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Harvesting Intensity Influences the Carbon Distribution in a Northern Hardwood Ecosystem

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Forest ecosystems are a significant pool for carbon. They store approximately 58 billion tons of carbon in the United States (Birdsey 1992); the north central and central regions of the United States store about 10 percent of this total. More than one-fourth of the carbon in this region is stored in northern hardwood ecosystems, primarily in the Lake States (Michigan, Wisconsin, and Minnesota).

The northern hardwood ecosystems in the Lake States are primarily even-aged (40-90 years old) resulting from extensive logging since the early 1900s. Most of these forests have reached maturity and are under some type of management. The most common management practice is partial cutting with different intensities of overstory removal.

The role of forest carbon sequestration is especially important and uncertain (Powell *et al.* 1993). To understand the potential for sequestering carbon in hardwood forests, the effects of harvesting intensity on carbon distribution need to be studied. Most studies have not been of sufficient duration to assess long-term effects of harvesting on soil carbon, or they have considered only whole-tree harvesting in hardwoods (Johnson 1992). I conducted a study to measure carbon in various components of a northern hardwood ecosystem that has been managed under different intensities for 40 years. My objective was to determine if different strategies of partial cutting affect aboveground and belowground carbon storage.

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MATERIALS AND METHODS

Study Area

The study area is located in northeastern Wisconsin on the Argonne Experimental Forest. Within the study area, there are three distinctly different upland land-type associations: drumlinized uplands, unpitted fans, and pitted plains. The associated soil series are Iron River-Wabeno, Padus, and Pence. Three habitat types (Coffman *et al.* 1984) are also present: *Acer/Viola-Osmorhiza*, *Acer-Tsuga/Dryopteris*, and *Acer-Tsuga/Maianthemum*. Within the three land-type associations, most (85-90 percent) of the study site is mapped as Iron River-Wabeno and the *Acer/Viola-Osmorhiza* habitat type, with a sugar maple (*Acer saccharum*) site index of 64-69 at 50 years. There is a strong successional trend toward sugar maple on the Iron River-Wabeno soil series. Currently, about 70 percent of the overstory is sugar maple and about 30 percent consists of primarily white ash (*Fraxinus americana*), basswood (*Tilia americana*), yellow birch (*Betula alleghaniensis*), and ironwood (*Ostrya virginiana*). Red oak (*Quercus rubra*), red maple (*Acer rubrum*), hemlock (*Tsuga canadensis*), black cherry (*Prunus serotina*), black ash (*Fraxinus nigra*), paper birch (*Betula papyrifera*), and aspen (*Populus*) are also present. Rainfall averages 79 cm annually, about half of which occurs during the growing season (May 15-September 15).

Experimental Design

The study is a randomized block design with five cutting treatments, including three levels of individual tree selection cutting, a diameter-limit cut, and a control (table 1), with three replications of each.

Table 1.—*Descriptive measurements of treated plots before and after cutting of trees 12 cm and larger in 1952*

Treatment	Basal area (m^2/ha)		Total tree biomass (Mg/ha)		Trees/ha		Quadratic mean diameter (cm)	
	Before	After	Before	After	Before	After	Before	After
Control	21.6	21.6	133	133	627	627	20.9	20.9
Diameter-limit	19.3	5.3	120	27	537	281	21.4	14.9
Individual tree selection								
Heavy	19.6	14.3	125	86	568	471	20.8	19.2
Medium	22.5	17.7	143	108	566	476	22.5	21.7
Light	23.9	20.2	149	124	626	550	22.0	21.5

Individual tree selection

The three levels of individual tree selection cutting are referred to in this paper as heavy, medium, and light, corresponding to residual basal areas of trees > 11.7 cm diameter at 1.37 m (d.b.h.) of 14.3, 17.7, and 20.2 m^2/ha, respectively. The three individual tree selection cutting treatments were applied during the winters of 1952, 1962, 1972, and 1982. Selected trees were cut to (1) release crop trees, (2) remove high risk and cull trees, (3) remove trees in overstocked size classes, (4) remove trees more than 70 cm d.b.h., and (5) reach a desired size class distribution with a q-value of 1.3.

Diameter-limit cut

All trees 20.3 cm and larger at a 30.5-cm stump height (about 18 cm d.b.h.) were cut in 1952. Residual basal area was 5.3 m^2/ha in 1952.

Control

No trees were cut in the control.

Data

D.b.h. was recorded for all trees 1.5 cm and larger from five-0.04-ha subplots in each treatment and replication. Individual tree biomass was estimated from equations adapted from Perala and Alban (1993) (table 2). Ground vegetation biomass was collected in four 1-m^2 plots per treatment. In these plots, all vegetation less than 1.5 cm d.b.h. was harvested at ground line, bagged, dried at 70° C, and weighed. The carbon concentration in the vegetation was assumed to be 50 percent of the dry biomass (Linder and Axelsson 1982).

One soil core was collected from each of four subplots used for gathering ground vegetation biomass. The soil was then composited for the four subplots by each of three soil depths (0-3 cm, 3-10 cm, and 10-40 cm). Samples were bagged, dried at 37° C, and analyzed for total organic carbon with a Carlo Erba C analyzer. There were 225 samples (5 treatments x five-0.04 ha measurement plots x 3 replications x 3 soil depths).

At three locations in each treatment, bulk density of the upper 25 cm of soil was determined by the irregular hole method (Howard and Singer 1981). The soil removed from the holes was transported to the laboratory, dried at 105° C, and weighed. Volume of the hole is determined as the volume of water needed to fill the hole. There were 45 bulk density samples (5 treatments x 3 replications x 3 locations).

The amount of soil carbon was estimated to a 40-cm depth from the laboratory analysis data and bulk density estimates.

Carbon in coarse woody debris was not measured. Most of the carbon from logging slash from the previous cuttings had either been incorporated into the soil or had been respired by microorganisms. Total ecosystem carbon used in this study is slightly underestimated because carbon from dead and down trees was not measured. However, this component

Table 2.—*Parameters used to estimate biomass of trees 1.5 cm d.b.h. and larger*[1]

Component	Species	Constant (a)	Exponent (b)
Bole bark			
	Sugar maple[2]	0.0246	2.2400
	White ash[3]	.0275	2.1002
	Basswood	.0422	2.0339
	Yellow birch	.0145	2.4510
	Red maple	.0210	2.1910
	Paper birch	.0220	2.2150
	American elm	.0173	2.2320
	Conifers[4]	.0065	2.3832
Bole wood			
	Sugar maple	0.1179	2.3467
	White ash	.0926	2.3879
	Basswood	.0499	2.4024
	Yellow birch	.0548	2.6190
	Red maple	.0969	2.3398
	Paper birch	.0806	2.3665
	American elm	.0548	2.5086
	Conifers	.0302	2.5231
Total tree, aboveground			
	Sugar maple	0.1676	2.3646
	White ash	.1634	2.3480
	Basswood	.0872	2.3539
	Yellow birch	.0872	2.5870
	Red maple	.1618	2.3100
	Paper birch	.1182	2.4287
	American elm	.0825	2.4680
	Conifers	.0705	2.4971
Roots			
	Generic	0.3000	1.7610

[1]Equation form is: Component dry weight (kg) = a*(DBH)^b; parameters adapted from Perala and Alban (1993).
[2]Includes black cherry and red oak.
[3]Includes black ash.
[4]Includes hemlock, balsam fir, and northern white-cedar.

would be minor compared to the total. Litter was not sampled because at the time of sampling (midsummer) most litter had been incorporated into the soil.

Data Analysis

Tree carbon was summed and ground vegetation and soil carbon was averaged for each 0.04 ha subplot for analysis. Analysis of variance was used to test differences between treatment means according to the model:

$$Y_{ijk} = \mu + R_i + T_j + RT_{ij} + S_{ijk}$$

where

Y_{ijk} = sample plot average of variable measured in replication i, treatment j, and subplot k
μ = overall mean
R_i = effect of the ith replication
T_j = effect of the jth treatment
RT_{ij} = interaction between the ith replication and jth treatment
S_{ijk} = random error

All effects were considered random. Comparisons between individual treatment means were made only when analysis of variance indicated significant differences among treatments ($p < 0.05$). Individual comparisons were then tested using the Least Significant Difference method with a common estimate of experimental error.

RESULTS AND DISCUSSION

Aboveground Carbon

Average aboveground carbon, including trees that were cut or had died during the period, did not differ by treatment (table 3). Aboveground carbon ranged from 152 Mg/ha to 167 Mg/ha for the control and light individual tree selection treatments, respectively. These data agree with Mroz and others (1985) data from an old-growth hardwood forest in the Upper Peninsula of Michigan where they found aboveground biomass of 284 and 325 Mg/ha (142 and 163 Mg C/ha) on two different sites. Aboveground carbon in my study also falls within the range of aboveground carbon reported for northern hardwood stands by Grigal and Ohmann (1992).

When components of aboveground carbon were differentiated, treatment differences were significant (table 3). The carbon in dead trees was greater in the control than in the four cutting treatments. Growth is occurring on the more dominant trees in the control plots and is accompanied by death of suppressed trees. Carbon from dead trees did not differ among the cutting treatments.

Differences of harvested trees among treatments reflect the intensity of cutting. The most intense cut (diameter-limit cut) had the least carbon harvested throughout the period because the treatment was applied only once (1952). The carbon harvested in the individual tree selection plots ranged from 65 Mg/ha to 84 Mg/ha for the light and heavy selection treatments, respectively.

The carbon in overstory trees (trees 1.5 cm d.b.h. and larger) in 1992 ranged from 116 Mg/ha to 65 Mg/ha in the control plots and heavy individual tree selection, respectively (table 3). The amount of carbon in the overstory again reflects the intensity of harvesting during the period. Although the diameter-limit plots were heavily cut in 1952, the residual tree growth response reached levels near but slightly less than in the control in 1992.

The sapling carbon is related to overstory crown cover (table 3). Sapling carbon was greatest in the medium and heavy individual tree selection plots (more than 6 Mg/ha), and the control had the least sapling carbon.

While the amount of carbon in the ground vegetation is smaller than that in other components, ecologically it is still important. The carbon in the ground vegetation was less in the individual tree selection plots than in the control and diameter-limit plots (table 3). Although more light penetrated the overstory canopy in the individual selection plots, it was absorbed by the sapling layer so that less light reached the ground vegetation.

Table 3.—*Mean aboveground carbon (Mg/ha) by cutting treatment for dead and harvested overstory trees 1951-1991, and live overstory trees, saplings, and ground vegetation in 1991*

	1951-1991		1991			
Treatment	**Dead**	**Harvested**	**Overstory**	**Saplings**	**Ground vegetation**	**Total**
Light[1,2]	9.4 b[3]	65.3 c	88.7 b	3.8 b	0.11 b	167.3 a
Medium[2]	11.5 b	73.6 bc	74.4 c	6.3 a	0.10 b	165.9 a
Diameter-limit	11.4 b	46.9 d	98.7 b	2.1 bc	0.20 a	159.3 a
Heavy[2]	4.5 b	83.7 ab	64.6 c	6.1 a	0.11 b	159.0 a
Control	33.5 a	0.0 e	116.4 a	1.6 c	0.21 a	151.7 a

[1]Treatment means are ranked by total aboveground carbon.
[2]Refers to levels of residual basal area after individual tree selection cutting.
[3]Means followed by the same letter in any column are not significantly different, $p < 0.05$.

Soil Carbon

Differences by treatment in soil carbon were significant only at the 3-10 cm depth (table 4), and the diameter-limit plots had significantly less carbon. Although when summed to a 40 cm depth soil carbon did not differ by treatment, a trend of decreasing carbon with increased intensity of harvest is significant (fig. 1). A similar response was noted by Rollinger and Strong (1995) for red pine.

Ecosystem Carbon

Total ecosystem carbon did not differ by treatment for any measured component (table 5). However, a similar trend was noted for total ecosystem carbon as was observed for soil carbon; there was less total carbon in the most intensively harvested treatments (diameter-limit and heavy individual tree selection cutting).

Although these differences are small and are not significant, they may represent major implications for the regional effects of hardwood management on sequestering carbon. They may also have global implications if the trend holds for other species in different regions of the world. For example, total ecosystem carbon in the diameter-limit plots was about 23 Mg/ha less than in the controls. If this difference was extrapolated to all northern hardwoods in the Lake States (about 4 million hectares), it would represent a difference of 93 million metric tons of carbon.

Plots treated with moderate to light cutting actually had higher ecosystem carbon than the controls.

CONCLUSIONS

Only slight differences were found among cutting treatments for aboveground, belowground, and total ecosystem carbon. Light to moderate cutting in northern hardwoods does not appear to alter carbon cycling. Moderate cutting in northern hardwoods was also shown in an analysis of this same study to provide acceptable tree diversity, to grow high-quality saw logs, and to be profitable (Niese and Strong 1992, Niese *et al.* 1995, and Strong *et al.* 1995). However, carbon may be lost from the ecosystem through heavier cutting. The question of where this carbon goes cannot be answered in this study. Carbon may be lost to respiration from soil microorganisms after the overstory is opened and

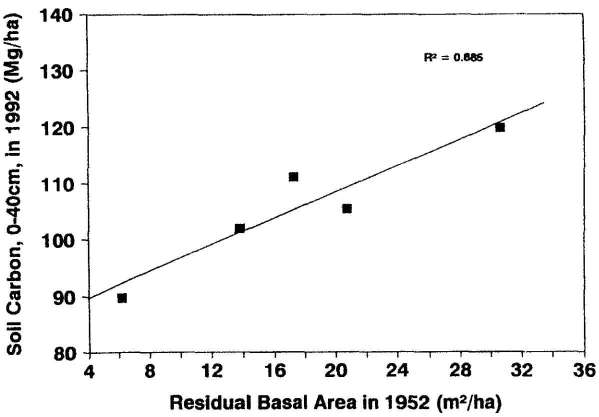

Figure 1.—*The relationship between soil carbon in 1992 (Mg/ha) and residual basal area (m^2/ha) in 1952.*

Table 4.—*Soil carbon (Mg/ha) by depth and treatment*

Treatment	Depth			
	0-3 cm	3-10 cm	10-40 cm	0-40 cm
Control[1]	21.5 a	30.3 a[2]	68.1 a	119.9 a
Medium[3]	21.6 a	28.6 a	61.0 a	111.2 a
Light[3]	18.4 a	32.5 a	54.6 a	105.5 a
Heavy[3]	16.7 a	28.5 a	56.7 a	101.9 a
Diameter-limit	17.5 a	21.4 b	51.0 a	89.9 a

[1]Treatment means are ranked by total soil carbon 0-40cm.
[2]Means followed by the same letter in any column are not significantly different, $p < 0.05$.
[3]Refers to levels of residual basal area after individual tree selection cutting.

Table 5.—*Ecosystem carbon (Mg/ha) by treatment for aboveground and belowground vegetation, soil to 40-cm depth, and total*

Treatment	Vegetation		Soil	Total
	Aboveground	Belowground		
Medium[1,2]	165.9	39.7	111.2	316.8
Light[2]	167.4	40.6	105.5	313.5
Control	151.7	37.3	119.9	308.9
Heavy[2]	159.0	38.2	101.8	299.1
Diameter-limit	159.3	41.3	89.9	290.6

[1]Treatment means are ranked by total aboveground biomass.
[2]Refers to levels of residual basal area after individual tree selection cutting.

the soil surface is warmed. If this hypothesis is true, heavy cutting of hardwoods in the Lake States not only may be reducing sustainability of these forests by loss of carbon in the soil, but also may be adding CO_2 to the atmosphere. A well-designed study to test this hypothesis should be installed in all regions to ensure that current management practices are not harming the environment.

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Studies the effects of five cutting methods on soil and vegetative carbon after 40 years of management in a northern hardwood forest in Wisconsin.

KEY WORDS: Carbon, biomass, uneven-age management, northern hardwoods.