Assessing Carbon Dynamics in Semiarid Ecosystems: Balancing Potential Gains With Potential Large Rapid Losses

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Introduction

"Understanding contemporary and possible future fluxes of carbon is the essential underpinning of sound policy to manage radiative forcing of the atmosphere."

(National Research Council 1999, p. 34).

Photosynthesis and respiration are the largest fluxes into and out of the biosphere (Molles 1999). Consequently, small changes in these fluxes can potentially produce large changes in the storage of carbon in the biosphere. Terrestrial carbon fluxes account for more than half of the carbon transferred between the atmosphere and the earth's surface (about 120 GigaTons/year), and current stores of carbon in terrestrial ecosystem are estimated at 2060 GigaTons. Increasing attention is being focused on the role of managing and sequestering carbon in the terrestrial biosphere as a means for addressing global climate change (IGBP, 1998; U.S. Department of Energy, 1999). Terrestrial ecosystems are widely recognized as a major biological scrubber for atmosphereic CO_2--and their ability to function as such can be increased significantly over the next 25 years through careful manipulation. The potential for terrestrial carbon gains has been the subject of much attention (Dixon et al., 1994; Masera et al. 1997; Cao and Woodward, 1998; DeLucia et al. 1999). In contrast to other strategies for reducing net carbon emissions, terrestrial sequestration has the potential for rapid implementation.

Strategies that focus on soil carbon are likely to be effective because in addition to being a storage pool of carbon, soil carbon also improves site productivity through improving soil quality (e.g., water retention and nutrient availability). The carbon pool in soils is immense and highly dynamic. The flux of carbon into and out of soils is one of the largest uncertainties in the total mass balance of global carbon (NRC, 1999; Lal et al., 1998; Cambardella, 1998). Reducing these uncertainties is key to developing carbon sequestration strategies. Soil carbon pools have been greatly depleted over recent centuries, and there is potential to increase storage of carbon in these soils through effective land management. Whereas carbon in vegetation can be managed directly through land use, carbon in soils generally must be managed indirectly through manipulation of vegetation and nutrients. Land management as well as climate changes have the potential to increase soil carbon, but also could trigger large soil carbon losses. Recently, the importance of accounting for countervailing losses in assessing potential amounts of terrestrial carbon that can be sequestered has been highlighted (Schlesinger, 1999; Walker et al., 1999). Realistic assessment of terrestrial carbon sequestration strategies must consider net results of an applied strategy, not simply projected carbon gains. In addition, large, rapid losses of carbon resulting from carbon management strategies could exacerbate the global warming rather than mitigating it. Such potential losses include rapid loss of carbon in vegetation due to fire and rapid loss of soil carbon triggered by reductions in ground cover (e.g., fire, drought). Therefore, strategies for terrestrial carbon sequestration must determine how to increase terrestrial carbon while minimizing the risk of large-scale catastrophic losses.

Our objectives in this paper are to (1) highlight approaches that are being considered in terms of terrestrial carbon sequestration, (2) highlight case studies for which large losses of carbon may occur, and (3) suggest future directions and application for terrestrial carbon sequestration.

Approaches

Increasing terrestrial carbon has been the goal of several approaches. One approach is increasing the density of woody vegetation, which has offset a significant portion of previous carbon emissions (Houghton, 1999). This approach has the potential for several negative outcomes unless these woody are managed properly (Covington et al. 1994). The potential negative outcomes include carbon loss through forest dieback and devastating crown fires caused by excess tree density and carbon loss through increased soil erosion brought about by detrimental reductions in herbaceous vegetation (Smith and Shugart, 1993; Woodward and Beering, 1997; IPCC, 1998; Kirelenko and Solomon, 1998; Neilson and Drapek, 1998; Walker et al., 1999; Allen and Breshears, 1998; Wilcox et al., 1996; Davenport et al., 1998; Lal, 1995; Lal et al., 1998). Proper management approaches must be developed that are based on better data on soil carbon along with other important parameters such as land type, soil water availability, and other climate factors. As illustrated in this approach, carbon sequestration must include a focus on managing and increasing soil carbon because of the potential for breakdown of the system but even more importantly, because of the increased land productivity that accompanies increased soil carbon. Approaches for increasing soil carbon include management intensive options such as amendments of water nutrients, and plant growth stimulation. Other approaches are less intensive and include managed grazing of rangelands and controlling the ratio of woody to herbaceous plants through thinning and fire management, which are particularly important for options for extensive semiarid lands. Developing these approaches to provide stable terrestrial sequestration requires better detailed knowledge of soil carbon at sites where increased amounts of carbon are to be sequestered (Smith and Shugart, 1993; IPCC, 1998; Kirilenko and Solomon, 1998; Goudriaan et al., 1999).

Results: Case Studies

We have several intensively studied semiarid sites where we have been evaluating eosystem patterns and processes related to carbon storage. Much of our work has focused on spatial heterogeneity and connectivity at the scale of canopy patches of trees and the intercanopy patches that separate them (Breshears and Barnes, 1999). We have measured a number of environmental variables at this scale at the Mesita del Buey Pinyon-Juniper Woodland Site in Los Alamos, NM. We have documented how these patch types differ with respect to soil carbon (Davenport et al. 1996), as well as soil morphology (Davenport et al. 1996), snow cover (Breshears et al. 1997b), near-ground solar radiation (Breshears et al. 1997b), soil temperature (Breshears 1998), soil water content (Breshears et al. 1997 b), and runoff and erosion (Reid et al. 1999). In addition, we have documented major modes of patch-scale connectivity related to use of shallow intercanopy soil water by woody plants (Breshears et al. 1997a), shading by woody plants (Martens et al. 2000), and the redistribution of runoff within and among patch types (Davenport et al. 1998, Reid et al. 1999). Further, we have estimated patch-scale carbon inventories for pinyon and for juniper canopy patches and for intercanopy patches and extrapolated them across an elevational gradient. These preliminary estimates of carbon were necessarily coarse due to limitations in the number of soil carbon samples that could be obtained and analyzed in a timely and cost-effective manner. The uncertainty of these estimates is large relative to potential carbon gains that could result from sequestration strategies. Hence, to evaluate carbon sequestration practices better measurement techniques are needed so that high resolution data can be collected to reduce these uncertainties in soil carbon pools.

As noted above, carbon sequestration practices and variation in carbon could result in carbon losses as well as gains. We recently documented rapid changes in vegetation (a landscape-scale shift in a forest-woodland ecotone—> 2 km in < 5 years—

through drought-induced tree mortality (Allen and Breshears, 1998). Changes in vegetation cover between 1954 and 1963 in the study area show 486 ha in ecotone shift zone, with other areas as persistent ponderosa pine forest (365 ha) or persistent pinyon-juniper woodland, (1527 ha). Additional data resolved the timing of the shift to between 1954 and 1958 (Allen and Breshears et al. 1998). These changes in vegetation apparently triggered a transition from low to high erosion rates of the type discussed by Davenport et al. (1998), illustrating how ecosystem dynamics can impact carbon sequestration. These accelerated erosion rates (2 cm/decade) have persisted for decades (Wilcox et al., 1996; Allen and Breshears, 1998; Davenport et al., 1998), likely providing a large release of carbon to the atmosphere from the soil (Lal, 1995; Bajracharya et al. 1998). Data are needed to characterize carbon losses associated with such ecosystem dynamics.

Recently several studies in the area have evaluated the response of herbaceous vegetation to thinning of woody plants—pinyon and juniper—and applying the slash to the soil surface (Chong 1994, Jacobs and Gatewood 1999, Loftin 1999). These studies clearly demonstrate the potential for increased herbaceous vegetation in response to the treatment, which could thereby increase soil carbon. The advantages of this technique is its potential for reducing carbon losses: the reduced density of woody vegetation reduces the probability of crown fires, while the increased ground cover from the added slash reduces potential erosion rates and associated carbon losses. Simultaneously, as pinyon and juniper are both able to extract shallow intercanopy soil moisture (Breshears et al. 1997a) and are likely competing with herbaceous vegetation for resources, herbaceous vegetation has the potential to increase, as observed at a variety of study sites.

Another important mechanism that could trigger large potential losses of carbon is forest fire. Due to fire suppression over the past century (Swetnam et al., 1999), the density of woody vegetation has increased dramatically (Covington et al., 1994), to the extent that it is actually believed to be a major carbon sink for the U.S. (Houghton, 1999). However, these dense forest stands are highly vulnerable to catastrophic crown fires. This was clearly highlighted by the numerous large severe fires across the western U.S. during the spring and summer of 2000. One such fire occurred at Los Alamos. Following this fire, rainfall simulation studies conducted in ponderosa pine forest (Johanson et al., unpublished manuscript) demonstrated dramatically increased erosion following fire. Carbon losses associated with these high erosion rates are expected and are currently being assessed. Hence, rapid loss of carbon from disturbances such as fire, as well as drought, need to be considered in developing carbon sequestration strategies.

Application

Management of terrestrial carbon is an important component of an overall sequestration strategy because it can be implemented rapidly and could provide benefits relate to soil quality and land productivity. However, if the potential for large soil carbon losses is not factored into management strategies, disturbances such as fire and drought—both of which may become more frequent and intense as climate changes progress—may offset anticipated carbon gains and could even exacerbate climate warming. Major management strategies to consider for increasing carbon in semiarid lands are (1) preventing large reductions in ground cover (e.g., due to heavy grazing) that could trigger rapid erosion rates, and (2) developing effective fire management strategies (e.g.thinning and control burning) that preclude large catastrophic crown fires from occur, in which case carbon is lost from both the soil and vegetation components.

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