Economic and Ecological Effects of Diameter-Limit and BDq Management Regimes: Simulation Results for Northern Hardwoods

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The long-term financial and ecological effects of diameter-limit regimes and basal-area-diameter-*q*-ratio (BDq) regimes were compared by simulation in the case of northern hardwood forests. Varying the cutting cycle between 10 and 20 years had little effect on returns or stand structure. A 28-cm diameter-limit cut gave the highest production and financial returns, and the highest species diversity, but considerably lower size diversity. A 38-cm diameter-limit cut and a heavy BDq selection harvest gave high returns, while maintaining high levels of diversity. On lands of equal site quality, Michigan's stands were more productive than Wisconsin's. The results suggest that it is possible to manage northern hardwood stands sustainably with diameter-limit cuts, combined with removal of poorly performing understory trees. Adjusting the diameter limit gave rise to stands similar in productivity and structure to those obtained by BDq cutting regimes. Given their simplicity of implementation and monitoring, more attention should be given to diameter-limit cutting regimes, with attendant stand improvement measures, as a practical means for uneven-aged management of northern hardwoods.

Keywords uneven-aged management, hardwoods, mixed-species stands, simulation, economics, diversity
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1 Introduction

Northern hardwood forests occupy the largest portion of timberland in the states of Wisconsin and Michigan in the north central United States (Leatherberry and Spencer 1996, Schmidt 1998). Thus, these forests have a large impact on the economic and ecological well being of both States, and they should be treated accordingly. Northern hardwoods are commonly managed under uneven-aged silvicultural systems to get sustainable, productive stands, with the intention of producing high quality trees (Erickson et al. 1990, Niese et al. 1995).

However, even though economic returns continue to be an important goal of forest management in this area as elsewhere, there is an increasing focus on maintaining a rich biological diversity. Diverse ecosystems tend to be more stable (Elton 1958, Hunter 1990), and the vegetation and wildlife of an ecosystem are closely entwined. In particular, stands with greater vertical stratification, which can be obtained by trees of different diameters (i.e., size diversity), provide more habitat for species with particular habitat niches (MacArthur and MacArthur 1961, Ambuel and Temple 1983, Hunter 1990). Thus, species diversity should also be an important management goal for the many owners who rank "recreation" and "aesthetic enjoyment" as primary reason for owning timberland (Roberts et al. 1986, Birch 1994).

Indeed, it is unlikely that biological diversity will be sufficiently conserved in the few, scattered reserved areas, which have been set aside. Thus, it is important that forests be managed for both commodity production and ecological diversity (Hansen et al. 1991). In fact, ecological diversity is totally consistent with the traditional forestry goals of ensuring high and sustainable levels of harvests, and multiple uses. For example, the variety of species found in diverse forests makes them less susceptible to pests and pathogens (Hunter 1990). Furthermore, although there is ultimately a trade-off between the two goals, tree diversity can be compatible and even complementary of economic gain over a wide range of diversity levels (Buongiorno et al. 1994).

Recognizing the importance of economic and ecological objectives in the management of northern hardwoods, the objective of this study was to provide more data regarding the effects of different cutting regimes. To that end, we simulated the growth and development of stands with different cutting regimes, and compared them in terms of economic returns, productivity, tree diversity (size and species), and stand structure.

2 Background and Previous Work

We compared two kinds of cutting regimes: basal-area-diameter-*q*-ratio (BDq) selection and diameter-limit cuts. The *q*-ratio is a widely cited method of defining the target residual stand (Leak and Filip 1975). *q* is the ratio of number of trees in adjacent DBH classes. With the basal area and the diameter of the largest trees it defines the distribution of the residual stand.

The choice of *q* determines the number and proportion of saplings, pole, and sawtimber trees in the stand (Leak and Filip 1975). A low *q* (e.g., $q = 1.3$) results, for a given basal area and maximum diameter, in a stand with fewer trees overall, but a larger number of sawtimber trees. The opposite is true for a high value of *q* (e.g., $q = 2.0$). Leak and Filip (1975) suggested *q* ratios of 1.8 to 2.0 (for 5-cm classes), because target distributions with lower *q* ratio left deficits in the larger size classes and would require heavy cutting in the small size classes. They proposed a maximum diameter of 56 cm and residual basal area between 16 and 18 $m^2 ha^{-1}$.

Hansen and Nyland (1986) compared, by simulation, the effect of *q* ratios of 1.2 and 1.8 (for 5 cm classes), and 40, 50, and 60 cm maximum diameters, with basal areas ranging from 10 to 25 m^2 per hectare over 10 and 30-year cutting cycles. Their results indicated that the volume of growth per year was highest for the 40-cm maximum diameter for both *q*'s. In virtually all cases, the large sawtimber volume growth was higher for $q = 1.2$. When the sustainability of the various distributions was compared, projections showed that for both *q* values the number of trees in several size classes fell below the target values, especially in the pole-sized classes. The problem was more pronounced with $q = 1.2$.

These findings illustrate one difficulty of the selection approach: the complex interaction between the effects of the *q ratio* itself, the basal area, and maximum diameter, all of which must be chosen simultaneously to define a particular BDq regime. The other difficulty is operational. Although the method is easily simulated on a computer, it is difficult to implement in the field. There is no quick way to mark trees so that the residual stand will conform to a specific BDq distribution. For that reason, BDq-cutting guides are always applied approximately at best. A quick prism check may be done on basal area, the largest tree size may be noted, but for all practical purposes the *q ratio* must fall where it may. Granted the difficulty of the method for a single species stand, it becomes even less practical in multi-species situations if *q ratio*, basal area and maximum tree size must vary by species. Indeed, BDq cutting guides by species have been rarely considered, in practice or theory. Yet, pooled size distributions of different species in an even-aged stand can give misleading impression of an uneven-aged stand (Muller 1982). This difficulty of BDq guides calls for the development, or rather the rediscovery, of simple and operational marking guides, that are easy to explain, to implement, and to verify.

A natural alternative of the BDq method is the diameter-limit cut. In its simplest form, it states that all and only the trees larger than a specific diameter limit may be cut. Refinements may specify different diameter limits by species. This kind of management has a long history and seems to have been applied frequently in Europe (Volin and Buongiorno 1996, Sterba 1999). It has, however, fallen into disrepute in the United States due seemingly to its confusion with high grading. We define high grading as taking from a stand only and all the trees that have commercial value. Silvicultural experience teaches that the long-term consequence of high grading is stands of inferior quality. This has been confirmed by simulation studies (e.g. Schulte and Buongiorno 1998). In our view, diameter-limit cutting is distinct from high grading because it requires taking all trees above a particular size, good or bad. Furthermore, it is easily supplemented by the removal of trees that are below the diameter limit, but of poor quality. Previous results for northern hardwoods suggest that diameter-limit cuts with complete removal of smaller non-commercial trees can be economically optimal (Lu and Buongiorno 1993).

Other diameter limits have been investigated in previous studies. Erickson et al. (1990) found that in a comparison of three selection cuts, four diameter-limit cuts, and a light improvement cut, a 41-cm diameter cut yielded the highest economic returns. Niese et al. (1992, 1995), however, found that the net present value of a 20-cm diameter-limit cut (which seems unusually low) was inferior to selection cuts and gave a much lower level of regeneration diversity.

2 Methods

2.1 The Northpro Simulation Program

The results of this study can be replicated with the information in this paper and with the growth equations in Kolbe et al. (1999). However, the computations are greatly simplified by the Northrop software. Northpro is a spreadsheet add-in program, that simulates the growth and management of uneven-aged stands (Kolbe et al. 1998). The core of the program is a density-dependent matrix growth model, originally calibrated with Wisconsin data (Lin et al. 1996). The program was recently updated with the latest inventory data, modified to account for site variations, and expanded to Michigan (Kolbe 1998). The data for model calibration and testing came from the North Central Forest Inventory and Analysis (FIA) Eastwide Data Base (Hansen et al. 1992). The selected FIA plots were all permanent re measured plots from the fifth forest inventory, classified in the "maple-beech-birch" forest type and "timberland" category. There were 623 plots from Wisconsin and 1259 plots from Michigan.

Northpro predicts the number of trees in each of three species groups (shade-tolerant, mid-tolerant, and shade-intolerant, defined in Lin et al. 1996) and twelve 5.1-cm size classes from 5.1 cm (DBH less than 7.6 cm) up to 61+ cm (DBH greater than or equal to 58.5 cm). The model has interdependent growth, mortality, and regeneration. Model predictions were checked against the growth of field plots not used in model calibration. Table 1 shows the means, across all validation plots of the actual and predicted number of trees per hectare, by size and species. Only in a few instances was the predicted mean statistically different from the observed, at the 5% level. Other tests also showed that the long-term steady state predicted by the model agreed with that of semi-climax stands (Kolbe et al. 1999).

Northpro allows managers to predict stand development, by year and for many decades. They choose an initial state, and the timing and intensity of future harvests. Cutting intensity can be set by a free-form target distribution, a BDq distribution, or a diameter-limit cut. Additional inputs include site index (as defined in the FIA database), stumpage prices, fixed administrative cost, and interest rate.

The output of Northpro consists of summary statistics such as net present value (*NPV*), basal area cut, residual basal area, and tree diversity indices. Tabulated and graphic results show diameter distributions, basal area, volumes, income, net present value, and stand diversity by species and size. The *NPV* measures the financial consequences of a particular regime:

$$NPV = \sum_{t=0}^{n} \frac{vh_{kt} - F_{kt}}{(1+r)^{kt}} \tag{1}$$

where n is the number of cutting cycles, k the length of the cutting cycle in years, $h_{kt} = [h_{ij}]_{kt}$ a column vector representing the harvest in year kt, $v = [v_{ij}]$ a row vector in which v_{ij} is the stumpage value of a tree of species group i and size j, and r is the interest rate.

Northpro includes two measures of tree diversity: diversity of species and diversity of size, measured with Shannon's index (Pielou 1977). Both are important in determining stand structure, quality of wildlife habitat, and aesthetics. With Shannon's index, maximum diversity occurs if species or sizes of trees are distributed uniformly. In Northpro, diversity is defined in terms of the distribution of the basal area of trees rather than number, to give more importance to large trees:

$$H = -\sum_{i=1}^{m} p_i \ln(pi) \tag{2}$$

Table 1. Predicted and observed average[a] number of trees per hectare.

Diameter class	Wisconsin		Michigan	
	Predicted	Observed	Predicted	Observed
Shade-tolerant species				
5	362.9	385.6	458.2	436.9
10	86.0	79.0	93.4	80.0
15	69.4 [b]	55.1	60.8 [b]	49.2
20	52.6	50.9	41.5	44.0
25	35.6	37.3	27.4	28.4
30	21.2	22.2	17.3	17.3
36	11.9	12.1	10.1 [b]	8.4
41	6.4	5.9	5.7 [b]	4.9
46	3.2	4.0	3.2	2.7
51	1.5	1.2	1.7 [b]	1.2
56	0.7	1.0	0.7	0.7
61+	0.5	1.0	1.2	1.0
Mid-tolerant species				
5	58.8	16.8	99.8	102.8
10	6.9	3.3	22.2	18.8
15	8.4	3.1	10.9	8.2
20	9.1	3.1	6.7	5.4
25	6.9 [b]	1.8	4.9	5.4
30	4.0	1.5	3.5	3.0
36	2.5	0.8	2.2	2.5
41	1.2	0.6	1.5	1.2
46	0.7	0.4	1.0	1.0
51	0.5	0.3	0.5	0.5
56	0.3	0.1	0.3	0.5
61+	0.3	0.2	0.3	0.5
Shade-intolerant species				
5	96.1	94.4	153.1	173.6
10	14.3	25.9	32.6	22.7
15	19.0	11.6	12.8 [b]	7.2
20	17.3	14.1	7.4 [b]	4.0
25	12.4	9.9	5.2	4.2
30	8.7	6.4	3.5	2.5
36	4.7	5.2	2.2	2.2
41	2.2	2.2	1.2	1.2
46	1.0	1.0	0.5	0.5
51	0.5	0.5	0.3	0.3
56	0.3	0.3	0.0	0.3
61+	0.3	0.3	0.0	0.0

a For 124 post-sample plots in Wisconsin and 248 in Michigan.
b Significantly different means at 5% level.
Source: Kolbe et al. 1999.

where p_i is the proportion of trees of species or size i. Thus, highest diversity of size or species is achieved with a uniform distribution of basal area. With three species groups, diversity of species could vary only between 0 (when all trees are in one species group) and ln(3) = 1.10 (when stand basal area is equally distributed among the three species groups). And, given 12 size classes, diversity of tree size can vary between 0 and ln(12) = 2.48[1)].

2.2 Simulation Parameters

For the purpose of this study, the time between harvests, or cutting cycle, and the target residual stand defined a management regime. The residual stand is defined by a number of trees in each species and size category. The harvest takes all and only the trees that exceed the target residual stand. The simulations were for 120 years and with cutting cycles of 10, 15, and 20 years.

We compared three BDq regimes and three diameter-limit regimes. The q ratio, largest tree diameter, and basal area of the residual stand defined each BDq regime. The q ratio was 1.7, approximately equal to the q ratio of the current average distribution on all the FIA maple-birch plots of Wisconsin and Michigan.

The residual basal area was set at 21 m^2, 17 m^2, and 14 m^2, corresponding to a light, medium, and heavy selection, according to Erdmann and Oberg (1973). A diameter of 61 cm was chosen as the maximum diameter for the light selection, 51 cm for the medium selection, and 41 cm for the heavy selection. These maximum diameters were meant to keep at least one tree per hectare in the largest size class with the chosen q ratio and residual basal area. The desired residual diameter distributions for each selection method are in Table 2. The desired number of trees was distributed by species in the proportions observed in the last inventory: 65% shade tolerant, 12% for mid tolerant, and 23% for intolerant species (Kolbe et al. 1999).

Alternatively, the diameter-limits were 28 cm (cut all sawtimber trees), 38 cm (cut medium and large sawtimber trees), and 53 cm (cut only large sawtimber trees). The Northpro simulator distinguishes trees by species and size, but not by quality. It was assumed that 5% of the trees below the diameter limit would be of no value. This is roughly the current frequency of cull trees in the FIA plot data of the maple-birch forest type.

Each selection and diameter-limit cut was simulated for Wisconsin and Michigan, with the growth model calibrated for each state (Kolbe et al. 1999). The initial stand state was the average distribution of all Wisconsin and Michigan plots. Site indices of 18 or 24 (defined as the height in meters of the dominant and co-dominant trees at age 50 years) were investigated. About 60% of the plots have site indices between 18 and 24 (Table 3). The first harvest was set to occur during the first year of the simulation.

The interest rate, r, was set at 3%, the average annual return of AAA corporate bonds, net of inflation, from 1950 through 1997 (U.S. Government Printing Office 1998). The cost of setting up and administering a timber sale, F_{kt}, in equation (1) was set at \$76 ha^{-1} [2)]. The tree value, v, in equation (1) is the product of tree vol-

Table 2. Desired target distribution by BDq selection regime (q = 1.7).

DBH class	BDq selection		
	Light	Medium	Heavy
5	189	165	146
10	111	97	86
15	65	57	51
20	38	34	30
25	23	20	18
30	13	12	10
36	8	7	6
41	5	4	4
46	3	2	0
51	2	1	0
56	1	0	0
61+	1	0	0
Basal area (m^2 ha^{-1})	21	17	14

1) Kolbe et al. (1998) documents how to install and work with Northpro, and gives more information on Northpro's growth model. It offers a tutorial, in the form of three examples, that explains how to start the program, enter simulation data, generate *BDq* distributions, add, delete, and retrieve setup files, execute single simulations and batches of simulations, plot summary statistics, and produce stock-and-cut tables and marking guides.

2) Cost in 1992, based on personal communication from T.J. Hittle, Steigerwalt Land Services, Inc., Tomahawk,WI.

Table 3. Number of plots by site index, fifth inventory.

	Site index 1)							
	9–12	12–15	15–18	18–21	21–24	24–27	27–30	Total
Wisconsin	2	23	96	218	177	74	33	623
Michigan	13	77	242	402	312	159	54	1259
Total	15	100	338	620	489	233	87	1882
% of Total	1	5	18	33	26	12	5	100

1) Dominant tree height at 50 years (m) (Hansen et al. 1992).

Table 4. Tree volume and stumpage value in Wisconsin, 1996–1998.

Tree		Diameter (cm)	Volume 1) (m^3)	Value (\$ $tree^{-1}$)
Shade-tolerant				
	Pole	15	0.09	0.31
		20	0.18	0.61
		25	0.32	1.05
	Sawtimber	30	0.19	11.34
		36	0.28	17.29
		41	0.38	24.60
		46	0.52	33.46
		51	0.68	43.46
		56	0.87	54.92
		61+	1.06	67.86
Mid-tolerant				
	Pole	15	0.06	0.20
		20	0.15	0.54
		25	0.28	1.02
	Sawtimber	30	0.14	7.60
		36	0.24	12.69
		41	0.35	18.94
		46	0.50	26.48
		51	0.66	35.01
		56	0.83	44.76
		61+	1.04	55.78
Shade-intolerant				
	Pole	15	0.11	0.42
		20	0.19	0.72
		25	0.30	1.17
	Sawtimber	30	0.17	10.59
		36	0.26	16.40
		41	0.38	23.45
		46	0.52	31.95
		51	0.66	41.49
		56	0.85	52.37
		61+	1.04	64.62

1) For a stand of 14 $m^2\,ha^{-1}$ basal area on site 21, pole size trees are counted as pulpwood.

ume and stumpage price. Single tree volume depends on tree species, diameter, stand site, and basal area (Kolbe 1998). Stumpage prices came from the Wisconsin Department of Natural Resources (1996 to 1998). Table 4 shows the volume, and value by tree species and size for a site index of 21 m and basal area of 14 $m^2\,ha^{-1}$ (the average site index and basal area of the Wisconsin and Michigan plots). Tree volume depends on site quality and basal area, thus, for a given diameter it is slightly higher for stands on better site and with higher basal area.

3 Results

3.1 Effects of Management Regimes on Net Present Value

The NPV of the different cutting regimes, over 120 years, varied little by site quality, other things being equal. Therefore, only the results for site index 24 are shown in Fig. 1. The largest difference in NPV value between Michigan and Wisconsin occurred for the light selection, which gave nil or a negative NPV in Wisconsin, and about \$500 ha^{-1} in Michigan. The smallest absolute difference was for the 28-cm diameter-limit cut, which gave 10% less NPV in Wisconsin. The cutting cycle had little effect on NPV, though cycles of 15 or 20 years tended to be slightly better.

The 28-cm diameter-limit cut yielded the highest NPV in all cases: about \$1200 ha^{-1} in Wisconsin and \$1500 ha^{-1} in Michigan. The 38-cm diameter-limit cut was second best in that re-

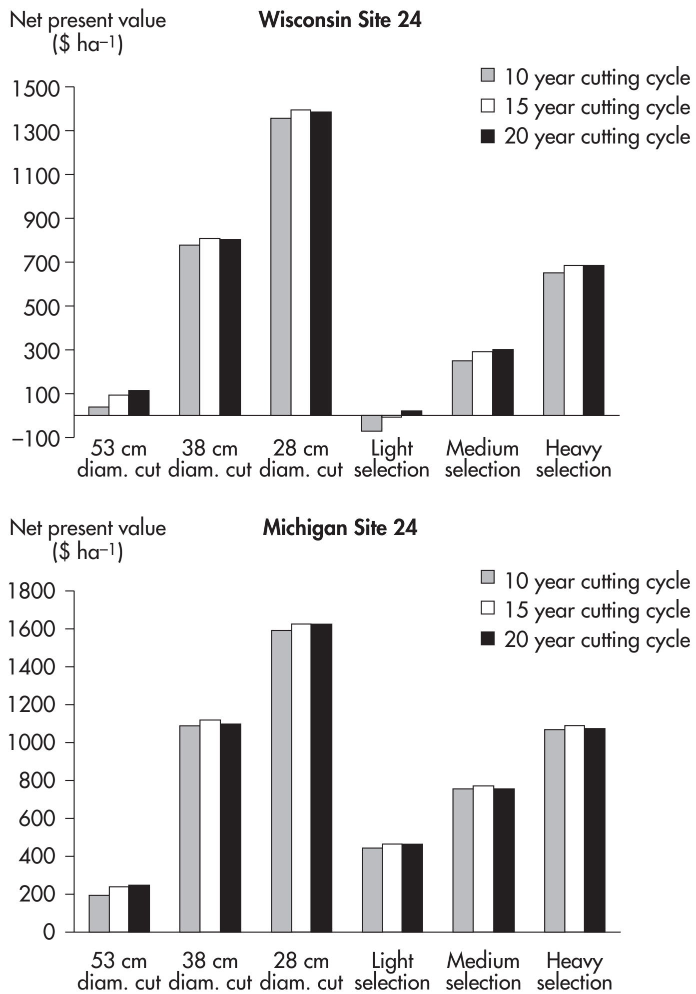

Fig. 1. Predicted net present value by cutting guide.

spect, on par with the heavy selection cut. The 53-cm and light selection cuts were the worst, especially in Wisconsin.

3.2 Effects of Management Regimes on Basal Area

In all the simulations, after 120 years, the stand basal area reached a semi steady state, where growth over a cutting cycle replaced the harvest almost exactly. For example, Fig. 2 shows how basal area developed with the 28-cm diameter-limit cut and a 15-year cutting cycle in Wisconsin for site index 18. Even under this heavy cutting regime there was no long-term depletion of basal area, but instead a gradual build up towards a steady state with an average residual basal area of 13 $m^2\,ha^{-1}$ and a harvest of about 2.5 $m^2\,ha^{-1}$ every 15 years. Basal area dropped initially because the initial condition had a high basal area, but the steady-state basal area reached after many years is independent of the initial stand condition and depends only on the site and management regime.

Table 5 shows the residual basal area and har-

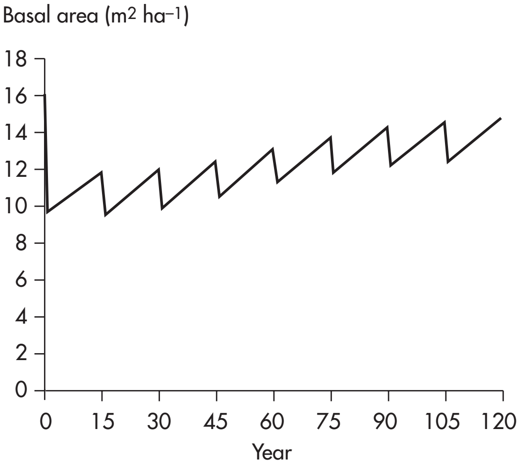

Fig. 2. Basal area obtained with a 28-cm diameter-limit cut and a 15-year cutting cycle in Wisconsin, on site 18.

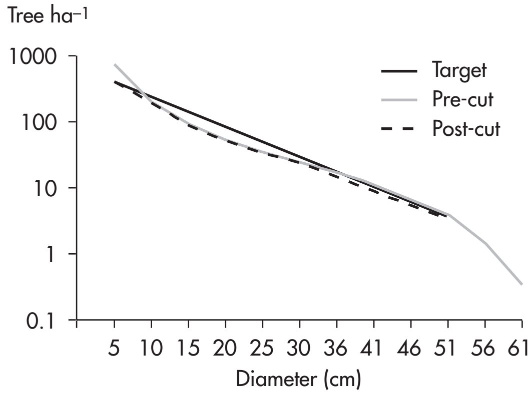

Fig. 3. Diameter distribution obtained after 8 cutting cycles with the medium selection regime and a 15-year cutting cycle in Wisconsin on site 24, after 120 years.

vest after 120 years, i.e. near the steady state. For the same site and cutting cycle, the 28-cm and 38-cm diameter limit gave about the same cut, but more residual than the heavy and medium selection, respectively. The 53-cm diameter limit gave less cut, but more residual than the light selection.

In none of the simulations of the BDq selection regimes did the basal area reach its target level (21 m^2 for the light selection, 17 m^2 for the medium selection, and 14 m^2 for the heavy selection, see Table 2). This was due to a deficit in pole-size trees. As an example, Fig. 3 shows the target, pre-cut and post-cut distributions in Wis-

Table 5. Effect of management regime on basal area, after 120 years.

Regime	Cutting cycle (years)	Wisconsin				Michigan			
		Site 24		Site 18		Site 24		Site 18	
		Cut	Left	Cut	Left	Cut	Left	Cut	Left
		m^2 ha^{-1}							
Diameter limit									
53 cm	10	0.5	18.1	0.4	16.5	1.6	19.9	1.1	18.8
	20	1.0	17.9	0.7	16.3	2.8	20.0	1.8	18.9
38 cm	10	1.2	15.8	1.0	14.8	2.1	15.4	1.7	14.9
	20	2.2	15.2	1.8	14.3	4.3	14.5	3.5	14.1
28 cm	10	1.8	13.1	1.5	12.5	2.3	12.9	2.0	12.6
	20	3.2	12.6	2.8	12.1	4.4	12.1	3.8	11.9
BDq selection									
Light	10	0.9	14.3	0.5	13.5	1.9	14.5	1.5	14.1
	20	1.5	14.9	0.9	14.2	3.7	14.5	2.9	14.2
Medium	10	1.2	12.6	0.9	12.0	2.2	13.0	1.8	12.6
	20	2.2	13.3	1.6	12.8	4.2	13.1	3.3	12.9
Heavy	10	1.5	10.7	1.3	10.2	2.4	11.1	2.0	10.8
	20	2.8	11.4	2.3	11.1	4.6	11.5	3.8	11.2

consin on site 24 for a 15-year cutting cycle, after 120 years of medium selection. On this logarithmic graph, the target distribution is a straight line. Although the post-cut distribution matches very well the target in sizes 30 to 51 cm, there is a deficit in sizes 10 to 25 cm. This deficit of basal area relative to the target, also noted by Hansen and Nyland (1986), might be decreased by not following the target distribution strictly, and keeping more of the smallest trees. Still, on the basis of basal area harvested and residual stand basal area, the complication of the BDq harvesting regime seems to gain little compared to the simple 38-cm diameter-limit cut.

3.3 Effects of Management Regimes on Diversity of Tree Species and Size

The effects after 120 years are summarized in Tables 6 and 7 for a cutting cycle of 15 years. The results were similar for cutting cycles of 10 and 20 years. Size diversity was slightly higher for longer cutting cycles, as expected since long-

Table 6. Effect of management regime on tree species diversity, 15-year cutting cycle, after 120 years.

Regime	Wisconsin				Michigan			
	Site 24		Site 18		Site 24		Site 18	
	Pre-cut	Post-cut	Pre-cut	Post-cut	Pre-cut	Post-cut	Pre-cut	Post-cut
	Shannon index							
Diameter limit								
53 cm	0.57	0.55	0.63	0.62	0.64	0.63	0.72	0.71
38 cm	0.58	0.58	0.62	0.63	0.70	0.70	0.75	0.75
28 cm	0.63	0.65	0.66	0.68	0.80	0.81	0.83	0.84
BDq selection								
Light	0.57	0.56	0.61	0.59	0.70	0.71	0.72	0.72
Medium	0.57	0.56	0.61	0.58	0.71	0.72	0.73	0.73
Heavy	0.59	0.57	0.61	0.59	0.73	0.73	0.75	0.74
No cut	0.45		0.55		0.30		0.50	

Table 7. Effect of management regime on tree size diversity, 15-year cutting cycle, after 120 years.

Regime	Wisconsin				Michigan			
	Site 24		Site 18		Site 24		Site 18	
	Pre-cut	Post-cut	Pre-cut	Post-cut	Pre-cut	Post-cut	Pre-cut	Post-cut
	Shannon index							
Diameter limit								
53 cm	2.4	2.1	2.3	2.0	2.3	2.0	2.4	2.0
38 cm	2.1	1.7	2.1	1.7	2.2	1.6	2.2	1.7
28 cm	1.9	1.3	1.9	1.3	2.0	1.3	2.0	1.3
BDq selection								
Light	2.4	2.2	2.4	2.2	2.4	2.2	2.4	2.2
Medium	2.3	2.0	2.3	2.0	2.4	2.0	2.4	2.0
Heavy	2.2	1.8	2.2	1.8	2.3	1.7	2.2	1.8
No cut	2.4		2.4		2.3		2.5	

er cycles lead to the presence of more trees in the larger size classes (see also Lin et al. 1996).

All of the cutting regimes improved species diversity, relative to not cutting the stand at all (Table 6). In general the more intense the cut, the higher the species diversity. This may be because the heavier cuts harvest proportionately more shade-tolerant trees and open up space for the less tolerant species to grow. In undisturbed stands, shade-tolerant species increase their dominance overtime to the virtual exclusion of other species (Kolbe 1998). However, the highest species diversity resulted from the 28-cm diameter-limit cut, although it left more residual basal area than the heavy selection.

Other things being equal, species diversity was somewhat higher in Michigan and on the poorest sites. There was little difference between pre and post-harvest species diversity, regardless of management regime.

Size diversity was affected by harvesting, but unlike species diversity it did not vary much between states or sites (Table 7). In all cases the harvest decreased the size diversity, because, except for the light selection, entire size classes were cut. Even the light selection gave lower size diversity, because substantial cuts occurred only in the larger sawtimber size classes, lowering their basal area relative to smaller trees. The size diversity of the diameter-limit cuts and the selection cuts decreased sharply with harvest intensity, as more and more size classes were cut, with the 28-cm cut showing the lowest size diversity. The 53-cm cut and the medium selection had levels that were similar, as did the 38-cm cut and heavy selection. In general, the size diversity of the stands that were not cut was greater than the size diversity obtained by any of the management regimes. Indeed, previous results suggest that undisturbed stand growth leads to the steady state (climax stand) of highest possible size diversity (Buongiorno et al. 1994).

Table 8. Effect of management regime on average annual growth, 15-year cutting cycle, over 120 years.

Regime	Wisconsin Site 24	Wisconsin Site 18	Michigan Site 24	Michigan Site 18
	m^3 ha^{-1} yr^{-1}			
Diameter limit				
53 cm	0.5	0.3	1.0	0.5
38 cm	1.1	0.8	1.7	1.2
28 cm	1.3	1.0	1.8	1.3
BDq selection				
Light	0.4	0.1	1.2	0.8
Medium	0.6	0.3	1.4	0.9
Heavy	0.8	0.5	1.5	1.0

3.4 Effects of Management Regimes on Volume Production

The productivity of the different cutting guides, in m^3 ha^{-1} yr^{-1}, is summarized in Table 8. The results are comparable to the productivity obtained by Niese et al. (1995) with field experiments: 0.9, 1.4, and 1.9 m^3 ha^{-1} yr^{-1} for a light selection, heavy selection, and a 20-cm diameter-limit cut, respectively. In all cases, the highest productivity was obtained by the 28-cm diameter-limit cut, followed by the 38-cm diameter limit, and the heavy selection. The light selection and 53-cm cuts gave the lowest annual production. However, these strong differences by cutting regime are due largely to the initial condition, which was set at the average stand state in Wisconsin and Michigan. As indicated by Table 5, the differences would decrease over time.

Productivity was systematically higher in Michigan than in Wisconsin (the initial condition was the same for the two states), the largest difference between states was for the light selection on site 24. The lowest for the 53-cm diameter-limit cut on site 18. The difference in productivity between site 18 and site 24 was 0.4 to 0.5 m^3 ha^{-1} yr^{-1} in Michigan, and 0.2 to 0.3 m^3 ha^{-1} yr^{-1} in Wisconsin, depending on the cutting guide.

3.5 Effects of Management Regimes on Stand Structure

The results showed that similar stand structures could be obtained with diameter-limit cuts, and with tree selection based on BDq distributions. For example, Table 9 shows the diameter distributions that resulted from the 53 cm, compared

Table 9. Effect of management regime on stand structure, site 18 in Michigan, 15-year cutting cycle, after 120 years.

DBH class (cm)	53 cm diameter limit		BDq medium selection		38 cm diameter limit		BDq heavy selection	
	Pre-cut	Post-cut	Pre-cut	Post-cut	Pre-cut	Post-cut	Pre-cut	Post-cut
	Tree ha^{-1}							
5	751.7	714.1	407.5	387.1	889.6	845.1	669.4	342.7
10	146.8	139.4	154.9	147.2	226.3	215.0	162.1	153.8
15	60.3	57.3	70.2	66.7	100.3	95.3	75.6	71.8
20	35.3	33.6	42.7	40.6	58.1	55.2	47.2	44.8
25	26.2	24.9	31.4	29.8	40.3	38.3	34.8	33.1
30	22.7	21.6	25.9	24.6	31.9	30.3	26.7	22.8
36	21.7	20.7	20.0	15.5	27.9	26.5	19.0	14.1
41	20.8	19.7	13.6	9.4	13.8	0.0	12.6	8.5
46	18.5	17.6	8.4	5.6	4.0	0.0	5.4	0.0
51	14.8	14.1	4.9	3.3	0.7	0.0	1.5	0.0
56	5.2	0.0	1.7	0.0	0.0	0.0	0.2	0.0
61+	0.7	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Basal area (m^2 ha^{-1})	20.4	18.8	15.4	12.9	17.0	14.5	14.0	11.0
Species diversity	0.72	0.71	0.73	0.73	0.75	0.75	0.75	0.74
Size diversity	2.35	2.04	2.36	2.00	2.19	1.66	2.24	1.76
NPV ($ ha^{-1})	143		586		979		934	
Growth (m^3 ha^{-1} yr^{-1})	0.5		0.9		1.2		1.0	

with the medium selection, and from the 38-cm diameter cut, compared with the heavy selection. To emphasize stand structure, the data for the different species group were aggregated. The results in Table 8 are for Michigan on site 18 and for a 15-year cutting cycle. The results for Wisconsin and on the site 24 differed slightly in the number of trees per hectare, but were similar in terms of the distribution of trees by size classes.

Comparing the 53-cm cut with the medium selection shows two similar stand structures, i.e. similar frequencies of trees by size class. The 53-cm cut kept fewer trees in the pole category, but more in the sawtimber classes than the medium selection. This is the reason for the much lower net present value of the 53-cm diameter-limit cut. In total, the 53-cm cut carried a much higher basal area than the medium selection. Diversity of species and size were essentially the same for the 53-cm diameter limit and the medium selection.

The 38-cm diameter-limit cut leads to a stand structure that was, in turn, similar to that produced by the heavy selection. The heavy selection kept more sawtimber trees and fewer poles. Size and species diversity were slightly higher for the heavy selection, but the net present value was somewhat lower than for the 38-cm diameter-limit cut. The basal area of the 38-cm cut was substantially higher than that of the heavy selection cut.

4 Summary and Conclusion

This paper has compared, with simulation methods, some economic and ecological implications of alternative management regimes in uneven-aged northern hardwood forests. Special attention was given to three diameter limit regimes and three BDq regimes.

The results showed that cutting cycles could vary between 10 and 20 years with little difference on economics or stand structure. Cutting cycles of 15 to 20 years slightly increased the net present value, and the stand basal area. Crow et al. (1981) also found little effect of cutting cycle on productivity, but Orr et al. (1994) found a 10-year cutting cycle to be best for interest rates between 2% and 4%.

The 28-cm diameter-limit cut was sustainable and gave the highest cubic foot productivity, the highest financial returns, and the highest species diversity, but considerably less size diversity than the other treatments. The 38-cm cut and heavy selection performed similarly, having high economic returns, as well as maintaining high levels of diversity. The 53-cm diameter cut kept the highest average basal area. The differences between a good and poor site were minor. Other things being equal, stands in the state of Michigan were more productive than those in Wisconsin.

One potential drawback of the results presented here is that they did not reflect possible variations in price per unit of volume arising from differences in tree quality within the sawtimber category (Erickson et al. 1990, Niese et al. 1995). Achieving higher tree quality may justify the holding of large trees and denser stands. However, the magnitude of the quality premium, and the extent to which it can be achieved by management are difficult to quantify.

Another limitation of the results is that they used a single q ratio of 1.7. Leak and Filip (1975) suggested instead a $q = 2$ in the pole size and $q = 1.7$ in the sawtimber classes. Hansen and Nyland (1986) suggested an array of q ratios for four size classes. The economic and ecological outcomes of such systems could be investigated with the same methods. However, such marking guides may be impractical. Even the simplest BDq systems are scarcely implemented to date, due to a lack of cost-effective methods. Diameter-limit cuts hold a great advantage in this respect. Even with the attendant removal of cull trees, they can be applied efficiently in the field. Moreover, their proper implementation can be verified easily from the size of stumps in the forest, or from that of the logs on trucks or at the mill.

More serious is the possible dysgenic effect of diameter-limit cuts. Removing the largest trees implies taking the fastest growing trees first, and giving more time to the slowest growing to reproduce. A defense against this would be to remove also the poorly performing trees (e.g. those damaged, of poor form, or suppressed) in the understory. The result would then be a diameter-limit cut, with stand improvement.

With these caveats, the results obtained here suggest that diameter limit regimes can be sustainable, and that by adjusting the diameter limit, it is possible to obtain stand structures and incomes that are comparable to those of BDq cutting rules. Possible refinements would include setting different diameter limits for different species categories (Lu and Buongiorno 1993). The consequences of such guides could also be investigated with the methods of this paper, as would other management regimes describable by a cutting cycle and a residual diameter distribution. However, whatever rule is devised will be of little help unless it is practical.

References

Ambuel, B. & Temple, S.A. 1983. Area-dependent changes in the bird communities and vegetation of S. Wisconsin forests. Ecology 64(5): 1057–1068.

Birch, T.W. 1994. Private forest-land owners of the Northern United States. USDA Forest Service, Resource Bulletin NE-136.

Buongiorno, J., Dahir, S., Lu, H.C. & Lin, C.R. 1994. Tree size diversity and economic returns in uneven-aged forest stands. Forest Science 40(1): 83–103.

Crow, T.R., Tubbs, C.H., Jacobs, R.D. & Oberg, R.R. 1981. Stocking and structure for maximum growth in sugar maple selection stands. USDA Forest Service, North-Central Forest Experiment Station, St Paul, Research Paper NC-199. 16 p.

Elton, C.S. 1958. The ecology of invasions by animals and plants. Methuen, London. 181 p.

Erdmann, G.G. & Oberg, R.R. 1973. Fifteen-year results from six cutting methods in second-growth northern hardwoods. USDA Forest Service, North Central Forest Experiment Station, Research Paper NC-100. 12 p.

Erickson, M.D., Reed, D.D. & Mroz, G.D. 1990. Stand development and economic analysis of alternative cutting methods in northern hardwoods: 32-year results. Northern Journal of Applied Forestry 7: 153–158.

Hansen, G.D. & Nyland, R.D. 1986. Effects of diameter distribution on the growth of simulated uneven-aged sugar maple stands. Canadian Journal of Forest Research 17: 1–8.

Hansen, A.J., Spies, A.T., Swanson, F.J. & Ohmann, J.L. 1991. Conserving biodiversity in managed forests. Bioscience 41(6): 382–392.

Hansen, M.H., Frieswyk, T., Glover, J.F. & Kelly, J.F. 1992. The Eastwide forest inventory data base: users manual. USDA Forest Service, North Central Forest Experiment Station, General Technical Report NC-151. 48 p.

Hunter, M.L., Jr. 1990. Wildlife, forests and forestry: principles of managing forests for biodiversity. Prentice Hall, NJ. 370 p.

Kolbe, A. 1998. A growth model for Wisconsin's and Michigan's northern hardwoods, and management implications. M.S. thesis, University of Wisconsin, Madison. 163 p.

— , Buongiorno, J.& Vasievich, M. 1999. Geographic extension of an uneven-aged, multi-species matrix growth model for northern hardwood forests. Ecological Modelling 121: 235–253.

— , Buongiorno, J., Schulte, B. & Vasievich, M. 1998. Northpro: a computer program for uneven-aged management of northern hardwood stands. Department of Forest Ecology and Management, University of Wisconsin, Madison. 44 p.

Leak, W.B. & Filip, S.M. 1975. Uneven-aged management of northern hardwoods in New England. USDA Forest Service Northeastern Forest Experiment Station, Research Paper NE-332. 15 p.

Leatherberry, E.C. & Spencer, J.S. Jr. 1996. Michigan forest statistics, 1993. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN, Resource Bulletin NC-183. 144 p.

Lin, C.R., Buongiorno, J. & Vasievich, M. 1996. A multi-species, density-dependent matrix growth model to predict tree diversity and income in northern hardwood stands. Ecological Modelling 91: 193–211.

Lu, H.S. & Buongiorno, J. 1993. Long and short-term effects of alternative cutting regimes on economic returns and ecological diversity in mixed-species stands. Forest Ecology and Management 58: 173–192.

MacArthur, R.H. & MacArthur, J.W. 1961. On bird species diversity. Ecology 42(3): 594–598.

Muller, R.N. 1982. Vegetation patterns of the mesophytic forest of eastern Kentucky. Ecology 63: 1901–1917.

Niese, J.N. & Strong, T.F. 1992. Economic and tree diversity trade-offs in managed northern hardwoods. Canadian Journal of Forest Research 22: 1807–1813.

— , Strong, T.F & Erdmann, G.G. 1995. Forty years of alternative management practices in second-growth, pole-size northern hardwoods. Canadian Journal of Forest Research 25: 1180–1188.

Orr, B.D., Reed, D.D & Mroz, G.D. 1994. Three basal area level harvest trials in uneven-aged northern hardwoods. Northern Journal of Applied Forestry 11(4): 117–123.

Pielou, E.C. 1977. Mathematical ecology. John Wiley & Sons, Toronto. 385 p.

Roberts, J.C., Wayne, T.G. & Jordahl, H.C. Jr. 1986. The Wisconsin private non-industrial owner: a profile. University of Wisconsin Cooperative Extension Service, Madison, WI.

Schmidt, T.L. 1998. Wisconsin forest statistics, 1996. USDA Forest Service, North Central Forest Experiment Station, Resource Bulletin NC-183. 150 p.

Schulte, B.J. & Buongiorno, J. 1998. Effects of uneven-aged silviculture on the stand structure, species composition, and economic returns of loblolly pine stands. Forest Ecology and Management 4439(1998): 1–19.

Sterba, H. 1999. Target diameter felling – a strategy to convert even-aged forests. Unpublished paper presented at IUFRO Conference "The Transformation of Plantation Forests", Heriot-Watt University, Scotland.

U.S. Government Printing Office. 1998. Economic report of the President. Washington, D.C. 402 p.

Volin, V. & Buongiorno, J. 1996. Effects of alternative management regimes on forest stand structure, species composition, and income: a model for the Italian Dolomites. Forest Ecology and Management 87: 107–125.

Wisconsin Department of Natural Resources. 1996 to 1998. Stumpage value rates. Register NR 46, Department of Natural Resources, Madison.

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