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Ecosystem Sustainability through Strategies of Integrated Carbon and Land-Use Management

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1. Introduction

Terrestrial ecosystems provide a number of key services to society that are linked to carbon (C) cycle processes, a few of which include controlling food and fiber production, basic building materials, energy sources, and soil water holding capacity. Human societies have developed a number of land-use practices to enhance biological C processes and increase the delivery of many ecosystem services. However, some of the modifications have led to unintended degradation of land systems in ways that have reduced the natural capacity of ecosystems to maintain a range of supporting, provisioning, and regulating services.

As society strives to sustain key ecosystem services while attempting to meet the challenge of a growing human population and manage for climate change, new and sustainable land-use strategies must play a role. Sustainable management practices – those that maintain the provision of ecosystem services at or from a location – should be a main component of any land-use strategy if we are to successfully deal with global environmental challenges. Society is now demanding much more from land-use systems to achieve multiple goals. Multiple ecosystems services are being required from these systems – to provide food, environments for maintaining biodiversity, and production of energy products, and for preventing pollutants from entering the air and waterways. Developing land-system practices and policies that consider the long-term dynamics of C cycling among competing ecosystem services will provide a framework to develop more sustainable land management.

Recent policy efforts have highlighted the role that land-use strategies can play in mitigating climate change by offsetting C emissions through C sequestration or substituting fossil fuel emissions with bioenergy. Land-based policy developments of the United Nations, such as reducing emissions from deforestation and degradation (REDD) and the Kyoto Protocol (i.e., Articles 3.1 and 3.4) on deforestation and afforestation, recognize the dynamic features of human-environment systems in affecting C permanence and its effect on C exchanges (see Chapter 17). Other land-management practices associated with cropping and grazing are also used in voluntary C offset markets and are being explored in a variety of compliance markets. In addition, production and consumption of bioenergy may further contribute to reduced C emissions; however, they may also lead to a situation where bioenergy systems compete for land needed for other uses or are allocated to lands that are more vulnerable to climate change (Fargione et al. 2008; Roberston et al. 2008, Ojima et al. 2009).

The resilience of terrestrial C stocks and sinks will be further challenged by a warming climate and other environmental effects associated with land-use practices and water scarcity. The impact of changing disturbance regimes such as fires, pest outbreaks, storm damages, flooding, and drought can negate management strategies to restore or build up C stocks in the landscape. How climate and societal dynamics play out into the future cannot be foreseen; however, the prudent use of various trend scenarios would provide guidance to identify strategies that will lead to greater resilience of terrestrial C dynamics in decades to come.

The development of sustainable land-management strategies to maintain and enhance C stocks and sinks can provide multiple societal and livelihood benefits. This can include the establishment of multipurpose forest systems for conservation and biodiversity, C farming, and wood production. A sustainability approach to the development of land-management strategies with respect to C can provide a framework to assess how society and livelihoods are affected in the short- and long-term by changes in environmental factors. Many of these factors can be linked to C dynamics, such as food production, soil fertility, and water holding capacity.

It is clear that sustainable C management will need to consider multiple criteria across an array of scales to capture the variety of biophysical and societal characteristics representing land-use systems across Earth. This chapter will look into the long-term implications of land-use strategies leading to resilient C cycling. To be effective, these strategies need to be developed within a coupled natural-human system context and incorporate ecosystem services into land-use decision-making processes at multiple scales.

2. Societal Context of Sustainability and the Carbon Cycle

Over the past half-century, the impacts of dramatic demographic and economic changes on land-use patterns have revealed the finite capacity of ecosystems to provide essential services (Daily et al. 2000; Foley et al. 2005; Parton, Gutmann, and Ojima 2007). In many parts of the world, a singular focus on managing land for production of food, fiber, forage, timber, or energy has resulted in land degradation, loss of regulatory services, and decreased resilience of socioecological systems (Haberl et al. 2007). In addition, recent pressure to expand bioenergy crops and sources of biomass have resulted in increased land competition and degradation of ecosystem services (Fargione et al. 2008; Searchinger et al. 2008; Howarth et al. 2009; Ojima et al. 2009). In a world of rapidly growing human population and per capita consumption of ecosystems services (Haberl et al. 2007), sustained delivery of these services requires an integrated land-management approach with greater consideration of spatial and temporal dynamics of the socioecological system from local to global scales. C, land-use, and land-management policies need to consider the impact of these interventions on C dynamics (e.g., loss of soil C to erosion and decomposition, removal of biomass that rejuvenates ecosystem services, or trade-offs between different provisioning services) and livelihoods of various stakeholders in a community or region.

The success of land-management policies will rely on the ability of land managers to maintain their livelihoods to sustainably manage to achieve multiple goals. Sustaining ecosystem services and maintaining and enhancing C stocks are highly linked. Degradation, especially of the supporting services such as soil organic matter formation, nutrient cycling processes, and changes in disturbance regimes, undermines the ability of ecosystems to sustainably store C and to recover from perturbations. The emergence of global markets and trade of goods across the Earth has created a situation whereby meeting the needs of food and biofuel in one country might lead to large greenhouse gas (GHG) emissions in a distant region – for example, emissions from land conversion in Brazil and Indonesia to produce ethanol, biodiesel, beef, and soya.

In addition, overexploitation of provisioning services can lead to reduced return of organic and nutrient residue resulting in the need to supplement inputs of nutrients to maintain production levels. Many land-use systems were developed with a limited perspective or set of goals in mind – for instance, maximizing the production of crops or timber while ignoring supporting services or associated slow variables such as nutrient cycling and soil organic matter formation that will ensure the long-term sustainability of the production system. These approaches have often led to degradation of ecosystem services and undermine the ability of socioecological systems to sustain production levels (Haberl et al. 2007).

In addition, socioeconomic dynamics affecting land-use choices, policy, and technological decisions related to food and energy security can affect the land system management in ways that affect the sustainability of the C cycle. Efforts to mitigate climate change through increased reliance on renewable energy sources may have a profound impact on the dynamics of C cycling, both directly, such as bioenergy technology development (Fargione et al. 2008; Searchinger et al. 2008; Ojima et al. 2009), and indirectly, such as competition of hydroelectric or nuclear power for scarce water resources. A focus on single goals can lead to perverse outcomes because of degradation of critical ecosystem services that undermine the sustainability of the land-use system, disrupt social structures, affect livelihoods, and lead to unintended consequences in other parts of the globe as experienced during the expansion of corn ethanol production in the past decade.

3. Drivers Leading to Destabilization of the Carbon Cycle

Sustainable land-management strategies can often be derailed due to unforeseen environmental and socioeconomic events. C stocks are vulnerable to climate-related conditions leading to fires, pest outbreaks, floods, storms, and other phenomenon that may cause C stocks to be transferred to the atmosphere or laterally deposited elsewhere in the landscape or watershed (Kurz et al. 2008a, 2008b; Moore et al. 2011; Van der Werf et al. 2010). Destabilization of C stocks and fluxes can also occur when land-use decisions and economic activities occur without consideration of other environmental drivers affecting the status of ecosystem services. For instance, bioenergy development on abandoned croplands or aridlands where water resources are often scarce can lead to significant decline of C stocks (Ojima et al. 2009). Greater awareness of, and accountability for, the effects of land-use decisions is an important dimension of sustainable C cycle management.

The dominant driver of GHG emissions, especially carbon dioxide (CO_2) emissions, are human activities associated with fossil fuel combustion and cement production, which are currently responsible for 85 to 87 percent of the total annual CO_2 emissions (Canadell et al. 2007; Le Quéré et al. 2009). Changes in land use contribute to the rest, which are primarily caused by tropical forest conversion to agriculture and pasture. In some tropical countries, land emissions account for up to half of the total national emissions (e.g., Brazil; Cerri et al. 2009).

Examples of human drivers leading to enhanced C emissions include expansion of croplands in tropical forest regions of the Amazon and peatlands of Indonesia. These conversions are responding to changes in market forces driving demand of global commodities such as palm oil, soya, and beef and are leading to deforestation in these tropics regions (Barona et al. 2010). In addition, road development has led to increased fire frequency and deforestation in the tropics (Nepstad et al. 2001; Nepstad, Stickler, and Almeida, 2006a; Nepstad et al. 2006b). Although these examples show an obvious correlation between drivers and impacts, it is more difficult to anticipate the interacting impacts of human and natural drivers. These interactions include the practice of selective logging that leads humid forests to become vulnerable to fire during drought brought by El Niño–Southern Oscillation (Nepstad et al. 1999) or the practice of drainage in tropical and high-latitude peatlands that combined with droughts lead to fires that can burn for months at a time (Field, van der Werf, and Shen 2009; Hooijer et al. 2010). In these cases, the impacts of fire on C emissions and other cascading effects on the regulation of hydrological and climate functions could only take place by two independently occurring drivers meeting in space and time.

After a disturbance, an ecosystem may recover its C stocks (e.g., after natural fires, windthrow, insect outbreaks), or only a fraction of it, depending on the land-use history and the impact on C stocks and ecosystem changes (Burke et al. 1989; Cole et al. 1989; Parton, Ojima, and Schimel 1996). Disturbances leading to regime shifts and loss of ecosystem capacity to recover C stocks due to vegetation changes, loss of nutrients, or changes to other supporting ecosystem services may create conditions that are more difficult to recover from and may in some cases not be possible (Randerson et al. 2002; Figure 1.5d, Chapter 1). An example is woody thickening in semiarid regions in the world (Archer, Boutton, and Hibbard 2001; Hudak, Wessman, and Seastedt 2003; Scott et al. 2006; Knapp et al. 2008), in some cases caused by changing land-use practices such as fire exclusion, severe soil erosion, or invasive species encroachment. Land application of biochar to degraded soils in drylands has garnered significant interest in policy and scientific circles and is an example of a possible human intervention that may enhance nutrient retention and restore soil fertility in ecosystems that have undergone regime shift (Lehmann, Gaunt, and Rondon 2006). How applicable the biochar strategy is in supporting enhanced soil C stocks is still under investigation.

In some regions of the world, climate change is leading to shifting disturbance regimes where events are being experienced with a higher frequency and intensity. This can lead to a permanent C loss, such as with fires in the western United States (Westerling et al. 2006), forest system dieback (Allen et al. 2010), and permafrost thaw in the Arctic (Chapin et al. 1995; Chapin et al. 2008; Schuur et al. 2009; Tarnocai et al. 2009; Liu et al. 2011). Frequently, natural C losses are amplified through past or current influences of human activities, leading to change and often unpredictable disturbance regimes. This phenomenon has been observed in managed forests in Canada, where increasing temperatures have increased fire and insect damage, shifting the forest from being a net C sink to a C source (Kurz et al. 2008a, 2008b).

In addition to the effects of rapid disturbances on C stocks and fluxes described in the previous section, climate variability and change, as well as land use and resource extraction, can also lead to more chronic perturbations of C stocks and fluxes. Some of the key C reservoirs include organic C in frozen soils (permafrost) and tropical and high-latitude peatlands, biomass C in tropical forest, and methane hydrates in permafrost regions and oceans (see Chapter 2). The size of these reservoirs is poorly constrained; however, they are potentially of very large proportions. For instance, permafrost C is estimated to be approximately 1,680 Pg C (Tarnocai et al. 2009). Methane hydrates, another C stock on land and in the ocean floor, are estimated to be as much as 5,000 Pg C, or equal to all current fossil fuel reserves combined (Krey et al. 2009). These reserves are many times bigger than all C accumulated in the atmosphere; therefore, even the destabilization of a very small fraction of the reservoir could cause a significant positive feedback to global warming (Raupach and Canadell 2008).

Global warming is observed most dramatically in the high latitudes, and various ecosystems such as the tundra and boreal ecosystems show great sensitivity to increased temperatures. Tundra and boreal ecosystems store on average one-third of the global soil C stock, which is proportionately higher than in temperate and tropical forests. Recent studies have found that enhanced temperatures in tundra and boreal ecosystems stimulate decomposition of litter and soil organic matter, leading to an increase in C emissions (Schuur et al. 2009; Canadell and Raupach 2009). Despite an increase of net primary production caused by a longer growing season and increased availability of mineralized nitrogen (N; Chapin et al. 1995), changes such as increased soil respiration and darkening of the surface from woody encroachment lead to an overall net acceleration of global warming (Euskirchen et al. 2009). These results are consistent with model results that predict an overall positive feedback to global warming from the future dynamics of high-latitude ecosystems (Zhuang et al. 2006; Koven et al. 2011; Schaefer et al. 2011).

In the example of fire in drained peatlands around the world, both in the tropics and high latitudes, the consequences extend from loss of productivity (local) to haze-causing health problems (regional), disruption of transportation and communications including flight paths (international), and increased GHG emissions (global) (Van der Werf et al. 2010; Field et al. 2009). Recent fires in Russia have led to an escalation of the price of wheat in the global market given the crop lost because of failed and burned crops. This complex chain of impacts involves a diverse set of actors and institutions seeking short- and long-term solutions. A comprehensive fire management program may be the common solution required to address the multiple impacts, potentially supported by a broad consortium of stakeholders, including farmers, health authorities, local and national governments, and international conventions. An alignment of agendas can lead to results that no single actor would be able to achieve on its own, although establishing appropriate institutional support is challenging.

Land-use practices have aimed to augment many of the natural ecosystem services through additions of water, nutrients, modification of species composition, and various aspects of the physical environment affecting the hydrological flow and aeration of soils. These alterations have led to tremendous increases in land productivity from enhanced animal and plant productivity and harvest efficiency. However, in many situations, the status of ecosystem services has been severely degraded, as observed in the reduction in soil organic matter levels, increased nutrient cycling rates, increased soil salinity and cation exchange capacity, and reduced biodiversity, including soil biodiversity (Ayres, Wall, and Bardgett 2009; Wall, Bardgett, and Kelly 2010).

In addition, other factors are leading to the degradation of ecosystem services, such as climate warming, intensification of rainfall events, and acid rain and nitrogen deposition. These interacting environmental stresses are further affecting the maintenance and quality of ecosystem services. As ecosystem services are being affected worldwide, the demand for increased land productivity is rising as well because of population increases and changing consumption patterns. Thus, despite improved production systems and development of better land-use practices, there is an increasing likelihood of conflict around the need to maintain and enhance C stocks and fluxes, as well as the need to develop a sustainable food and energy strategy with uncertainties associated with local climate-change effects. Restoring ecosystem services in a way that reduces the need for fossil fuel inputs will enhance the resilience of systems under climate change and maintain production levels.

To restore or enhance ecosystem services, socioenvironmental considerations will need to be incorporated to gain community engagement; understand demographic impacts; meet equity issues; and operate within institutional constraints related to tenure, access, and land allocation. The transparent evaluations of trade-offs associated with different land-management options provide analysis to avoid unintended consequences.

Atmospheric N deposition is highest in industrial areas, and because it arrives in plant-available form, deposited nitrogen enhances primary productivity in all nitrogen-limited ecosystems (Vitousek and Howarth 1991). The effect of N deposition tends to be higher in seminatural grasslands (Phoenix et al. 2003) and temperate forests (Holland et al. 2005) in mid-latitudinal areas. However, if the load of N deposition crosses a critical threshold, ecosystem C gain may be reversed because of C losses accompanied by loss of N through surface runoff and leaching (nitrate [NO_3^-]) or through volatile losses (nitrogen oxide [NOx] and nitrous oxide [N_2O], diatomic nitrogen [N_2]) (Del Grosso et al. 2005; Townsend and Davidson 2006). It is this nonlinear behavior of global change drivers and the interaction of major biogeochemical cycles (Melillo, Field, and Moldan 2003) that are rarely incorporated in analysis of C management practices or included in sustainability considerations of these practices. However, knowledge of these interactions and feedback processes is pivotal for the development of sustainable C management strategies.

Although many ecosystems may recover soil and plant C stocks after a disturbance (e.g., natural fires, windthrow, insect outbreaks), human-induced changes often lead to permanent C losses, especially when ecosystems have crossed a critical resilience threshold. A critical resilience threshold crossing occurs, for example, when soil erosion outstrips the ability of ecosystem processes to replenish C and other nutrients, resulting in a decline in productivity and soil water holding capacity. Natural processes and human activities contribute to large changes in C stocks. Recovery and maintenance of sustainable C stocks require a novel holistic ecosystem management model applicable to a variety of eco- and land-use systems imposing the critical link between fundamental biogeochemistry and adaptive learning in social systems and adaptive management in the coupled human-environmental system for a sustainable future. Thus a major challenge to sustainable strategies is to incorporate an evaluation of land-use effects as a driver of change in C stocks and fluxes, which includes recognition of C changes associated with globalization, climate change, exploitation of goods and services, and the acceleration of biogeochemical cycles (Vitousek et al. 1986, 1997; Haberl et al. 2007). These consequences from direct and indirect human actions are expressed differently in various regions of the world, reflecting different land-use practices and disturbance regimes.

4. Local to Regional Sustainability Considerations for Carbon Management and Land-Use Decision Making

The C cycle plays a major role in linking ecosystem services and societal well-being. Strategic planning for sustainable C management can provide a baseline or framework for a more general sustainability assessment. The use of C as an overarching indicator is possible because of the multiple dimensions of sustainability in which C dynamics participate. Thus sustainable C land-use strategies may include reduced CO_2 and other GHG emissions from agriculture, forestry, and other land uses, such as bioenergy production; thoughtful considerations of conservation management practices, such as in tropical agricultural systems, which may enhance the sustainability of these productions systems (Nepstad et al. 2006a); and consideration of vulnerable C stocks, such as C-rich peat soils. Evaluation of the contributions that C cycling make to maintain ecosystem services (e.g., plant productivity, soil formation, GHG emissions, and landscape diversity) and the additional contributions to meeting societal needs for C-based goods and services defines a socioecological framework to assess the sustainability of various land systems. However, the development of management protocols that incorporate cross-scale processes and consideration of trade-offs can be challenging.

Recovery and maintenance of sustainable C stocks and sinks require a holistic ecosystem management model applicable to a variety of ecosystems and land-use systems (Tschakert et al. 2008). This management model incorporates both adaptation and mitigation options (Ojima and Corell 2009), recognizes that multiple objectives are expected from land systems, and recognizes that multiple benefits are being achieved through human interventions with sustainable land-management practices (Tschakert, Coomes, and Potvin 2007). These land-management practices can provide critical links between fundamental biogeochemistry and adaptive learning in social systems aimed at meeting livelihood goals. These practices incorporate adaptive management strategies leading to sustainable development.

Terrestrial C stocks may be saved and augmented by purposeful actions through the implementation of various land-use options, such as reduced deforestation and reforestation activities in the tropical regions (e.g., United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries [UNREDD] strategies) or bioenergy practices that reduce net emissions of C and other GHGs to the atmosphere (although parallel reductions in fossil fuel emissions are also necessary to minimize the likelihood of dangerous climate change (Jackson and Schlesinger 2004). Recent developments in sustainable forest management practices integrate timber production, conservation, C sequestration, and cultural objectives. A case study in the tropical forests of Guyana, the Iwokrama International Centre for Rainforest Conservation and Development,[1] provides an example of efforts to define and meet multiple socioecological goals. The forest management system incorporates the indigenous population in decision making, provides a timber harvest practice that takes into account the diversity of wood products available to them and provides a sustainable harvest rotation, and sets up forest conservation areas to maintain and enrich the diversity of biota present in the preserve. These practices have developed over the past twenty years and are constantly monitored given changes in various factors related to markets, tourism, and climate change.

Grassland systems around the world have been managed sustainably for many centuries. These have been typically nomadic pastoral systems in arid to semiarid regions of the world. Recent efforts to impose more sedentary livestock practices have led to rangeland degradation. However, rangeland management schemes are reevaluating stocking rates and movement of livestock so that sustainable rangeland use can be attained (Chuluun and Ojima 2002; Kemp and Michalk 2007; Chuluun et al. 2008). A key aspect of land-use strategies in these regions is to reconnect fragmented rangelands (Galvin 2008; Ojima and Chuluun 2008) so that animals and land-use intensity are less concentrated on limited rangelands and C stocks can be maintained and restored. Development agencies and other organizations are exploring potential rangeland management options to enhance C sequestration (Abberton, Conant, and Batello 2010),[2] with extensive projects in regions of China and Mongolia (the Asian Development Bank project; the Department for International Development–funded project "Adapting to Climate Change in China,"[3] the Food and Agriculture Organization of the United Nations [FAO] 2010), and as a mechanism to offset desertification throughout the arid and semiarid regions of the world (the United Nations Convention to Combat Desertification's focus on desertification, land degradation, and drought).[4]

Global patterns of markets and policies affect regional sociopolitical factors that influence C dynamics and land-use and land-management decisions. Interregional C fluxes are primarily determined by factors associated with economic and political development strategies, trading relationships, and market access. For example, recent concern over coffee and cacao production has resulted in changes in land-use practices to those that value sustainable production systems (Castellanos et al. 2008; Nelson et al. 2010). The sustainable production efforts and fair trade labels provide market incentives to promote good land stewardship and in many cases take into account reduced losses of C from the land system. Consequently, markets, institutions, and

[1] http://www.iwokrama.org (accessed March 23, 2012).
[2] http://www.fao.org/docrep/013/i1880e/i1880e.pdf (accessed March 23, 2012).
[3] http://www.dfid.gov.uk/r4d/SearchResearchDatabase.asp?ProjectID=60662 (accessed March 23, 2012).
[4] http://dsd-consortium.jrc.ec.europa.eu/documents/CSTConfSynthesis20100621.pdf (accessed March 23, 2012).

policy instruments can affect land use and C management practices through commodity pricing and market expansions. In addition, these rapid expansions of market-driven land-use change can lead to inappropriate land-use practices in areas less suitable for production of these commodities and lead to less-sustainable practices to meet short-term demand for certain commodities, as has recently occurred in bioethanol production in Brazil (Martinelli and Filoso 2008) or in quinoa production in Bolivia (Reynolds et al. 2007; J. R. Reynolds, personal communication). Among economically stressed communities, changes in commodity prices and market demands may have a more immediate effect on land-use practices related to fuelwood extraction, conversion of marginal lands, or abandonment of sustainable land-use systems that destabilize regional C cycles.

REDD strategies have emerged to focus on how we can manage the changes in forest practices to avoid and reduce CO_2 emissions (DeFries et al. 2007, Baker et al. 2010). Although C sequestration strategies associated with REDD consider a hierarchical structure of decision making (Baker et al. 2010), the importance, impact, and feedback of decisions on interregional C flow is not well developed or understood. In general, regional decision making is usually aimed at the well-being of communities, states, or nations, whereas local decision making is aimed at private progression including strong property rights and livelihood considerations (Tschakert et al. 2008). Development of regional decision-making processes along hierarchical scales needs to include direct and indirect effects on ecosystem services and socioeconomic considerations. In addition, full accounting of land-use changes over a region and across the entire globe is needed to evaluate unintended consequences of land-use policies and to capture land-use changes associated with "leakage" of land-use practices (see Chapter 17 for more about the role of REDD, leakage, accounting for unintended consequences, and regional C flow).

Building economically and environmentally resilient land-use systems that can better sustain ecosystem services under climate change and changes in socioeconomic demands, as well as stabilize C stocks, will be a critical step for long-term societal well-being (Tschakert et al. 2008). Developing and enhancing current land-use practices and technologies to meet production and emission targets will take a concerted effort. Consideration of regional diversity can present a challenge to meeting sustainability goals among various communities. Issues related to the source of governance and rights of various members of different communities may be a major constraint to consensus among decision makers and result in inequalities from the outcomes of land-use decisions.

Regional C budgets can provide useful information to guide development of more sustainable land-management systems as well as more well-balanced C policy and land-management strategies. The technical and scientific components for producing accurate regional C budgets and assessments are becoming well established (see Chapters 3, 6, 9, and 17). However, far less is known with respect to how these scientific budgets and assessments are to be put into practice so that they may contribute to decision-making matters that concern industry, environment, economy, institutions, and livelihoods.

Recent efforts to develop C management strategies and their economic returns are beginning to provide guidance for decision makers and investment programs related to C markets. Further development of C pricing systems will also provide a mechanism to evaluate land-use strategies, and these evaluations will most likely rely on regional C budget projections in the decision-making process. To facilitate budget projections, the development of decision-making tools are required that include the end-to-end consideration of C in land-management practices, production and conversion systems, and ecosystem services. In many cases, these tools are used in an integrated life cycle analysis to guide sustainable land-use and C management strategies within the context of the socioeconomic, environmental, political, and cultural contexts of the region.

5. Summary and Conclusions

Effective, long-term strategies for C cycle sustainability will require an integrated, adaptive approach to land use and land management that recognizes the complexity of our coupled human-natural system. At the same time, avoiding competition to meet the needs for food, fiber, building materials, energy, biodiversity, and regulatory ecosystem services (e.g., climate, water purification) is key to success. The growing societal demands for goods and services from land systems will continue to challenge how we manage ecosystem services. Development of land management practices that enhance ecosystem services and resilience of the coupled human-natural system will also lead to a more sustainable strategy. Maintenance of C stocks and fluxes within ecosystem components will enable these strategies to function over the long term in support of sustainability goals.

Strategies that will lead to sustainable C dynamics will need to consider livelihood goals and management of ecosystem services based on local to regional considerations. This cross-scale outlook is needed to garner a greater appreciation of how social systems can be used to manage natural capital and maintain flows of ecosystem services over the long term within the socioecological context of the system under consideration. Regional to global strategies can also lead to the development of strategies seeking more resilient systems and a stabilized C cycle. This allows the possibility that local, regional, and global actors can contribute in an interactive manner to address negative impacts and explore new opportunities for sustainable development and for stabilization of C stocks and related ecosystem services.

In addition, landscape processes and cultural uses of interconnected landscapes need to be considered in developing a sustainable land–C system. The landscape perspective provides a way of evaluating cross-boundary ecosystem processes related to differential land-management practices on different landscape units. This landscape management dimension will reduce the possibility of perverse effects emerging from managing one landscape without consideration of others.

Finally, sustainability of terrestrial C stocks and neutralization of net emissions from the terrestrial biosphere will be further challenged by a warming climate that may overwhelm the land-use management strategies. Efforts to reduce fossil fuel emissions must be continued with urgency, as these land-use activities are incorporated to reduce other sources of C emissions to the atmosphere. These considerations of multiple stresses on ecosystem services and transitional conditions of the coupled human-environmental system are challenges to current land-use and land-management schemes, and development of adaptive system approaches are needed to meet sustainability goals to enhance integrity of the coupled human-natural system.

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