CURRENT KNOWLEDGE ON EFFECTS OF FOREST SILVICULTURAL OPERATIONS ON CARBON SEQUESTRATION IN SOUTHERN FORESTS

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Abstract—Incentive programs to reduce carbon dioxide (CO_2) emissions are increasing in number with the growing threat of global warming. Terrestrial sequestration of CO_2 through forestry practices on newly established forests is a potential mitigation tool for developing carbon markets in the United States. The extent of industrial and non-industrial private timberland in parts of the southeastern United States is increasing rapidly with the reforestation of marginal or abandoned croplands. The afforestation or reforestation potential of Mississippi and the rest of the Lower Mississippi Alluvial Valley may play a significant role in the creation of new sequestration forests in Mississippi. This study reviews research pertaining to the effects of various forest management practices on the above- and below-ground carbon fluxes of southern forests.

INTRODUCTION

The level of carbon dioxide (CO_2) in the atmosphere currently averages 365 parts per million (ppm) which is approximately 35 percent greater than the pre-industrial revolution levels of 270 ppm (Groninger and others 1999). Burning of fossil fuels such as oil, coal, and natural gas is the primary man-made source of this greenhouse gas. This accelerated release of carbon (C) into the atmosphere alters the global C cycle, resulting in higher atmospheric CO_2 levels (Post and others 1990). Deforestation due to land use changes such as urbanization and agriculture convert areas that either (1) have an essentially neutral C flux, but contain large amounts of stored C (as in the case of old-growth forests) or (2) are young forests that act as C sinks to sources of CO_2 to the atmosphere (World Resources Institute 2003). The release of CO_2 from tropical deforestation is the forest's largest contributor to climate change. This is amplified by practices associated with forest clearing such as burning, fertilizing agricultural fields, and the rotting of slash material which produce other greenhouse gases as well (World Resources Institute 2003).

Other greenhouse gases are less abundant in the atmosphere than CO_2 but have more potent effects. Nitrous oxide, for example, is only 0.001 as common as CO_2, but is 200 to 300 times as effective at trapping heat; it also remains in the atmosphere far longer than CO_2 (Cambridge Scientific Abstracts 2004). Chlorofluorocarbons, which were not present in the atmosphere prior to the Industrial Revolution, have warming effects ranging from 3,000 to 13,000 times that of CO_2 and persist for up to 400 years. Other greenhouse gases include hydrofluorocarbons, methane, sulfur hexaflouride, and perfluorocarbons. Directly reducing the emission of these greenhouse gases is currently the only effective method of reducing their concentration in the atmosphere. CO_2 is unique in that it occurs naturally in higher concentrations and is sequestered by photosynthetic organisms in both terrestrial and marine environments.

CO_2 levels are maintained naturally in the atmosphere where the gas acts as a barrier trapping radiant heat from escaping back into space. This phenomenon is referred to as the "greenhouse effect" and is an important natural process which regulates and maintains the Earth's climate (World Resources Institute 2003). Rapid increases in the atmospheric level of CO_2 due to human activity results in an increased amount of radiant heat trapped near the Earth's surface. This may potentially increase the mean global temperature causing significant climatic changes as atmospheric levels of CO_2 rise.

Silvicultural practices such as reforestation, afforestation, and the management of existing forests have enormous potential for sequestering atmospheric C. Existing projects vary in scale and are located throughout Europe and the Americas. Currently, C sequestration programs in Mississippi offer landowners an initial one-time payment of $400 to $450 per acre for placing their land in a 70-year easement (The Carbon Fund 2003). However, the magnitude of C that may be stored in terrestrial ecosystems is not fully understood.

The effects of most silvicultural practices on the soil C pool are poorly understood, and research results from such studies conclude only short term effects. Also, these effects have typically been studied individually, so the amount of C storage resulting from plantation forestry over many rotations and silvicultural operations has yet to be quantified. This paper addresses the results of studies conducted to quantify C fluxes resulting from silvicultural practices as well as those attempting to place an economic value on stored C.

Market impacts resulting from this increased value of forests and probable increase in plantation forest area are also discussed in light of available research. In some cases, taxes on fossil fuel use are used to provide additional incentive to implement plantation forestry and move toward more emission-free technologies.

SOIL CARBON

Soil possesses the greatest capability of storing C for long periods of time, and silvicultural practices directly affect the rate and amount of C stored in the soil. Therefore the relationship between belowground storage and common silvicultural practices is one that must be fully understood before forestry's use as a CO_2 emission mitigation tool can be valued. Aboveground storage rates have been established with the understanding that the temporal scale at which C in aboveground biomass is stored depends on whether the material is

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harvested or what the final products are if it is harvested. However, total belowground storage capacity and how different types of forestry operations affect it, is not fully understood. This section therefore identifies general methods by which C is stored in soil and reviews research regarding the storage or loss of C under various cover types and management regimes.

There is tremendous capacity for the storage of C in soils. World soils contain an estimated 3.2 trillion tons of C within the top 6 feet. Approximately 2.5 trillion tons of this C is in the form of soil organic matter; the rest is comprised of inorganic forms such as calcium and magnesium carbonates (Wojick 1999). Soil organic matter is easily affected by land use practices and can be divided into two major categories: stabilized organic matter, which is highly decomposed and stable, and the active fraction, which is being actively used and transformed by living plants, animals, and microbes (University of Minnesota Extension Service 2004).

VEGETATIVE CARBON

Delcourt and Harris (1980) constructed a C budget of the Southeastern United States biota from 1750 to 1950 to determine the pre-settlement C pool, document losses from deforestation, and determine whether the region is a source or sink for atmospheric CO_2. U.S. agricultural census statistics and forest survey records provided the data for determining land use changes during the settlement of the region. Estimates of the total volume of virgin and secondary forests were used to calculate total C content, including detrital soil C. Due to the rapid clearing of forests and prairies during European settlement, from 1750 to 1950 the southeast was a net source of atmospheric C at an average rate of 0.13 gigatons per year. However, due to the increased acreage and productivity of commercial forests in the last 20 to 30 years, the region has become a net sink of 0.07 gigatons of CO_2 per year. Such general measurements are useful, but more precise means of monitoring and verifying quantities of stored C are needed. Measurements on a smaller scale are especially needed when determining effects of different site disturbances.

An important aspect of implementing a large-scale C storage program to mitigate emissions is determining where C is stored in a tree. Slash material and root systems left after harvesting constitute a large amount of the total biomass accumulated over a rotation. Laclau (2003) developed regression equations relating root dry weight, root volume, and C storage to tree diameter for ponderosa pine plantations. Lacalu's equations produced a total root biomass estimate of 0.688 mg acre^{-1} with 0.324 mg acre^{-1} of total root C for a 10-year-old stand. Total root biomass for a 20-year-old stand was estimated at 10.93 mg acre^{-1} with 5.18 mg acre^{-1} of total root C. The range of data collected for this experiment limits the application of its results since varying age class, tree size, and other site factors disrupt the predictive capabilities of the regression equations.

The potential for C sequestration through forestry practices varies by region and depends mainly on the soil type and growth rates of each region's predominant plantation species. All trees, regardless of species or age, have approximately the same C to dry weight ratio. Matthew's (1993) research suggests that C contents tend to range between 49 and 51 percent with broadleaved species having a slightly lower C content than conifers and tropical species. Therefore, a value of 50 percent or 0.5 times the dry tree weight is probably an appropriate estimate for most large-scale calculations.

SILVICULTURAL IMPACTS ON CARBON STORAGE

Schroeder (1991) used computer simulation models to estimate the effects of thinning on C storage. Douglas-fir [Pseudotsuga_menziesii (Mirb.) Franco] and loblolly pine (Pinus tadea L.) were the example species. Thinning was generally shown to cause a decrease in C storage with the exception of very dense young stands. A 35-year rotation with an initial planting density of 607 trees per acre was assumed, with 20 and 40 percent basal area removals occurring at age 20. At the lighter thinning level, the final C yield was about the same as the unthinned stand. At the 40 percent thinning level, there was a 12 to 18 percent decrease in final yield. However, if the thinnings are included in the final totals (assuming long-lived products), there is little difference between thinned and unthinned plantations.

Harvesting

The effects of harvesting on soil C content have been examined in many studies with varying results. Johnson (1992) summarized the effects of harvesting alone in 13 different studies. Despite the expected significant change in forest floor mass, the majority of studies reported little (<10 percent) or no change in mineral soil C. However, other studies reported either increased or decreased C contents. Cultivation or intense fires are noted as having the most dramatic effect on soil C. Cultivation alone resulted in significant losses (at least 20 percent) of C in soils that had relatively high C contents and a slight increase in soils with an initially low C content (e.g., 11 percent in Udolls of the Central United States).

Site Preparation

Site preparation (burning, chopping, windrowing, disking, bedding) studies on soil C content have provided varying results. Morris and Pritchett (1983) found only slight changes in mineral soil C on a Florida slash pine (Pinus ellioti Engelm.) site. However, Burger and Pritchett (1984) found significant (20 to 40 percent) reductions in soil C following site preparation on another Florida slash pine site. The effects of fire on soil C is very dependant on the intensity of the fire, with greater fire intensities resulting in greater C loss (Johnson 1992). Site preparation may become less of a mechanical operation due to the advent of herbicides with forestry labels and the realization of the negative site impacts of mechanical operations. This is especially true for the reforestation or afforestation of conifers that many times replace natural hardwood stands.

Species Composition

Species composition has been shown to have extremely variable effects on soil C (Johnson 1992). Results suggest in some instances that soil C was significantly greater (35 to 57 percent) in radiata pine (Pinus radiata D. Don) plantations than in native eucalyptus forests. Other studies involving the same species resulted in the reverse effects, and some instances showed little or no difference. Turner and Lambert (1988) attributed these results to the initial site fertility with results that suggested radiata pine plantations have a higher soil C (than eucalyptus forest soil) content on low fertility sites and lower soil C on high fertility sites. Lane (1989) showed the soil C content to be unchanged 23 years after the conversion of a hardwood forest to loblolly pine. Converting hardwood stands to pine may involve implementation of silvicultural practices, such as fertilization, that typically do not apply to hardwood stands due to the length of time the investment must be carried. This, along with shorter rotations and greater site adaptability of pine species, give pine plantations a significant role in future C sequestration projects.

Fertilization

The fertilization of southern pine forests is increasing rapidly, from 40,031 acres in 1988 to 850,660 acres in 1998 (Johnsen and others 2001). Fertilization increases C sequestration by increasing standing biomass, increasing C stored in forest products, and increasing belowground C pools. Johnsen's 2001 study focused on the latter and presented data from 5 experiments ranging spatially from the Virginia Piedmont to the Alabama Coastal Plain and ranging in age from 1 to 17 years. Fertilization increased belowground biomass by 250 percent. All experiments resulted in an increase of below and aboveground mean biomass (ranges from 120 to 300 percent increase). It is noted here that research needs include studying the long-term fertilization effects and designing optimal fertilization methods for forestry practices. Fertilization increases the rate of C storage; but long-term storage is more practical in hardwood stands that are generally not fertilized and, unlike pine, may be left indefinitely to mature into old-growth climax forests.

Rotation Length

Optimal rotation length for C sequestration can potentially conflict with the financially optimal harvest age. Liski and others (2001) examined the effects of shortening the rotation age of Scots pine (Pinus sylvestris L.) and Norway spruce [Picea abies (L.) H. Karst.] in Finland from 90 to 60 years. Results suggest shortening the rotation length towards the peak age of mean annual increment decreased the C stock of trees but increased the C stock of soil, because the production of litter and harvest residues increased. They concluded longer rotation ages would be favorable for C sequestration at the cost of decreased revenue for landowners. Cooper (1982) also concluded that harvesting stands at financial maturity by shortening rotation length reduced lifetime C storage to perhaps 20 percent of the potential maximum. This trend will probably continue to grow with the genetic or other manipulation of existing stock to select for faster growing genotypes.

Tree Improvement

Genetic improvements in seedling stock positively affect production as well as C sequestration. Jayawickrama (2001) estimated the gains in C sequestration by applying genetic improvement to radiata pine plantations in New Zealand. By selecting the best 50 of 500 parents for dry-weight production and the best 10 of 1,000 parents (and making crosses between these parents), 14.6 and 22.2 percent gains were achieved, respectively. Gains varied by region and management regime and were compared to a baseline estimation of unimproved stock calculated using the C_Change option in the stand growth simulator STANDPAK.

CARBON INCENTIVE PROGRAMS

The particular silvicultural practices allowed under a given C sequestration agreement can affect incentives needed to promote a sufficient amount of plantation forestry and resulting C storage. Rotation age, species composition, allowed thinnings, and other harvesting requirements that affect the landowner's potential income can positively or negatively affect their willingness to enter a C sequestration program. Dixon (1997) assessed 40 nations to determine the impact of silvicultural practices on the amount of C stored in forest systems. Impacts of silvicultural practices on C flux, added C sequestration resulting from silvicultural practices, economic costs of applied silvicultural practices, and the area of land suitable for application of these practices were identified. Results suggested that additional C sequestered and the cost of additional sequestration varied greatly, but practices such as weeding, fertilization, drainage, thinning, and modified harvesting increased C sequestered on a given tract of land. Also acknowledged was the fact that large areas of the southeast are suitable for improved C storage, but the silvicultural techniques used and the cost of implementing improvement practices varied greatly by region. This implies that, depending on the particular restrictions of a C storage easement and the region in which the agreement is applied, the amount of C potentially sequestered and the resulting compensation possible varies greatly. This indicates the compensation (and resulting incentive to enter a C storage agreement) to an individual landowner depends significantly on the location of the land holding and restrictions set forth by available C sequestration programs.

Given that forest management as a whole typically increases the amount of C stored over other land uses, and the fact that there is a developing market for C storage, landowners and other entities are likely to take advantage of the additional income this may provide. However, the value of this additional C storage, and the impacts to the timber market that significantly increasing the number of forested acres will have, must now be quantified. This will ensure existing and future projects will not have a negative effect in other areas thereby negating any initial positive contributions.

DISCUSSION

CO_2 levels in the atmosphere are increasing at a rate that makes forestry practices alone an inadequate means of stabilization. However, terrestrial sinks of C, such as natural and plantation forests, have a significant potential for emission mitigation. Despite the existence of current C sequestration programs, there has been no standard economic value assigned to a given unit of stored C. Researchers examining the effects of including C revenues into forestry investments have varied the value applied to a unit of stored C as well as the discount rate applied.

Research does exist, however, concerning the management and policy effects these potential revenues have on forestry investments. Since growth rate and C sequestration rate are positively correlated, most silvicultural practices that are traditionally implemented to improve timber production also improve the amount of C stored per unit time on a given tract. Also, the additional revenues obtained from marketing stored C make these silvicultural practices more economically attractive and can therefore potentially improve the health of forests on a very large geographic scale. However, some restrictions may apply to silvicultural practices under a C storage agreement, and a thorough management plan must be prepared upon entering a C sequestration easement.

Implementing large scale plantation forestry for the purpose of removing CO_2 from the atmosphere certainly will have impacts on timber prices as well as the price assigned to a unit of sequestered C. Creating plantation forests on a large enough scale to significantly affect the concentration of atmospheric CO_2 could flood the market with timber (if harvested) and C credits, effectively reducing the value of each. This could have negative effects on the incentive of private and industrial landowners to invest in forestry projects.

Current limitations of C sequestration programs resulting from the variability of C unit values does not remove the incentive for landowners to enter such programs. However, given the length of such an agreement (70+ years) and the uncertainty of future C sequestration programs, it would seem imprudent to enter an agreement such as the one available to Mississippi landowners, which offers $400 to $450 per acre, before knowing what the near future holds for C values. Nevertheless, given the ability to manage and harvest timber as specified in an approved management plan, C values can only improve the attractiveness of forestry as an investment opportunity. This fact should increase the incentive to practice forestry thereby expanding forested areas while simultaneously allowing silvicultural practices that maximize timber growth. This would result in a terrestrial ecosystem more capable of sequestering C from the atmosphere.

Other limitations to using terrestrial ecosystems to mitigate CO_2 emissions are the absence of sufficient data regarding the capacity of different soil types to store C over long periods of time. Each soil type (and corresponding cover type) reaches a different C storage equilibrium depending on factors such as climate, nutrient availability (particularly the C:N ratio), species, and soil physical properties. However, little information exists on just how much C the soil can store and how each of these factors, as well as others, affects this storage. Information on this subject, in addition to those areas currently being studied (i.e. soil C fluxes resulting from management practices), will certainly have to be better understood before the extent of forestry's contribution to global greenhouse gas reductions can be defined.

CONCLUSIONS

Research conducted to better understand the terrestrial C cycle and how it may be affected by land use practices, coupled with the growing incentive to remove CO_2 from the atmosphere through natural processes, should improve the incentive for landowners to practice forestry. Potential C payments and recently implemented fossil fuel taxes (where they apply) are the primary motivation for storing C in forests. C payment incentives can significantly improve the financial profitability of forestry projects. The Southeastern United States has a large amount of land suitable for reforestation or afforestation and should have a major role in the creation of C sequestration forests and tradeable C credits for the purpose of greenhouse gas emissions mitigation.

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