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ECOLOGICAL SOUNDING

The importance of rapid, disturbance-induced losses in carbon management and sequestration

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ABSTRACT

Management of terrestrial carbon fluxes is being proposed as a means of increasing the amount of carbon sequestered in the terrestrial biosphere. This approach is generally viewed only as an interim strategy for the coming decades while other longer-term strategies are developed and implemented — the most important being the direct reduction of carbon emissions. We are concerned that the potential for rapid, disturbance-induced losses may be much greater than is currently appreciated, especially by the decision-making community. Here we wish to: (1) highlight the complex and threshold-like nature of disturbances — such as fire and drought, as well as the erosion associated with each — that could lead to carbon losses; (2) note the global extent of ecosystems that are at risk of such disturbance-induced carbon losses; and (3) call for increased consideration of and research on the mechanisms by which large, rapid disturbance-induced losses of terrestrial carbon could occur. Our lack of ability as a scientific community to predict such ecosystem dynamics is precluding the effective consideration of these processes into strategies and policies related to carbon management and sequestration. Consequently, scientists need to do more to improve quantification of these potential losses and to integrate them into sound, sustainable policy options.

Key words Carbon management, carbon sequestration, disturbance, forest dieback, erosion, fire, reforestation.

Management of terrestrial carbon fluxes is being proposed as a means of increasing the amount of carbon sequestered in the terrestrial biosphere and thereby slowing the rate of build-up of atmospheric carbon dioxide and associated global warming (IGBP, 1998; U.S. Department of Energy, 1999; IPCC, 2000; Follett *et al.*, 2001). This approach is generally viewed only as an interim strategy for the coming decades while other longer-term strategies are developed and implemented — the most important of the longer-term strategies being the direct reduction of carbon emissions (Falkowski *et al.*, 2000). However, for terrestrial carbon sequestration to be effective, even as an interim strategy, the net results must be considered rather than simply the projected gains of a given sequestration strategy (Overpeck, 1996; Cao & Woodward, 1998; IGBP, 1998; Walker *et al.*, 1999; IPCC, 2000). Many strategies proposed initially for terrestrial sequestration were not evaluated fully with respect to countervailing losses, i.e. carbon losses inherent in the proposed sequestration approach, and consequently the net amount of carbon sequestered for many strategies is likely to be much less than originally estimated (Schlesinger, 1999, 2000; Walker *et al.*, 1999; Schulze *et al.*, 2000).

Accurate estimation of the net amount of carbon sequestered by any given strategy depends not only on factoring in countervailing losses but also on accounting for the potential of large, disturbance-induced carbon losses. Climate-induced disturbances such as forest fire and forest dieback, along with the associated increase in erosion rates that both can trigger, are processes by which large amounts of terrestrial carbon can be rapidly lost. These types of carbon losses are likely to become more significant due to the increasing probability and magnitude of extreme climatic events (Easterling *et al.*, 2000). The effects of such climate-induced changes are likely to be exacerbated by the increasing intensity and extensiveness of land-use changes (IPCC, 2000). Climate-induced disturbances in conjunction with land use changes could result in large and possibly uncontrollable losses in both plant and soil carbon pools. Such large disturbance-induced carbon dynamics could result in net carbon loss rather than gain from lands being

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managed for carbon sequestration. Such terrestrial carbon losses to the atmosphere could also trigger a positive feedback that could amplify global warming (Smith & Shugart, 1993; Woodwell *et al.*, 1995; Solomon & Kirilenko, 1997; IPCC, 1998; Houghton *et al.*, 2000).

Recent assessments of carbon management and sequestration strategies acknowledge the possibility of these types of large, rapid carbon losses, but they generally do not account for them adequately. Of particular note is the recent review by the Intergovernmental Panel on Climate Change of land use alternatives associated with carbon management (IPCC, 2000). There remains a pervasive underlying paradigm that terrestrial soils and biota are in close equilibrium with climate (e.g. IPCC, 2000: 190), and that variation in the tracking of climate by vegetation can be controlled adaptively by management. Although the risk of uncontrolled, disturbance-induced carbon losses is recognized and incorporated into some of the conceptual models of carbon sequestration (e.g. IPCC, 2000: 16, 192, 256, 271), the associated accounting alternatives focus primarily on direct human land-use changes, seemingly discounting the probabilities of extensive, disturbance-induced carbon losses. Quantifying the probability and magnitude of such rapid non-equilibrium losses has been difficult, but this does not negate their potential importance in the global carbon budget and associated carbon management and accounting strategies.

We are concerned that the potential for rapid, disturbance-induced losses may be much greater than currently appreciated, especially by the decision-making community. Here we wish to: (1) highlight the complex and threshold-like nature of disturbances that could lead to carbon losses; (2) note the global extent of ecosystems that are at risk of such disturbance-induced carbon losses; and (3) call for increased consideration of and research on the mechanisms by which large, rapid disturbance-induced losses of terrestrial carbon could occur. Our current inability as a scientific community to predict and quantify adequately such global ecosystem dynamics is apparently resulting in ecosystem processes being largely discounted from proposed approaches for carbon management and sequestration and associated societal assessments of risk and policy. Consequently, scientists need to do more to quantify these potential losses more fully and to integrate them into sound, sustainable policy options.

Large, rapid losses of carbon associated with disturbance often exhibit complex behaviour and may have nonlinear, threshold-like responses. Our lack of ability to understand and predict these disturbance-induced responses can result in 'environmental surprises' (Brown & Postel, 1987; Overpeck, 1996; Bright, 2000; Camill & Clark, 2000; Rinaldi & Scheffer, 2000; NAST, 2001). Such threshold-like responses related to climate and land use are exemplified by crown fires and drought-induced tree mortality, as well as by the changes in erosion rates that can accompany both of these. The complex nature of these types of responses could lead to large, rapid and perhaps uncontrollable carbon losses.

Here we highlight examples of landscape-scale disturbances related to fire and drought in the Jemez Mountains in northern New Mexico, United States, during the last 50 years. During the la Niña year of 2000, the Cerro Grande Fire burned 17 000 ha in this mountain range, much of it severely. This was part of the roughly 3 million ha that burned in the western United States that year. The volatilized carbon from much of the burned area included all foliage and litter, much of the wood, and likely some of the soil organic matter. In addition, the loss of ground cover resulting from the fire triggered a major increase in soil erosion rates (Johansen *et al.*, 2001), probably further increasing site carbon loss (e.g. Bajracharya *et al.*, 1998). While some of the carbon post-fire simply may have been translocated by erosion ('lateral fluxes of carbon' in the terms of IPCC, 2000), a significant amount was likely transferred to the atmosphere (Trumbore, 1997). The severity of the fire was a consequence of land use practices that included fire suppression over the past century, and this practice allowed fuels to build up to excessively high levels (Swetnam *et al.*, 1999). The interaction of climate and land use has also caused rapid landscape-scale changes in the Jemez Mountains in association with drought. A severe drought in the 1950s produced landscape-scale mortality of ponderosa pine (*Pinus ponderosa*) at the ecotone between the ponderosa pine forest and piñon–juniper woodland, shifting the ecotone by more than the 2 km in less than 5 years (Allen & Breshears, 1998). Apparently, the drought also produced extensive mortality of the herbaceous understorey, as observed elsewhere for the 1950s drought (Herbel *et al.*, 1972); this loss of ground cover triggered a transition from low to high erosion rates (Wilcox *et al.*, 1996; Davenport *et al.*, 1998). The tree mortality was probably exacerbated by the fire suppression of the past century, which allowed piñon (*P. edulis*) and juniper (*Juniperus monosperma*) to establish in the ponderosa pine understorey prior to the drought. Both piñon and juniper are effective at obtaining shallow soil water (Breshears *et al.*, 1997) and are less sensitive to cavitation under conditions of low soil water content (Pockman *et al.*, 1995; Linton *et al.*, 1998; Pinol & Sala, 2000). Hence, both fire- and drought-induced changes and associated increases in soil erosion can exhibit complex and threshold-like responses to the effects of climate and land use in ways that can lead to large, rapid carbon losses.

Large, rapid disturbances that could trigger terrestrial carbon losses are increasingly being documented in forests globally. The extensive high-latitude forests of Canada exhibited a reduction in ecosystem carbon storage during the 1980s due to large increases in fire and insect disturbances (Kurz & Apps, 1999). In the northern temperate zone, changes in land use and climate trends have enabled woody vegetation to increase in extent, density and productivity, resulting in substantial sequestration of carbon in recent decades (Houghton *et al.*, 1999; Pacala *et al.*, 2001), but this initial increase in sequestered carbon actually increases the potential for carbon loss through catastrophic crown fire, particularly in western forests (Covington *et al.*, 1994), as observed in the western United States during 2000. Higher tree densities can also exacerbate the extent of tree mortality following drought via increased competition (e.g. Fensham & Holman, 1999). In tropical forest ecosystems current land use patterns are expected to lead to continued net carbon loss through a marked increase in wildfire activity and fire susceptibility (Cochrane *et al.*, 1999), in addition to biomass collapse of increasingly fragmented tropical forests (Laurance *et al.*, 1997). Synergies among these processes are even more likely to produce complex responses (e.g. Laurance *et al.*, 2000).

Although these recent studies clearly highlight the importance of potential rapid losses of carbon, to date there are few quantitative estimates of the possible magnitude of disturbance-induced carbon losses, and those few estimates are highly uncertain (Smith & Shugart, 1993; IPCC, 1998; Kirilenko & Solomon, 1998; Goudriaan *et al.*, 1999). There is a pressing need for improved predictions of the effects of disturbances associated with climate variability on carbon losses. With respect to fire, our ability to predict regional–scale interactions between vegetation, climate and fire is progressing (e.g. Lenihan *et al.*, 1998; Swetnam & Betancourt, 1998) but is not yet well integrated with post-fire changes in hydrology such as accelerated runoff and erosion. With respect to drought, our ability to predict tree mortality remains poor, and predictions are based on few empirical data (Shugart, 1998). However, new advances in understanding the relationship between tree water stress and cavitation (Pockman *et al.*, 1995; Linton *et al.*, 1998) offer promise for improving our ability to predict tree mortality. Both fire and drought can produce secondary effects, such as triggering high soil erosion rates, and neither are integrated into our predictive capability yet. These larger-scale threshold responses in erosion are likely to be related to small scale heterogeneity in vegetation pattern and can be difficult to predict (Davenport *et al.*, 1998; Klausmeier, 1999; Ludwig *et al.*, 1999). Hence, ecological and hydrological dynamics are tightly interrelated and an improved integration of these processes is needed to evaluate the complex responses of carbon loss following disturbance.

The potentially large magnitude of losses of terrestrial carbon stocks is unlikely to be offset simply by remedies such as reforestation, particularly because woody mortality losses can occur much faster than tree growth gains (Allen & Breshears, 1998; Walker *et al.*, 1999). Because of the potential for these large carbon losses, global carbon management plans need to include explicit strategies to mitigate carbon losses; these strategies include pre-emptive thinning and controlled burning of temperate forests (Covington, 2000), improved soil conservation techniques (Gregorich *et al.*, 1998) and protection of large unfragmented blocks of remaining tropical forests (Laurance *et al.*, 2000). The implementation of such strategies to maintain current land stocks of carbon, particularly for forests, in concert with important carbon sequestration initiatives such as reforestation (where appropriate and sustainable), is essential for minimizing further net losses of terrestrial carbon.

It is critical that assessments of carbon management and sequestration account more fully for the potential for large, rapid disturbance-induced carbon losses. Advances are urgently needed to improve quantification of these processes so that such carbon losses can be factored more fully into strategies and policies for carbon management and sequestration.

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