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Part I

Introduction

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Excerpt
More information

1

Linking Land Use and the Carbon Cycle

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AND BRADLEY C. REED

1. Introduction

The last few millennia have seen significant human intervention in the Earth system. For most of this time, the influence of humans on ecological processes, including the carbon (C) cycle, was limited to local-scale impacts through hunting and gathering and then through cultivation and animal husbandry. However, the start of the Industrial Revolution in the eighteenth century saw the collective action of humans begin to alter the C cycle at a global scale by changing the composition of the Earth's atmosphere (Hegerl et al. 2007). It is arguable that human impacts on global levels of atmospheric methane (CH_4) and carbon dioxide (CO_2) can be traced back thousands (not just hundreds) of years, largely driven by extensive land management through use of fire (Ruddiman 2003). Although the dominant anthropogenic influence on the global C cycle has resulted from the burning of fossil fuels, it has been estimated that land changes and land degradation have directly affected 39 to 50 percent of the land surface (Vitousek et al. 1997) and contributed to 30 percent of the total anthropogenic efflux of CO_2 to the atmosphere (see Chapter 3). Humans have become integral actors in the C cycle – at both local and global scales – to such a degree that many now argue that no point on the surface of the Earth, or ecosystem, has escaped the effects of human activity (e.g., Ellis et al. 2010; Turner, Lambin, and Reenberg 2007).

Central to the theme of this book is the notion that as humans alter the surface of the land through land use and land management, they change the pools and fluxes of C across the Earth. Human actions affect the fundamental structure and function of the ecosystems, therefore altering the amount of C stored above- and belowground; the rate of transfer between the surface and the atmosphere; and how much ends up in the rivers, streams, lakes, and oceans. For example, when a forest is burned to clear the land, a large portion of the aboveground C is released to the atmosphere, some remains on site, and some is leached into the hydrological system. Not all of these fractions are known with a high degree of precision, but they vary by ecological

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context and frequency, duration, and intensity of fire. If the land is then used for agriculture, tilling practices and plant uptake typically reduce soil C by 10 to 40 percent depending on, among other things, the depth of till, previous forest type, and soil texture (Robinson, Brown, and Currie 2009). However, as Chapter 15 points out, the effects of tilling are still incompletely known.

The effects of human activities that alter the C cycle are difficult to isolate. We can place most human activities into one of two broad categories: land use and land management, which is concerned with human choices about how to use the land and what types of activities and technologies are associated with manipulating the land, and fossil fuel usage, which involves human use of C-based fuels. Throughout this text, we are concerned primarily with land use and land management. These anthropogenic processes are difficult to untangle within the coupled natural-human system because they are driven by both the social and ecological contexts of people and locations. Biophysical characteristics such as land form, soil quality, and climate influence the productivity of a location for agriculture and simultaneously influence the aesthetic and economic appeal of a location for development or agricultural production. Geographic characteristics (e.g., distances to transportation infrastructure, water, and population) influence the economic returns from various land uses. Access to market opportunities, technical knowledge, and institutional constraints on the rights to use land (i.e., land tenure) affect the set of options available to users of the land. The resulting land system acts at the intersection of social and ecological contexts that collectively work to define the value of land, how it is used and who uses it, the approaches taken to manage the land and how land use and land management alter land cover, and the corresponding ecosystem functions and services provided by natural land covers (Figure 1.1).

The challenge for a successful integration of our understanding of land use and C cycle science research is to integrate knowledge of specific resources, human decision making and behavior, and feedbacks so that they may be leveraged to mitigate the impacts of resource use and land conversion on atmospheric C concentration. Furthermore, we need to be able to identify thresholds beyond which these systems might change and produce significant shifts in ecosystem function. An additional challenge lies in marshalling empirical observations about feedbacks between natural and social phenomena. Effectively, what is required is a holistic view of coupled natural-human systems that includes measurements and models of drivers and outcomes under various use and management strategies.

In addition to helping us understand the role and potential of land change in mitigating atmospheric C, the adoption of this point of view addresses the call “to consider forcings other than greenhouse gases” (Pielke 2009) when considering drivers of climate change. Because land use and land management influence the behavior of biophysical (e.g., albedo, evaporation, and heat flux), biogeochemical (e.g., C and nutrient cycling), and biogeographical (e.g., location and movement of species)

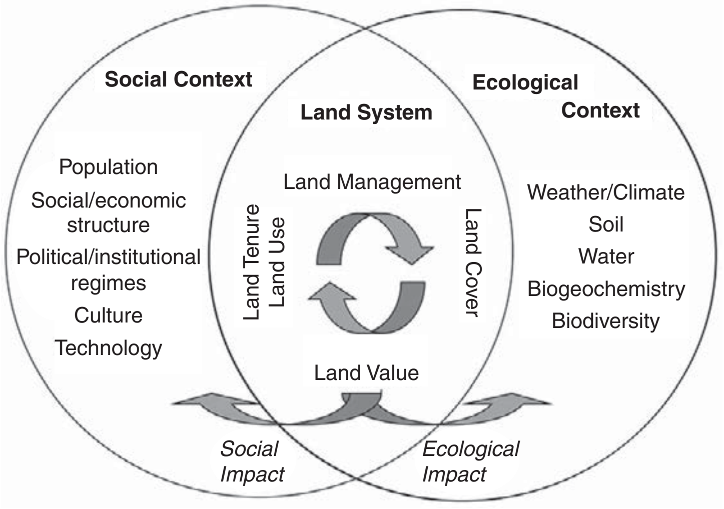

Figure 1.1. The land system acts at the intersection of social and ecological contexts. Collectively, these contexts define the value of land, who uses it and for what purpose, how the land is managed, and how these human alterations modify ecosystem functions and services.

processes, a better understanding of how natural and human systems are coupled will improve our ability to link demographics, behavior, policy, markets, and other human drivers of land use and land management "with their (broader) ecological ramifications and feedbacks to society" (Riebsame et al. 1994, p. 58).

1.1. The Role of Natural Processes in the Carbon Cycle and Climate Change

A long history of natural processes and events has altered the distribution of C among the Earth's land, atmosphere, and oceans. These processes have led to the storage of C in long-term organic reservoirs such as permafrost, coal and petroleum deposits, and ocean sediments, whereas events such as wildfires, volcanic eruptions, and even meteor strikes have released massive quantities of stored C to the atmosphere over short periods of time (Beerling and Woodward 2001). The consequences of these shifts in the amounts of C in different storage pools and the rate at which they occur have significant implications for human systems. For example, high atmospheric oxygen (O_2) concentrations during the carboniferous period led to the dominance of plant groups with high lignin concentrations. Over time, the plant remains were buried and formed the coal and petroleum deposits that humans depend on for fuel (Beerling and Woodward 2001).

Although C can change forms among liquids (e.g., carboxylic acids [CH_3-COOH]), solids (e.g., calcium carbonate [$CaCO_3$]), and gas (e.g., CO_2), the total amount of C within the Earth system remains virtually unchanged. This closed system permits

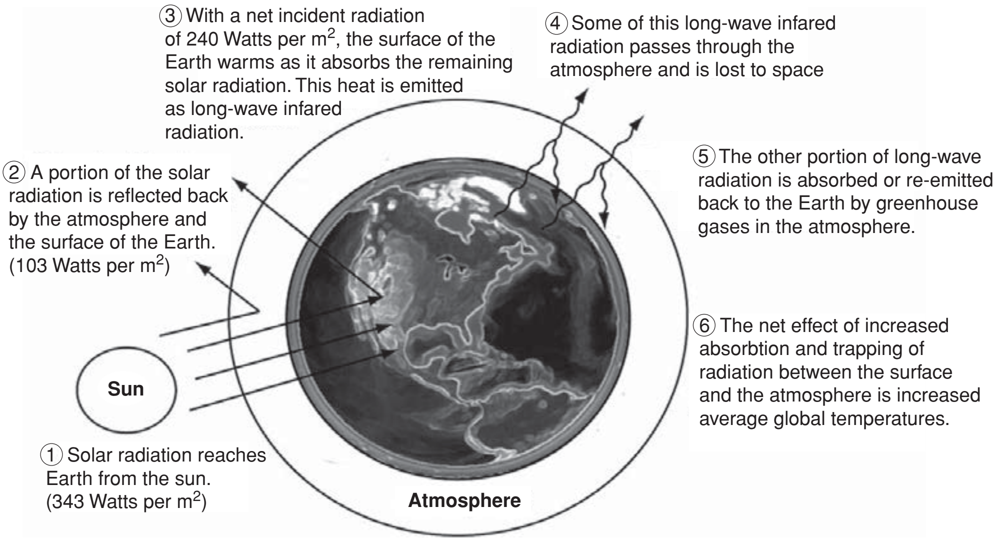

Figure 1.2. The pathway of solar radiation and formation of the greenhouse effect.

scientists to use mass balance and C tracking approaches (see Chapter 3) to understand how and when C is transferred from one pool to another. The C pools that have reasonably short turnover periods or experience flux over shorter time periods are termed *active* (e.g., vegetation, soil, oceans, atmosphere). Active pools differ from long-lived C pools (e.g., fossil C in coal, oil, and carbonate minerals in rock) by the relative ease with which C is transformed from one state to another by natural processes. We focus on transformations of active C pools in the context of contemporary land-system dynamics.

Global CO_2 concentrations in the atmosphere contribute, along with other gases, to the greenhouse effect (Figure 1.2). Short wavelengths of incident solar radiation pass through the Earth's atmosphere. When incident radiation reaches the surface of the Earth, a portion is absorbed and subsequently emitted from the surface toward space as long-wave radiation. The long-wave radiation is absorbed in the atmosphere by gases (e.g., CO_2, water [H_2O], CH_4), reflected back to the Earth, or radiated back to space. The process repeats itself in a long-wave radiation exchange between the Earth and its atmosphere. The trapping of a portion of the long-wave radiation in the atmosphere constitutes a natural greenhouse effect that helps to maintain a mean average global surface temperature of about 14°C (Le Treut et al. 2007). The proportion of long-wave radiation captured (i.e., radiative trapping) is correlated with the amount of atmospheric CO_2 and other greenhouse gases (GHGs) in the atmosphere, which is affected by natural and anthropogenic processes at the surface.

During periods of naturally high atmospheric CO_2 concentration, increases in air temperatures have caused an increase in water evaporation into the atmosphere, among a host of other effects. Water vapor, like CO_2, acts as a GHG to absorb outbound radiation and redirect it back toward the surface of the Earth. In addition to increasing global average air temperature, this process also alters general patterns of atmospheric circulation within the Earth system. Therefore, the magnitudes of various C pools and the dynamics associated with C fluxes between land, atmosphere, and ocean are important drivers of global climate change.

As reviewed in detail in Chapter 2, the use of atmospheric CO_2 by land- and water-based plants to grow C-based tissues, and subsequent CO_2 release during respiration and decomposition, are the primary mechanisms of C flux between the surface of the Earth and the atmosphere. The effects of CO_2 and energy flows between the land and atmosphere are reasonably well known, but its ecological consequences and feedbacks between these climatic effects and other Earth-system processes are difficult to untangle. Depending on the distribution of nitrogen and other nutrients in ecosystems, cellular activity increases when temperatures increase, resulting in greater rates of decomposition and respiration of CO_2. An increase in global average temperatures will increase ice melt, which releases CO_2 and reduces surface albedo (i.e., reflectivity). With higher temperatures, some areas will experience increased levels of drought and susceptibility to fire.

2. Definitions

Because of the multidisciplinary nature of research on coupled natural and human systems involving both natural and social science disciplines, we review concepts at this intersection that are relevant to understanding the linkages between land use and the C cycle.

Land cover. Land cover refers to the biophysical characteristics of the land surface, whether constituted of primarily natural or human-built components. Land cover can be described and mapped as discrete states (e.g., forest, shrubland, and wetland) or continuous variables (e.g., percent tree canopy cover). Because land cover partially determines land-surface variables such as albedo, leaf-area index (LAI), surface emissivity, and infiltration, the land-cover characteristics interact directly with Earth-system processes such as energy transfer, water, and nutrient cycles. These biophysical properties also make land cover and land-cover change more easily observable than land use, both by the naked eye and Earth-observing systems.

Land use. Land use describes the purpose for which land is used by humans. It is defined by human activity and derives its meaning from human action and valuation of land. Like land cover, land use can be described either using discrete states of use (e.g., agriculture, human settlements) or degrees of use (e.g., high-, medium-, or low-density residential). Because multiple uses might be in play at a given place and time, and because these uses may or may not lead to any discernible physical impact on a place, classifying and mapping land use can be challenging. Understanding land use usually requires some understanding or information about the institutional

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arrangements affecting users of land, such as *land tenure* – which sets the rules that define how property rights to land are to be allocated within societies – and what practices are permitted (e.g., zoning and set asides).

Land and resource management. Land and resource management refers to the factors of production (i.e., capital and labor) and sets of decisions, plans, and actions implemented on a parcel of land or resource at a given place and point in time. Land-use and land-management decisions involve trade-offs between different bundles of natural resources (Loomis 2002). Whereas land-use choices can change the set of outputs or services that land provides, land management can determine how effectively a set of outputs or services are provided. Changes in land management may be made without affecting a change in land cover or land use. For example, changes in land management might result in changes in the harvest rotation schedule for a forest plot; tillage practices on an agricultural field; fire management regime in a wildland area; or the mowing, fertilizing, and irrigation schedules on a golf course.

Carbon source and sink. The C sources and sinks refer to the direction of C movement among atmosphere-, land-, and aquatic-based pools of C. These C pools are reservoirs in which C is stored in relatively stable forms. A pool is referred to as a sink when it accumulates C and as a source when the amount of C in it decreases. In the case of the land, these pools include living and dead organisms and mineral-based nonorganic C minerals (C-based rocks). Anthropogenic sources of C are those fluxes into the atmosphere caused by human activity. The stability or permanence of a C pool is an important determinant of its value as a sink, in the context of attempts to mitigate an increase in atmospheric C.

Carbon sequestration. In C sequestration, there is deliberate removal of C from the atmosphere or from emission sources into a permanent or long-lived pool (Sundquist et al. 2009). This C sequestration often comes about through the creation of artificial or anthropogenically controlled sinks. In addition to geoengineering approaches for C capture and storage, which attempt to store C underground, land management for C sequestration is an important option for mitigating increases in atmospheric C. Such approaches take advantage of the Earth's natural sequestration processes through vegetation photosynthesis (primary production) and other biological processes.

3. Carbon Cycle Science

The C cycle has always been of scientific interest because it is fundamental to the functioning of the Earth's biosphere. The focus of the science in this area is on understanding C pools and fluxes among them. In the context of land change as it is used in this volume, we are primarily concerned with the terrestrial C cycle, which includes C fluxes to and from all land-based ecosystems (forests, agriculture, grasslands, shrublands, and urban areas).

A better understanding of the C cycle has been rapidly evolving in recent years in response to our need to understand changes in atmospheric GHGs as the primary driver of climate change. Many of these gases are C based (e.g., CO_2, carbon monoxide [CO], and CH_4) and are directly affected by anthropogenic or naturally driven land change. To facilitate the science of global climate change and support research, modeling, data collection, and capacity-building initiatives, scientists and government agencies, as well as international organizations under the auspices of the Global Climate Observing System (GCOS), have identified a list of essential climate variables (ECVs; GCOS 2010). The ECVs provide a minimum number of variables needed to understand how climate changes and are defined so that they can be measured and observed over time. A subset of ECVs is specific to the interactions between the land system and the C cycle. Specifically, land cover, the fraction of absorbed photosynthetically active radiation (FAPAR), LAI, aboveground biomass, soil C, fire disturbance, and soil moisture are ECVs that are helpful in understanding land-system dynamics driven by human and natural processes that affect global C balances.

The uptick in knowledge associated with efforts to bring together local, national, and global science programs is facilitated through the advent of comprehensive, global methods for C monitoring and modeling, in large part due to improvements in methods using satellite remote sensing systems to understand the global system. Development of coarse-resolution satellite systems that map global phenomena, such as the productivity of vegetation, ocean color, and atmospheric composition, at daily time steps, has revolutionized our understanding of the Earth as a whole. It has allowed a more complete view of factors relevant to C cycling at continental and regional scales as well, providing a way to effectively and efficiently detect and monitor the critical functions of the Earth system that affect C exchange between the land, oceans, and atmosphere.

Policy forces that have driven mandates to improve our monitoring capabilities have come about as these technical capabilities have evolved. The Kyoto Protocol, an international agreement linked to the United Nations Framework Convention on Climate Change,[1] was adopted by several countries in 1997 and provided an impetus for many industrialized countries to curb C emissions, develop measurement and monitoring standards, and develop methods to model C exchange. Subsequent agreements in Cancun in late 2010 have laid the groundwork for international agreements and protocols that would place monetary value on C stored in land-based stocks, further incentivizing work on monitoring of these C stocks.[2]

Over the same time frame, the United States, which was not a signatory to the Kyoto Protocol, developed internal structures to advance C cycle science activities. In particular, the U.S. Carbon Cycle Science Program (USCCSP) was put in place

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[1] http://unfccc.int/kyoto_protocol/items/2830.php (accessed July 5, 2011).

[2] http://cancun.unfccc.int/mitigation/further-specific-decisions-under-the-kyoto-protocol/ (accessed July 5, 2011).

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by the U.S. Global Change Research Program (USGCRP) with the 1999 document *A U.S. Carbon Cycle Science Plan* (Sarmiento and Wofsy 1999). In 2007, the *State of the Carbon Cycle Report* (SOCCR) was released by the U.S. Climate Change Science Program to document the state of knowledge in C cycle science with the intention of providing periodic updates. The Global Carbon Project Scientific Steering Committee recognized the USCCP as an Affiliated Office of the Global Carbon Project in 2007. In 2008, a new planning effort was begun by the USCCSP to update and revise the 1999 C cycle science plan.[3] The revision of the 1999 C cycle science plan was completed in 2011, and it expands on research questions about the role that the pattern and dynamics of anthropogenic land-surface changes have on atmospheric C concentrations (Michalak et al. 2011).

One of the science activity working groups that was created to implement the mandates defined by the USCCSP policy initiative is the North American Carbon Program (NACP). The NACP is a multidisciplinary research program designed to develop and improve scientific understanding of North America's C sources, sinks, and changes in C stocks. This science-based information is needed to meet societal concerns related to C cycling and climate change and to provide tools for decision makers who need to know the mechanisms and magnitudes of C flux to properly manage resources. The NACP provides an interagency structure to coordinate U.S.-based research activities, including observational, experimental, and modeling efforts regarding terrestrial, oceanic, atmospheric, and human components. The NACP supports and uses a diverse array of existing observational networks, monitoring sites, and experimental field studies in North America and its adjacent oceans. Integrating these different program activities and maximizing synergy among them requires expert guidance provided through the interagency structure.

A large number of other national and international C projects and programs have been put into place by a range of different countries. An initiative called the Joint Canada-Mexico-USA Carbon Program (CarboNA) coordinates C cycle science research throughout North America and adjacent coastal waters.[4] To assist the international science community in establishing a common and mutually agreed upon knowledge base, the Earth System Science Partnership (ESSP) established the Global Carbon Project in 2001. The project also aims to support policy making and actions to slow the rate of increase of GHGs in the atmosphere. The CarboEurope integrated project was funded by the European Union (EU) as a five-year project in 2004 to advance understanding in a multidisciplinary and integrated way, addressing similar scientific questions for that continent.[5] These and other country-based and

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[3] http://www.carboncyclescience.gov/carbonplanning.php (accessed July 5, 2011).
[4] http://nacarbon.org/carbona/index.htm (accessed July 5, 2011).
[5] http://www.carboeurope.org/ (accessed July 8, 2011).