?* Finnish data indicate that increased tree productivity with lowered peatland water tables may help to offset increased soil C losses,[5,6] and afforestation of drying peatlands may be a potential mitigation mechanism under climate change. Data are needed on the economic feasibility and the short- and long-term mitigation potential of such projects in different regions, and on the susceptibility of peatland forest plantations to catastrophic C losses by fire.

3. *How can C accumulation in disturbed peatland sites be restored, and how can new functional wetlands be created?* Active restoration and the re-creation of functional wetlands can reverse effects of human disturbance and restore the GHG and environmental benefits of wetland systems (Chapters 10, 16, and 18). Practical knowledge gaps that limit restoration projects and assessment of their long-term GHG benefits include the long-term sustainability of restored water levels, potential effects of invasive species, and the selection of suitable species complements to maintain wetland function (or C sequestration) under a changing climate.

21.2.6 Methodological and Interdisciplinary Issues

Numerous compounding factors complicate the prediction of climate-change effects on ecosystem C dynamics. Interactions between climate change and altered disturbance regimes, for example, or cumulative impacts arising from the joint action of climatic and anthropogenic change, may produce effects that are hard to predict from current data. Given the complexity of climate–human–C-cycle interactions, there is a strong need for integrated data management, and for across-scale and across-ecosystems studies that look beyond narrow disciplinary interests. Modeling plays a key role in this process because it can simulate complex phenomena, integrate different types of data, and bridge conceptual, temporal, and spatial scales. Key methodological challenges that span different fields of climate-change research are the following:

1. *Development of multimodel, multiscenario approaches to generate climate projections and conduct risk assessment.* Variations in the output from different models reflect uncertainties in our current understanding of relevant processes and carbon–climate interactions. As discussed in Chapter 5, a multimodel, multiscenario approach is needed to assess likely effects of climate change at local and regional (management-relevant) scales and to constrain scenario predictions and their associated measures of uncertainty.
2. *National databases and frameworks.* There is a pressing need to establish national databases for information such as C stocks for predominant land-cover types and classes. National data banks can be an integral component of regional data banks and can supplement more-detailed local data sets. Data-access protocols to permit use by researchers, land managers, and policy makers must be established.
3. *Development of methods for the measurement and monitoring of C stocks and fluxes in a precise, transparent, and credible manner to support accounting frameworks*. There are many practical obstacles to the effective integration of agricultural, forest, and wetland ecosystems into C accounting frameworks. These include, for example, the economic impossibility of directly measuring local changes in soil C stocks over the short interval of commitment periods (Chapter 19), and a lack of technologies to accurately measure livestock feed intake or GHG emissions (Chapter 12). The

development of practical, cost-effective methods to support accounting frameworks is critical to the success of these economic mechanisms.

4. *Integration of measurements with respect to space and time.* Temporal and spatial scaling techniques are critical to our ability to monitor current ecosystem C distributions and fluxes and to the prediction of climate change impacts. As discussed in Chapter 17, an ability to use large-scale measurements from remote sensing may allow for long-term, cost-effective monitoring of terrestrial C stocks and dynamics. Development of reliable methodologies to achieve this is an important research need. Satellite-derived estimates need to be fully verified against ground data, and new ground data will be required in some areas.
5. *Assessment and propagation of uncertainty.* Uncertainties associated with projections of climate change and climate-change impacts are an important component of risk assessment. Methods are needed to more accurately quantify the uncertainty associated with model estimates, and to propagate errors through coupled climate and biosphere models, as well as other assessment procedures (Chapter 17).

21.3 CONCLUSION

Climate change is real. While not all of the changes currently observed are directly attributable to human causes, several challenges of global significance are directly or indirectly related to climate change. Food productivity and security; the availability and safety of water supplies; catastrophic events and their impacts on the quality of human lives and economic systems — all make climate change a key phenomenon and challenge of the 21st century. The issues discussed in this chapter are a summary of major research needs relating to climate change and its interaction with biosphere processes and management. Beyond the broad conceptual framework established by the subheadings, points are presented in no specific order, and no attempt has been made to rank their relative importance. While this may appear as a major omission to many readers, differences in geography, economies, mandates, and priorities render a single ranking practically impossible. The way this list should be used depends on context.

As an obvious example, differences in the importance of methane in GHG budgets of different countries (Chapter 12) translate directly into differences in the potential impact of CH_4-reduction mechanisms relative to those for CO_2 and N_2O. Similarly, individual agencies within each country have very specific mandates, and consequent priorities will differ when it comes to the allocation of funds. Finally, decisions about adaptation or mitigation strategies in particular are made within economic and political contexts, and such contexts may vary in space and time. Countries like Canada that have large forest resources, for example, may have to weigh the relative benefits of managing forests for timber, C stocks, or biofuel production (Chapters 9 and 11), and "correct" answers (and consequent research priorities) may depend on the relative weighting of long- and short-term benefits.

Given likely limits to how much C can be sequestered into Earth's biota — and its often limited permanence — strategies to offset emissions through terrestrial C fixation will only be effective over limited (decadal to century) timescales.[7] During this critical period, however, they can serve as an important bridging mechanism while technologies to replace fossil fuel–based energy are put into effect. In the long term, the only solution to GHG-related warming is to curb fossil-fuel emissions, and some of the technologies that may help achieve this end are also biomass based (Chapter 11). This means that biosphere management could be an important part of future energy strategies, and afforestation projects in particular may yield both short- and long-term GHG benefits.

Finally, responsible ecosystem management is about more than just GHGs or carbon. A large number of C sequestration projects, for example, may be economically unviable in a GHG context alone (Chapter 19), but many yield ancillary benefits that may justify their implementation. Management practices that increase C retention in degraded soils, for example, yield both GHG benefits and are a long-term investment in soil quality (Chapter 4). Management for multiple landscape attributes such as C stocks, biodiversity, and recreational appeal can complicate assessments of additionality in an accounting context (Chapter 19); it is nonetheless responsible ecosystem management. Economic incentives related to C and GHG accounting are likely to play a key role in future land management strategies, and scientists have to provide policy makers with the information they need to devise incentives that promote ecosystem health and sustainability, as well as achieving effective long-term reductions in GHG emissions.

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