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Journal of Environmental Management 00 (2003) 1–10

Journal of Environmental Management

www.elsevier.com/locate/yjema

Carbon management and biodiversity

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Received 2 August 2002; accepted 8 August 2002

Abstract

International efforts to mitigate human-caused changes in the Earth's climate are considering a system of incentives (debits and credits) that would encourage specific changes in land use that can help to reduce the atmospheric concentration of carbon dioxide. The two primary land-based activities that would help to minimize atmospheric carbon dioxide are carbon storage in the terrestrial biosphere and the efficient substitution of biomass fuels and bio-based products for fossil fuels and energy-intensive products. These two activities have very different land requirements and different implications for the preservation of biodiversity and the maintenance of other ecosystem services. Carbon sequestration in living forests can be pursued on lands with low productivity, i.e. on lands that are least suitable for agriculture or intensive forestry, and are compatible with the preservation of biodiversity over large areas. In contrast, intensive harvest-and-use systems for biomass fuels and products generally need more productive land to be economically viable. Intensive harvest-and-use systems may compete with agriculture or they may shift intensive land uses onto the less productive lands that currently harbor most of the Earth's biodiversity. Win–win solutions for carbon dioxide control and biodiversity are possible, but careful evaluation and planning are needed to avoid practices that reduce biodiversity with little net decrease in atmospheric carbon dioxide. Planning is more complex on a politically subdivided Earth where issues of local interest, national sovereignty, and equity come into play.

Keywords: Biodiversity; Carbon trading; Carbon sequestration

1. Introduction

Atmospheric carbon dioxide is increasing as a result of fossil-fuel combustion and the destruction of terrestrial vegetation. Because carbon cycles readily among the biosphere, the atmosphere, and the oceans, it should be possible to influence the store of carbon in the atmosphere by managing the store of carbon in the biosphere. Can society manage the biosphere in ways that reduce the concentration of the greenhouse gas carbon dioxide in the atmosphere without creating conflicts with other services that the biosphere provides?

As summarized in the third assessment report of the intergovernmental panel on climate change (IPCC), 'Land is used to raise crops, graze animals, harvest timber and fuel, collect and store water, create the by-ways of travel and the foundations of commerce, mine minerals and materials, dispose of our wastes, recreate people's bodies and souls, house the monuments of history and culture, and provide habitat for humans and the other occupants of the Earth' (Kauppi et al., 2001). Some of these services of land are valued in commercial markets and others have significant value with regard to the quality and resilience of life on Earth even though they are not clearly valued in commercial markets. Creating incentives to store carbon at the Earth's surface, i.e. in the terrestrial biosphere, will give market value to sequestered carbon. Increased carbon storage will presumably occur if there are economic incentives and carbon sequestration can compete with the market value of other land services. The discussion here is focused on the impact that giving market value to one environmental service of land, carbon sequestration, might have another environmental service that does not currently have market value. In particular, if carbon has value and is traded in markets, how might this impact the ability of land to 'provide habitat for humans and the other occupants of the Earth'? What are the potential impacts of carbon sequestration on biodiversity?

In this paper we summarize some basic principles and patterns of biodiversity. We then consider how an international treaty on climate change, such as the Kyoto

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0301-4797/03/$ - see front matter © 2003 Published by Elsevier Science Ltd.
PII: S0301-4797(02)00190-1

Protocol, might influence carbon management in the terrestrial biosphere, and thus land management. Finally, we discuss ways in which these influences on land management might impact the Earth's biodiversity. We have not attempted a comprehensive review of either biodiversity or carbon management but rather have tried to develop some general ideas on how the latter might impact the former.

There are several aspects of carbon sequestration and carbon trading that could have implications for biodiversity. Although the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC, 1997) has not yet come into force, it has been ratified by 74 countries (as of 4 June, 2002) and we use it here as a point of reference for what a global system of carbon credits and carbon trading might be like. In particular, the Kyoto Protocol establishes binding national limits for the emission of greenhouse gases to the atmosphere but permits emissions from other sources to be partially offset by increasing carbon stocks, or perhaps by protecting threatened carbon stocks, in the terrestrial biosphere (carbon sequestration). The Kyoto Protocol is an agreement between countries and describes national commitments for greenhouse gas emissions, but presumably, each ratifying country would implement some similar set of internal policies in order to meet the national commitments. Many of the countries that emit large quantities of CO_2 have ratified the Kyoto Protocol. Although the largest single emitter, the USA, has indicated that it does not intend to ratify the Kyoto Protocol, it has expressed concern about the rising concentration of atmospheric CO_2 (i.e. USA Department of State, 2002) and it played a major role in negotiating many of the details of the Protocol.

In pursuit of the goal of minimizing net greenhouse gas emissions, the Kyoto Protocol provides specific incentives for maximizing afforestation and reforestation and minimizing deforestation. It also provides, explicitly or implicitly, incentives for using biomass fuels, using wood products with low energy intensity, increasing the efficiency with which forest products are harvested and used, achieving high rates of biological productivity, relocating some land-management activities, and joint international activities in land management. In this paper we discuss the land management activities that might be encouraged or discouraged by an international system for managing and trading carbon credits, how these activities are likely to be distributed within and among countries, and how these activities might impact biodiversity in various locations on national and global landscapes.

2. Biodiversity

2.1. What is biodiversity and why is it important?

Biodiversity is a general term that refers to the variety of forms of life found in a particular location. This location might be a study plot, a region, or the entire globe. Biodiversity can be evaluated in terms of the number of different types of biological structures present. These biological structures can range in size and complexity from individual genes or genotypes, to species (or subspecies), to higher taxonomic levels such as classes or phyla, or even to whole groups of organisms within their environment (ecosystems). The most common measure of biodiversity is the number of species in an area, and the primary concern about human effects on biodiversity is expressed in the loss of species. This loss might be from a local area or it might be the permanent loss from all locations, where the species occurred, i.e. global extinction.

Organisms regulate the flux of carbon between the atmosphere and the biosphere through primary production (the conversion of atmospheric carbon dioxide and water, using light energy, to plant tissue) and decomposition (the conversion of plant tissue back into carbon dioxide through consumption and decomposition by animals, bacteria, and fungi). The organisms that comprise the Earth's biodiversity perform the economic functions of agricultural and forest productivity and these are a subset of the carbon cycle processes that sustain all life on Earth.

Maintaining any specific process, such as plant growth, requires many different types of organisms in addition to the plants themselves. Decomposers are required to break down dead plant material to release nutrients essential for the growth of new plant tissue, insects are necessary for pollination of flowers to produce the next generation of plants, etc. As long as all of the required functional types of organisms are present, the number of species within any particular functional type is less critical. While biodiversity in the broad sense regulates the cycling of carbon and other ecosystem processes, the total number of species involved in these processes has relatively little effect on the processes themselves (Hooper and Vitousek, 1997; Huston, 1997; Huston et al., 2000; Loreau et al., 2001).

Ecosystems with many species are not necessarily more productive than ecosystems with few species. Many highly productive natural ecosystems are near monocultures of a single plant species. However, having multiple species performing a particular function does provide some insurance that the system will continue to function even if one of the species is lost. Similarly, as environmental conditions fluctuate, the presence of multiple species performing a particular process should reduce fluctuations in that process if different species reach their optimum performance under different conditions. High diversity should also reduce temporal instabilities caused by natural variation in climate, by disturbances that kill organisms, or by other factors (Loreau et al., 2001). Numerous benefits have been demonstrated for multi-species agricultural and forestry systems (Vandermeer, 1989; Vandermeer et al., 1998; Wolfe, 2000).

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2.2. Patterns of biodiversity and carbon cycle processes

All animal life depends on the productivity of plants. Consequently, the number of animal species tends to increase as plant productivity increases (Huston, 1994). This relationship can be found at all spatial scales, from hillsides to the entire globe. Plant productivity is regulated by the availability of the resources essential for plant growth; particularly water, sunlight, plant nutrients, and favorable temperatures. At a global scale, the length of the growing season, which is controlled primarily by above-freezing temperatures and adequate water, determines how long plants can grow and, thus, the annual amount of plant production. At a local scale, where the growing season is relatively uniform, the annual amount of plant production depends on soil nutrients and water. The rate at which plant material accumulates is a function of the rate of carbon dioxide removal from the atmosphere and the rate at which the plant material is consumed and decomposed by animals.

Whereas some form of life can be found virtually everywhere on, above, or within the surface layers of the Earth; some areas have many more species than others. Different types of species reach their greatest abundance in different environments and the diversity of species also varies greatly among environments. For example, ungulates (antelopes, deer, bison, cattle, etc.) are found on all continents except Antarctica but have their greatest diversity in Africa. Penguins, highly specialized birds, are found only in the Southern hemisphere—along coasts bordering the Southern ocean. The patterns of biodiversity are much better known for the large organisms such as mammals, birds, fish, and trees; and are poorly known for small organisms such as insects, bacteria, fungi, and nematodes.

The patterns of plant diversity differ dramatically from the patterns of diversity for many types of animals. In contrast to the diversity of large animals, which tends to be highest at high levels of productivity, the diversity of plants generally declines at high levels of productivity and is low in high productivity forests with massive trees. This counter-intuitive pattern is caused by competition among plants, which is most intense when plants are growing rapidly and achieving large sizes. A consequence of this intense competition is that a few of the fastest-growing, largest, or otherwise strongest competitors generally crowd out other species. In contrast, where plants do not grow as well, the competitive process operates more slowly and more species are able to co-exist. Natural systems that tend to have high productivity and low species diversity of plants include phytoplankton and algal blooms, salt marshes, freshwater marshes, riparian forest in the tropics and temperate zones (e.g. *Populus deltoides* and *Prioria copaifera*), bamboo forests, redwood forests, Douglas fir forests, and some eucalypt forests. High diversity plant communities are generally found on relatively less-productive sites, examples of which are chalk grasslands, Mediterranean shrublands, and rainforests on nutrient-poor oxisols and ultisols (Lawes et al., 1882; Dawkins, 1959, 1964; Grime, 1979, 2001; Huston, 1979, 1980, 1993, 1994; Berendse, 1994; Mahdi et al., 1998).

A widely observed pattern of plant diversity is an increase from low levels of diversity under conditions of very low productivity (approaching zero under extreme conditions) to a maximum at intermediate levels of productivity and then a decrease to relatively low levels where productivity is highest. This unimodal or hump-backed pattern, first described by Grime (1973a,b, 1979), has important implications for the tradeoffs between biodiversity conservation and other human uses of land—including carbon management. The critical fact is that much of the Earth's plant biodiversity is located on lands that are relatively less productive and poorly suited for intensive agriculture.

The diversity of small animals, in contrast to that of large animals (which tends toward highest biodiversity with highest productivity), tends to follow the basic pattern of plant diversity, with a maximum on relatively less productive lands (Huston and Gilbert, 1996). This includes most insects and many birds. While many of the low productivity/high diversity lands are not suitable for intensive agriculture, they are suitable for less intensive uses such as forestry or grazing.

The highest diversity of many types of land organisms (primarily plants and small animals) is found in tropical rain forests, while the highest diversity of many types of marine organisms (primarily herbivores and carnivores in many different phyla) is found in tropical coral reefs. For most types of plants and animals the number of species found in a fixed area decreases with distance from the equator. Although there is no scientific consensus to explain this latitudinal gradient of species diversity, an obvious consequence of this pattern is that the developed countries of the North have many fewer species, and overall lower biodiversity, than do the less-developed countries of the tropics. This inequality in the global distribution of biodiversity is the mirror image of the global distribution of wealth, as estimated by per capita GNP (Huston, 1993). Within any region, either tropical or temperate, there is also variation in the distribution of biodiversity, and this variation tends to be correlated with conditions that also influence human activities such as agriculture and forestry.

2.3. Biodiversity and land use

The correlation between patterns of biodiversity and the same environmental conditions that also influence human activities is not surprising, given that humans are one of the life forms found on Earth and a component of its biodiversity. The cause for concern is that this single species has been able to affect the planet so strongly. Human impacts on the Earth's surface, waters, and atmosphere have led to the extinction of thousands of species to date and hundreds of thousands of species are threatened with extinction in the next few 100 years.

Much of the conflict between man and nature is centered in areas of high plant productivity (Huston, 1993, 1994). It is here that human agriculture and other intensive uses of land, i.e. for urbanization, have replaced the natural ecosystems that once supported large numbers of grazing animals and their predators. Recent estimates suggest that humans are now using or dominating between 39 and 50% of the Earth's terrestrial biological production (Vitousek et al., 1997). Human manipulation of the planet's high productivity environments tends to increase the short-term rate of carbon uptake over that of the original natural ecosystems. However, human manipulation generally reduces the total amount of carbon stored in the system by keeping plant size small through harvests and by increasing the rate of decomposition of dead plant material. The impacts of human management on the biodiversity of these productive areas are primarily through the loss of natural habitat and landscape complexity. In addition, extreme reduction of animal populations increases the probability of their eventual extinction.

Any human efforts to regulate atmospheric carbon dioxide by manipulating the carbon cycle will interact with other human uses of the landscape, as well as with the natural biodiversity of the landscape. Understanding the relationship between biodiversity and productivity should allow us to minimize the negative effects on biodiversity and essential ecosystem services of any land-use changes designed to decrease atmospheric carbon dioxide.

The continuing human demand for food guarantees that the most productive land areas will remain under intense human use, primarily for cultivated agriculture. It is over the rest of the landscape that human land-use decisions will affect the carbon balance between the atmosphere and the biosphere, as well as determine what portion of the Earth's biodiversity will survive into the future. Human patterns of land use have always been strongly driven by the natural patterns of productivity and this relationship has been intensified by market-based economics. The best and most productive lands in any region have always been the first taken for human use (Wheeler, 2000), while the poorest and least productive lands have been left for public uses such as national parks, grasslands, and forests (Huston, 1993, 1994; Scott et al., 2001) (Fig. 1). The consequences of human land-use patterns for biodiversity have been mitigated by the natural patterns of plant diversity, which includes lower biodiversity on the most productive lands. The consequences of human land-use patterns for biodiversity can be mitigated further by awareness, understanding, and appropriate land-management strategies.

These natural patterns of biodiversity and human land-use provide the template on which solutions to many human-caused environmental problems must be based, particularly problems related to biodiversity and the carbon cycle. The fundamental carbon cycle processes occur at different rates in different environments. This offers the possibility of manipulation or spatial management to optimize the ratio of the two primary carbon cycle functions, production and decomposition, and thus to regulate carbon fluxes.

2.4. Carbon credits and debits from land management

The Kyoto Protocol currently provides incentives for two different types of land management activities that could reduce atmospheric CO_2 concentrations, one explicitly and the other implicit in the details of the Protocol. Removal of CO_2 from the atmosphere by sinks (carbon sequestration) is explicitly discussed in the Protocol. Implicitly, substitution

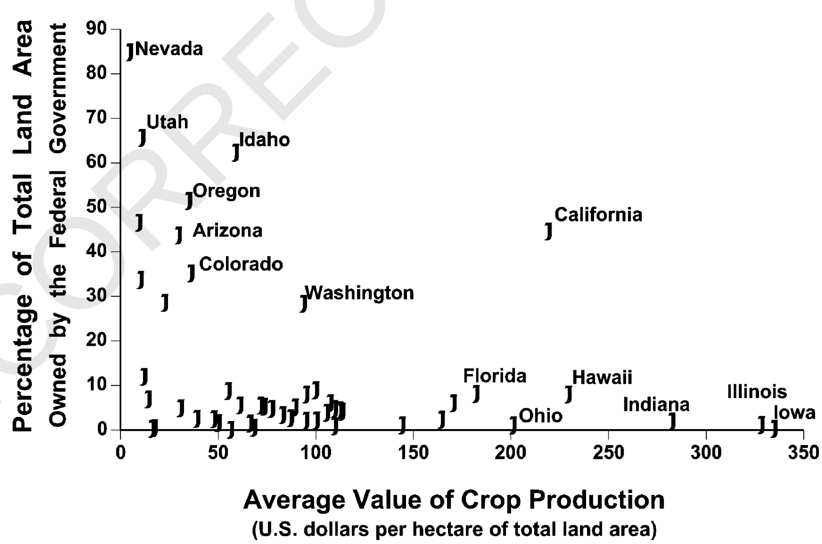

Fig. 1. Percentage of land area in each of the lower 48 states plus Hawaii of the United States that is owned by the Federal Government as public lands (such as national parks, national forests, national rangelands) in relation to the average value of crop harvest per hectare of total land area in each state (based on data from US Department of Commerce (1990)).

of biomass energy for fossil-fuel energy or of biomass-based materials for alternate, more energy-intensive materials can reduce a country's emissions of CO_2. Whereas all combustion of fossil-fuels results in emissions of CO_2 that would need to be counted under the Kyoto Protocol, the combustion of recently grown plant material is counted only if it results in a change in the standing stock of plant biomass. These two types of activities raise interesting, but different, challenges for conservation of biodiversity because the harvest of biomass fuels or biomass products has different land-use implications than does carbon sequestration.

2.5. Carbon sequestration

IPCC defines carbon sequestration as an increase in carbon stocks other than in the atmosphere (IPCC, 2000). Consistent with this, the Kyoto Protocol prescribes that 'emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities' are to be 'measured as verifiable changes in carbon stocks'. In this text we use the terms 'credits' and 'debits' to represent offsets or additions to greenhouse gas emissions that might be included in emissions inventories.

Although the language of the Kyoto Protocol initially restricted credits or debits for changes in carbon stocks to afforestation, reforestation, and deforestation; subsequent agreements would allow inclusion (within specified limits) for carbon sequestered by agricultural soils and by other forest management activities (UNFCCC, 2002). The consequences of this Kyoto language (for developed countries) include: (1) activities that increase the standing stock of carbon on a landscape would yield credits in a carbon trading regime; (2) activities that decrease the standing stock of carbon on a landscape would have to report emissions of carbon, i.e. debits; and (3) any harvest and use of forest or other biomass products (e.g. for use as a fuel) would not yield either carbon debits or carbon credits so long as there was no change in stocks. Harvest would not result in a debit as long as production was on a sustained yield basis where the rate of harvest is equal to the rate of replacement growth, and there would be no credits unless there was long-term storage of the harvested products. Fuel substitution is discussed in Section 2.6 of this paper.

The ecosystem processes that regulate carbon sequestration are (1) plant growth, which determines the rate of biomass production, (2) plant death, which determines how long plants live, and thus how large they become and how much carbon they can store, and (3) plant oxidation, which determines the amount of plant material left on the landscape. As discussed earlier, plant growth rates are determined primarily by climate and nutrients, although fertilization and other management can have some effect on the size distribution of plants. Plant death and oxidation result from natural processes such as fires and insects, as well as from human intervention such as harvesting and deforestation. Plant growth rates determine how rapidly carbon is removed from the atmosphere, and the time interval between mortality events plus the exposure to oxidation determine how much carbon is removed from the biosphere.

Schlamadinger and Marland (1996) have shown that the economics of carbon credits for sequestration depend not only on rates of productivity but also on the size of the initial standing stock (for carbon maintenance) or the time period over which carbon sequestration is allowed to occur (for carbon accumulation). While carbon will accumulate more rapidly on productive sites, even slowly growing forests can accumulate a large amount of biomass if given sufficient time. Natural, undisturbed forests represent a large amount of carbon storage. Similarly, undisturbed soils can accumulate a large amount of carbon over time. Disturbance of these landscapes can result in rapid release of large amounts of carbon that will be re-captured only slowly as the forest re-grows or the soil rebuilds (Harmon et al., 1990).

If the biosphere is used for carbon sequestration, the incentive is to achieve large standing stocks. This can be achieved most effectively by reducing natural and anthropogenic plant mortality and oxidation over large areas, areas where it is not essential that plant productivity be high. Slowly growing forests, which cover large portions of the landscape on many continents, are not good candidates for intensive harvest-and-use systems for biofuels or wood products. However, such forests are important reservoirs of plant and animal biodiversity (Fig. 2) and their use for carbon sequestration can have large benefits for biodiversity, as well as for other ecosystem services such as water storage and regulation of local climate.

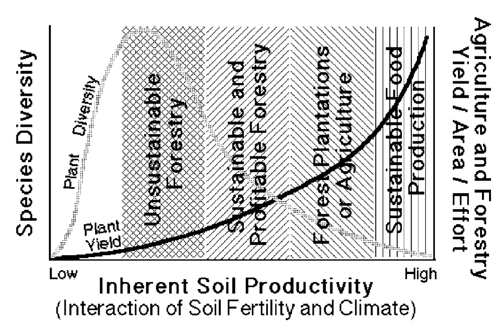

Fig. 2. Unimodal species diversity curve for plants in relation to productivity, as influenced by soils and climate. Note that plant diversity is naturally low in very productive areas, and reaches a maximum under relatively unproductive conditions. The economics of production dictate a hierarchy of land uses over the natural variation in productivity found on all landscapes, with agricultural food production on the best soils and forestry on less productive soils. The relatively poor soils on which the species diversity of plants and many animals is highest are generally unsuitable for intensive, sustainable forestry; but are suited for long-term carbon sequestration (from Huston and Gilbert, 1996).

2.6. Biomass fuels and other biomass products

Replacing fossil fuels and other products with fuels and products produced by recent plant growth is the second major strategy for using the terrestrial biosphere to reduce the CO_2 concentration of the atmosphere. Because the Kyoto Protocol and the underlying UNFCCC would measure releases of carbon from the biosphere as the changes in stocks, there would be no reportable CO_2 emissions from biomass fuels produced on a sustained yield basis. To the extent that biomass fuels replace fossil fuels, net carbon emissions to the atmosphere will be reduced.

The use of bio-based products such as paper and construction lumber could yield carbon credits in two ways. First, biomass products often require less fossil-fuel energy for their production and use than do the products for which they substitute. Second, long-lived biomass products can be produced on a sustained yield basis. If some of the harvested material is stored as long-lived products such as construction lumber, the stock of carbon stored in products will increase with time, which is, by definition, carbon sequestration.

When biomass is used as a fuel or to produce bio-based products, the incentive for carbon credits is to achieve high yields and hence high harvest rates. Such high productivity can be achieved efficiently on fertile soils under favorable climates. The preferred portions of the landscape are the same areas that tend to be used for production agriculture and it is expected that modern production of competitively priced biofuels will largely compete for land with agriculture (Kszos et al., 2000). These are also the same portions of the landscape that are most favorable for the diversity of many types of animals, particularly large vertebrates and their predators; but they are distinct from the less productive areas where the diversity of plants and smaller animals is often higher.

Studies to date show that biofuels plantations on productive lands have higher animal biodiversity than do the annual agricultural systems they replace (largely because of the longer harvest intervals and greater physical structure), but lower biodiversity than natural forest stands in the same environments (Cook and Beyea, 2000). Forest management can be designed to maintain or restore natural patterns of biodiversity (Oliver and Larson, 1996; Hunter, 1999; Huston et al., 1999), but the associated management practices are applicable primarily for longer harvest rotations rather than for intensive short-rotation forestry. Many of the effects of forest management on biodiversity are analogous to the effects of natural disturbance, which can impact forests at any successional stage. Forest disturbances shift forest structure and composition toward an earlier successional stage. Disturbed or early successional forests generally have higher tree diversity than late successional forests, although some other components of biodiversity are typically higher in late successional forests. Boreal forests, many of which have rapid growth during the short growing season, generally have low tree biodiversity regardless of successional stage. Consequently, frequent harvests and intensive forest management may have little effect on tree diversity in boreal forests.

Analysis by Schlamadinger and Marland (1996) has shown that when forest productivity is high and the initial standing stock is low (e.g. previously deforested lands), harvest and use can often be accomplished with high efficiency and low-energy input. In this case, the optimum strategy for carbon credits is to harvest and use biomass products. However, if the initial standing stock is large, the conversion to a harvest-and-use system can require multiple harvest cycles to overcome the carbon lost during the removal of the initial carbon stock. The period and number of harvest cycles required to achieve a positive net carbon balance is a function of site productivity, and constrain harvest-and-use systems to high productivity sites. This represents a very different set of economic constraints than those that favor carbon sequestration.

2.7. Carbon trading

If carbon credits and debits have value in meeting national commitments to limit greenhouse gas emissions, we can envision that these credits could be traded in national and international financial markets. The Kyoto Protocol acknowledges this principle and would allow trade of carbon credits among countries, with some restrictions. The Protocol would create two classes of countries with different obligations and opportunities for greenhouse gas emissions and trading of emissions credits. Countries listed in Annex B of the Protocol (developed countries and countries with economies in transition) would have commitments to limit greenhouse gas emissions while those countries not specifically listed in Annex B (developing countries) would have no such commitments. These two classes of countries are roughly analogous to other geopolitical groupings, such as 'North' and 'South' or 'Temperate' and 'Tropical'. While the economic disparities between these groupings have long been recognized, the environmental and biological disparities have been less appreciated. At the global scale, the developing economies tend to be in the tropical countries with relatively poor soils (Fig. 3) and high biodiversity, while the developed countries tend to be temperate countries with more fertile soils and lower biodiversity (Huston, 1993, 1994). These disparities offer opportunities for a financial market in carbon credits that could be mutually beneficial to the countries involved in addition to being globally beneficial through effects on atmospheric carbon dioxide, biodiversity and other ecosystem services (Daily, 1997). This, of course, was part of the motivation behind inclusion of the 'Clean Development Mechanism' in Article 12 of the Kyoto Protocol.

The Kyoto Protocol would allow trading of emissions permits ('credits') among Annex B countries with few

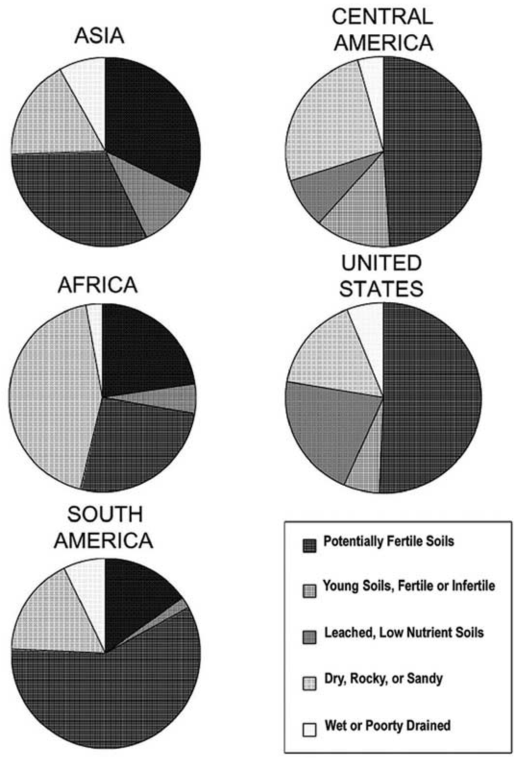

Fig. 3. Distribution of major soil classes for the three tropical regions (all land area between 23°N and 23°S), plus Central America and the continental United States for comparison. Note the high proportion of potentially fertile soils in the temperate United States, as well as the differing ratios of potentially fertile to low nutrient soils among Asia, Africa, and South America (based on Richter and Babbar, 1991).

restrictions because the global total of emissions permits would presumably not be changed by such trading. Trading of emissions 'credits' between Annex B and non-Annex B countries, however, would be limited, e.g. to 'reductions in emissions that are additional to any that would occur in the absence of the certified project activity' (UNFCCC, 1997). In the initial stages, credits for activities in developing countries would be generated only by afforestation and reforestation (UNFCCC, 2002). There are arguments that carbon credits should also accrue for forest protection projects in non-Annex B countries if forest clearing would have occurred in 'the absence of the certified project activity', but this is not yet embraced by Kyoto-related negotiations. Protection of tropical forests for long-term carbon sequestration represents an opportunity for a land-use strategy that simultaneously maximizes carbon sequestration and protects biodiversity.

That developing countries would not have commitments on carbon emissions under the Kyoto Protocol leads, however, to an asymmetry in carbon markets. The value of carbon credits and debits would depend on their location. Carbon emitted in non-Annex B countries could create no debits, i.e. have no negative value in carbon markets. Hence, for example, wood harvested in a developing country and burned as a fuel in a developed country, would reduce reportable carbon emissions from the developed country even if the wood was not produced from a sustained yield operation and there was a decrease in carbon stocks in the biosphere of the developing country. The result could be a shift of some forest harvest from areas of higher productivity in developed countries, with higher opportunity cost, to areas of lower opportunity cost and productivity, but higher biodiversity, in developing countries.

For forests in developed countries, the initial standing stock of carbon is an important consideration in balancing the carbon benefits of forest protection versus the harvest-and-use of forest products (Schlamadinger and Marland, 1996). In contrast, under current carbon accounting plans, the initial standing stock of forests in developing countries would be less of a consideration, since accounting might not reflect the loss of initial standing stock. However, any reduction of standing stock from natural forests will generally result in a loss of biodiversity, and negative effects on other ecosystems services as well.

3. Discussion

Our discussion of carbon management and biodiversity has been a qualitative review using basic principles, but there are important quantitative elements that need to be considered. For carbon management we can quantify the amount of carbon stored in a landscape or the amount of fossil fuel saved as a result of substituting bio-based materials. As with intensive agriculture, the more production that can be achieved on a given landscape, the less area will be required to meet demand, e.g. for food production or carbon sequestration. To the extent that production can be achieved in a smaller area, a larger area can be left for nature (Avery, 1995; Huston, 1995; Victor and Ausubel, 2000; Waggoner and Ausubel, 2001). There is no comparable numeric to describe the value or demand for biodiversity. One of the challenges of considering biodiversity generally is the lack of useful numerics for comparing and valuing biodiversity.

The quantitative challenge now is that both carbon sequestration and production of biomass fuels could put very large demands on the land resource base. For example, replacing all fossil-fuel use in the US with biomass grown at the average productivity of current forests would require an area greater than the land surface of the USA. An early workshop on biomass energy worried that 'the loss of species, habitat, and ecosystem structure could accelerate substantially, if biofuel production were to expand enough that bioenergy became a major energy source, without giving due consideration to biodiversity' (Beyea et al., 1991). A critical issue for both carbon management and biodiversity is where, how much, and how the biomass is produced. Making these decisions requires sensitivity to societal priorities and the relationships among site productivity, the economics of extractive land uses, and biodiversity. Proponents for biofuels do not advocate development of biofuels at anything approaching the scale of fossil-fuel use in the US and do not suggest conversion of natural forests to biomass plantations. Walsh et al. (2000) suggest that 7 million ha of cropland (4% of USA cropland) could supply 2.65% of the electricity currently produced in the USA. A major focus of the US biofuels research program has been to increase yields (Kszos et al., 2000). This has largely been to improve economics, but it would also decrease the land area required for a given level of output.

The economics of biofuels suggests that the need for high productivity will limit biofuels plantations to highly productive lands and compete with agriculture rather than with forest lands. This constraint limits the extent to which fossil fuel displacement could play a role in addressing climate change. However, the economics of lumber and pulp production do not require as high productivity as biofuels, and consequently may replace natural forests on less productive soils, as is currently happening in the southeastern United States, southern Brazil, and throughout the world.

Over the wide range of productivities found across the Earth it is conceptually possible to allocate land use to optimally meet multiple objectives simultaneously. Some objectives would inevitably conflict, such as the need to produce food for society and the desire to preserve large herds of native herbivores in their natural habitat. Other objectives might have less conflict than initially expected, such as the need for intensive agriculture and the need to preserve large areas for conservation of plant and animal diversity, maintenance of hydrologic function, and possibly carbon sequestration. However, achieving optimal balance is complicated on a politically subdivided Earth and where resources are differently valued according to their location. Sustainable management of the Earth's natural resources could be globally optimized by allocating the use of different types of land in a way that maximizes the comparative advantage of each area to meet the need or needs for which it is best suited; but practically this will be tempered by political subdivision, national sovereignty, equity, personal property rights, and the perceptions of local 'optimum' within each political subdivision.

Despite the multiple values of preserving tropical forests, there remains an accounting challenge in tradable credits for protecting carbon stocks. Carbon protected from emission to the atmosphere 1 year should not yield additional credits if it is protected again the following year. However, a system that compared actual emissions each year from a protected forest (in a non-Annex B country) with emissions that would have occurred in the absence of protection would yield annual credits in the early years even if the same level of carbon stocks was reached in the long run. In this case, a forest that was protected initially could yield a series of debits in later years if deforestation was occurring. However, a completely unprotected forest would likely have already been completely deforested. Although the flow of early carbon credits could be counter-balanced by a later flow of carbon debits, there would still be net value in financial markets. As a consequence of discounting, the net present value of carbon stored (i.e. not released) sooner is greater than the negative value of carbon released later. In addition, the delay (even if temporary), slows the rate of carbon release to the atmosphere and the damage to biodiversity, and holds out the potential for long-term protection (Marland et al., 2001).

4. Conclusions

The two principal approaches for reducing atmospheric carbon dioxide through managing changes in land use have contrasting implications for biodiversity and other ecosystem services. To significantly increase the scale for replacement of fossil fuel with biomass fuel, or for substitution of wood products for more energy-intensive alternatives, would require relatively frequent harvests on high productivity lands. Depending on economic incentives, this practice may compete with agricultural land uses and/or push more intensive land uses toward the less productive lands that are currently the primary reservoirs for the remaining biodiversity. Without thoughtful planning, conversion of existing natural forest to a biomass production system will have a net negative effect on biodiversity and other ecosystem services, and could have a net negative effect on atmospheric carbon (i.e. an increase in atmospheric carbon dioxide) over short to intermediate time frames, depending on the initial standing stock of carbon, and the rate of productivity. Conversely, conversion of existing land in row crops to production of perennial biofuel crops is likely to have a net positive effect on biodiversity.

In contrast, carbon sequestration in living plants and soils, either through long-term protection of currently mature forests, or long-term protection of re-growing forests, is likely to have an immediate net positive effect on atmospheric carbon dioxide, plus a positive effect on biodiversity and other ecosystem services. Protection of existing mature forests keeps the living plant carbon out of the atmosphere and preserves the current level of biodiversity. Protection of re-growing forests provides an annual carbon sink and also allows recovery of biodiversity associated with forests. This mutual benefit for biodiversity and carbon sequestration reaches its maximum in relatively unproductive forests, where biodiversity is high and the economics are less favorable for sustainable harvest-and-use systems.

The unequal distribution of soil fertility, forest productivity, and biodiversity among the countries of the world, and any unequal treatment of carbon in carbon-trading markets, sets up the opportunity for both win–win and lose–lose scenarios for carbon sequestration and biodiversity in economic or carbon-trading interactions. Trading of carbon credits from sequestration should increase both carbon storage and biodiversity in exchanges within, among, and between developed (Annex B) and developing (non-Annex B) countries. However, the carbon accounting practices proposed for the implicit carbon credits that could be obtained by fuel or product substitution have the potential to shift biomass harvests, with no net positive effect on atmospheric carbon dioxide and a net negative effect on biodiversity. The magnitude of the carbon sequestration effort and the way in which activities are distributed on this politically sub-divided Earth will be very important in determining the effect of carbon management on biodiversity.

An understanding of the relationships among climate and soil fertility, the economics of agricultural and forest production, and the different components of biodiversity provides the foundation for land management planning that can help to reduce atmospheric carbon dioxide concentrations, while preserving and restoring biodiversity in both developed and developing countries.

Acknowledgements

This work was supported by the USA Department of Energy's Office of Science, Biological and Environmental Research Program. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the USA Department of Energy under contract DE-AC05-00OR22725.

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