CARBON STORAGE IN MANAGED FORESTS OF THE NORTHERN GREAT LAKE STATES

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Abstract: Carbon (C) storage in forest ecosystems is a significant part of the total terrestrial C pool, and may potentially be manipulated as an important C sink. The influence of management on C pools must be understood before guidelines can be suggested for maximizing C sequestration in forests. Studies of hardwood, red pine (*Pinus resinosa* Ait.), aspen and hybrid poplar stands located primarily in Minnesota, Wisconsin and Michigan have been and are currently being conducted to address the effects of common management practices on C storage. Factors studied include: (1) the effect of harvest intensities on soil and biomass C, (2) the effect of forest conversion from second growth hardwoods to red pine, and from old fields to hybrid poplar plantations or red pine, on ecosystem C, (3) the effects of soil compaction and biomass removal on stand productivity. Total aboveground C ranged from 303 to 335 Mg/ha, and did not differ by harvest intensity 40 years after partial cutting northern hardwoods on a ten-year cycle. However, distribution of C among aboveground components was significantly different (proportionately more C was in the understory with increased intensity of harvest). In both hardwood and some red pine stands, increasing harvest intensity appears to reduce C storage in soil. Soil compaction and forest floor removal reduced aspen shoot biomass and quantity of C in the forest floor. Total ecosystem C continued to decrease for five years after aspen harvest. However, the ecosystem began to gain C after seven years and accumulation continued until C reached a maximum at 70 years post-harvest. Total soil C was generally unchanged after aspen clear-cutting. Adjacent red pine plantations and hardwood stands on the same soils averaged the same mass of C in vegetation, in soil across the entire profile, and in total ecosystem C (211 and 206 Mg/ha, respectively), although the hardwood averaged 14 years older than red pine. Soil C accumulation in twelve to eighteen year old hybrid poplar plantations exceeded that on adjacent agricultural fields.

INTRODUCTION

In the United States, forest C pools constitute approximately 558 billion tons of C (Birdsey 1992). The land has been losing C to the atmosphere since about 1860, and until the end of the 1970s more C came from terrestrial ecosystems than from fossil fuel combustion (Houghton *et al.* 1983). Because soil, litter, and peat contain more than twice as much C than does the atmosphere, and because forested ecosystems can store substantial C in vegetation and soil (Birdsey 1992), speculation has arisen on how afforestation, land management and reforestation strategies can be employed to mitigate the rise in atmospheric CO_2 and expected global warming (Keeling 1984, Schneider 1989, Thompson and Matthews 1989). Among these strategies is the choice of which species to grow, and practices employed to manage those species.

The northern Great Lakes forests are located within the transition zone between the northern hardwood type and boreal forests. Prior to large scale logging that began in the middle 1800's until the early 1900s, forests were approximately 30 percent pine (Benzie 1977), with the remainder being upland mixed hardwood, hardwood/conifer, and lowland conifer types. Following upland logging, second growth deciduous forests, primarily even-aged, have become established on most of the area. Pines occur primarily in plantations. Trees in most of these forests have reached merchantable size and are under some type of management.

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The effect of both forest harvest practices and species conversion on the size of ecosystem C pools have been studied in this area. Manipulations associated with tree harvest were hypothesized to affect stored carbon including harvest intensity, soil compaction and forest floor removal (Alban *et al.* 1994, Perala and Alban 1993, Strong 1995). Land use conversion studied included the planting of red pine on second growth hardwood sites and planting hybrid poplars on old fields (Perala *et al.* 1995, Hansen 1993).

METHODS

Although the seven case studies featured in this review were conducted independently, the methods share some common features. Individual tree biomass was usually established from published regression equations (Perala and Alban 1993, Hansen 1992) or from a combination of plant diameter, height, and directly measured biomass relationships obtained by felling and drying. Understory biomass was estimated using techniques similar to those used for trees, and root biomass was also estimated. Biomass of coarse woody debris (minimum measured diameter varied among studies from 1 to 2.5 cm; too sound to be penetrated by a soil coring device) was estimated from oven-dried subsamples. Soil samples were collected from small pits, and usually separated into forest floor (exception, Hansen 1993) and various depth layers of mineral soil to a maximum depth below the main rooting profile (varied among studies from 40-100 cm). Bulk density was determined for each layer collected and percent C was measured either with a Carlo Erba C analyzer or by relationships with loss on ignition. Soil C was based on percent of C concentration in the soil and bulk density measurements.

CASE STUDIES

Cutting intensity among hardwoods

In this study, C was measured in various components of a northern hardwood ecosystem that has been managed under different intensities for forty years (Strong 1995). These data provide information on current effects of and potential forest management strategies on above- and below-ground forest C resources. Five cutting treatments were evaluated in 1992, including a control, a 20 cm stump diameter-limit cut, and three levels of individual tree selection cuts. The individual tree selection cuts were: heavy - 13.8 m^2/ha, medium - 17.2 m^2/ha, light - 20.7 m^2/ha residual basal area of trees 12 cm dbh and larger after cutting. The individual selection treatments had been cut at ten-year intervals since 1951. The diameter-limit treatment was only cut in 1951. Total aboveground biomass was separated into the following components: dead trees from 1951-1992, cut trees from 1951-1992, overstory live trees in 1992 (trees 12 cm dbh and larger), saplings in 1992 (trees and shrubs 2 m tall to 12 cm dbh), and ground vegetation in 1992 (all plants less than 2 m tall). The ratio of C to biomass was assumed to be 50 percent. The study was a randomized block. Data were analyzed by analysis of variance.

Differences in total aboveground biomass of components were significant among treatments. Generally, increased harvesting resulted in a greater proportion of biomass in saplings, and less in dead trees and ground vegetation. However, these differences were not significant when components were combined. Average total aboveground biomass for the treatments (331 Mg/ha) is similar to that estimated by Mroz *et al.*(1985) for northern hardwoods in the same region.

Soil C at the 3-10 cm depth differed in the diameter-limit treatment from other treatments. No differences were detected among treatments at the other depths, or when C was summed to 40 cm. However, linear regression revealed a trend of less soil C with increasing intensity of cutting ($p= 0.028$, $R^2 =0. 84$). Soil C summed to 40 cm ranged from 90 Mg/ha in the diameter-limit treatment to 120 Mg/ha in the control treatment. Soils under red pine have a similar trend (Rollinger, unpublished data).

No differences in total ecosystem C were detected among treatments. However, a trend of less ecosystem C with greater cutting intensity appears to exist. Distribution of C in over- and understory vegetation and soil was similar among all treatments; total ecosystem C ranged from 291 Mg/ha to 317 Mg/ha for the diameter-limit treatment and medium individual selection treatment, respectively.

Aspen harvesting method

Aspen (*Populus tremuloides* Michx. and *Populus grandidentata* Michx.) in the Lake States is rapidly being harvested for pulpwood (Hackett 1992), often using the whole-tree method with large equipment in clear-cuts. In the eastern USA, typical rotations range from about 35-50 years (Alban *et al.* 1991). Aspens are short lived, early successional trees, and in general are fast growing and ubiquitous throughout temperate North America. Quaking aspen (*P. tremuloides*) also extends into high altitude and boreal forests. The distribution, harvesting issues and silvicultural qualities of these trees have stimulated interest in the effects of aspen management on long term site productivity, C sequestration, and resulting impacts on global climate change (Alban *et al.* 1991 and references therein). This discussion will focus on two studies of aspen management, one on the effect of clear-cutting disturbance on C storage (Alban and Perala 1992), the other on the effects of biomass removal and soil compaction on these ecosystems (Alban *et al.* 1994).

A range of aspen ecosystems (including a chronosequence from 0 to 80 years) was surveyed for C in soil and vegetation (Alban and Perala 1992). Neither stand development nor timber harvesting affected soil C, but changes in total ecosystem C were correlated with changes in standing biomass. Total ecosystem C in these northern Great Lakes forests reached a maximum between 60 and 80 years (> 200 and < 250 Mg/ha). Soil compaction did not influence the results of in this study, because trees were harvested during the winter when the ground was frozen.

As part of a long term site productivity project, plots with various intensities of soil compaction and biomass removal were established within aspen stands (Alban *et al.* 1994). Both forest floor removal and soil compaction reduced biomass and height of 2-year-old aspen sprouts. Forest floor C decreased by about 9 t/ha immediately after forest floor removal, but there was little or no immediate change in mineral soil C. One year after harvesting, C in the forest floor and in the 0-10 cm mineral layer increased, probably because of root death. Within several years, this ongoing study should produce estimates of rates of soil recovery and effects of treatments on vegetation growth. Relatively mild levels of soil compaction and severe forest floor removal had similar effects on aspen growth.

Old field conversion

The interest and practice of growing trees on formerly agricultural land are increasing. Trees are often grown, because the land owner no longer cultivates crops, or are grown as a biological fuel source. During the first 20 years of cultivation, most grassland soil C decreases, particularly if the soil had high initial C (Burke *et al.* 1989, Mann 1986). Recovery of soil C after cultivation in certain systems is therefore a possible future C sink. The amount of C released by energy crops in combustion is equal to that captured in the material used for fuel; however C sequestered belowground as decomposed leaves, roots or root exudates could serve as a C sink. Trees, not grown for energy, on the other hand, could store C in the aggrading vegetation.

The C in soil under hybrid poplar plantations was compared to that in adjacent row crops or mowed grass at locations in Minnesota, Wisconsin, eastern North Dakota, and in Iowa (Hansen 1993). The Establishment of these plantations resulted in early soil C loss, but the trend later reversed and soil C became positively associated with plantation age. Significant amounts of soil C were sequestered by hybrid poplar plantations older than about 6 to 12 years-old, grown on previously tilled agricultural land. The higher quantity of C under poplars was particularly noticeable among the deeper sampled layers (below 30 cm). Flux of C out of the soil C pool most frequently occurred in the shallowest layers (above 30 cm), indicating the loss was due to mineralization.

Forty-six years after establishment, a red pine plantation converted from an old field showed a decrease in C per unit soil depth per volume of soil (Pregitzer and Palik unpublished manuscript). However, this change in C mass could be almost entirely ascribed to decreased soil bulk density: C concentration did not change significantly. Carbon gain to this plantation occurred in forest floor, understory and tree biomass.

Conversion of second growth hardwood to red pine

The distribution of C in soil and biomass was studied across Minnesota, Wisconsin, and Michigan, U.S.A., in 40 pole-sized red pine plantations paired with adjacent hardwood stands (Perala *et al.* 1995). Pine and hardwood stands shared a common boundary and soil. Hardwood stands were mixed species, naturally regenerated second growth following logging.

Carbon in total standing crop averaged the same in both hardwood (AVG=96 Mg/ha, SD=24) and red pine (AVG=97 Mg/ha, SD=20) forest types, although the hardwoods averaged 14 years older than the red pine. Coarse woody debris, shrubs, and herbs contained little C. Only the forest floor carbon pool was different between forest types, with a greater mass beneath red pine (AVG=23 Mg/ha) than hardwoods (AVG=17 Mg/ha). There was no significant difference in total ecosystem C between red pine and hardwood stands (211 Mg/ha, SD 48; and 206 Mg/ha, SD 41, respectively). Total mineral soil aggregated with depth contained the same total C in both pine and hardwood stands. However, the C occurred in different vertical patterns. Amounts of C in the upper levels of soil (0-4 cm) were higher under hardwoods, and amounts were higher under red pine at the 8-16 cm and 16-32 cm soil depths. Grigal and Ohmann (1992), in contrast, found that red pine sequestered less total soil C than did sugar maple or aspen, trees common to the hardwood stands studied by Perala *et al.* (1995). This discrepancy is likely due to the different study objectives and hence different site selection criteria. The paired design adopted by Perala *et al.* (1995) allowed careful same-soil pairing of stands.

Regression modeling showed that red pine stored carbon more efficiently both in the forest floor and deep in the soil, in areas where July air temperatures were relatively cool. Red pine also sequestered more C in mineral soil with increasing April-September precipitation. In warmer, drier climates, hardwood stands stored more soil C. July average air temperature was the only climate variable to be related to total ecosystem C, a decline of 21.5 Mg/ha/°C. Thus, restoration of pine to historically pine forested areas rather than conversion to second growth hardwood stands may increase stored C in the soil and vegetation of these ecosystems, provided that the climate remains relatively cool and moist. Further C increases can be expected in red pine biomass accumulation. Similarly, conversion of historically hardwood forest back to hardwoods from red pine may slightly increase C stored in the soil in relatively warm and dry climates.

Comparisons among forest types

Grigal and Ohmann (1992) sampled 169 forest stands, across Minnesota, Michigan and Wisconsin for total ecosystem C. Stands represented major regional upland forest types: balsam fir (*Abies balsamea* [L.]), jack pine (*Pinus banksiana* Lamb.), red pine, quaking aspen, and northern hardwoods. Regression analysis showed that about 63 percent of total ecosystem C variation was explained by forest type, stand age and soil clay content. Among the forest types measured, jack pine averaged the least total ecosystem C (13.9 kg/m^2) and northern hardwoods the most (23.4 kg/m^2). Time since disturbance influenced C in vegetation and the forest floor. Both components stored more C with increased time.

CONCLUSION

Differences in harvesting techniques and forest conversion usually had little or transitory effects on the total stored C in the ecosystem. However, within components of the ecosystem, at least some effects were noticed in every case. In general, tree harvesting activities slightly reduced carbon storage. Cutting intensity of typical mixed hardwood stands apparently affected the size of the stored soil C pool, but the effect was not significant when considering total ecosystem carbon. Carbon in aspen stands was reduced by compaction and forest floor removal, but the significance of the effect varies among years. The mineral soils in these stands were unaffected by clear-cutting. The effect of conversion of old fields to tree plantations varied with the type of trees planted. Hybrid poplars increased stored ecosystem C compared to agricultural crops and mowed field species. In contrast, red pine did not increase carbon stored in soil after conversion from an old field, but did increase biomass C. When maximization of C accumulation is a factor in choosing the trees to plant, managers should consider the potential of certain species to store more C than others, and climatic factors. Over the entire region, conversion of second growth hardwoods to red pine neither increased nor decreased total ecosystem C. However, when the two stand types were corrected for age differences, the C pool in red pine vegetation could be expected to be larger than that in hardwoods. Whether red pine or hardwood stands were expected to accumulate more C depended on warm season precipitation. Dominant species also affected C pools, with jack pine stands having the least total ecosystem C. Although certain of these studies found effects of harvesting technique and forest conversion on mineral soil C, effects on forest floor and biomass C were more common and of larger magnitude. Vegetation and forest floor are also sensitive to disturbance related to stand replacement.

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