Long-Term Structural Change in Uneven-Aged Northern Hardwoods

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ABSTRACT. The diameter distributions of 10 previously unmanaged northern hardwood stands on the Bartlett Experimental Forest in New Hampshire were analyzed to determine changes over a 35 yr period since a single cutting by the diameter-limit or single-tree selection methods. The diameter distribution of an uncut old-growth stand (the Bowl) provided a comparison. The cuttings left residual basal areas of 25 to 96 ft^2 of basal area per acre (5.7 to 22.0 m^2/ha), as well as a wide range in diameter distribution. Basal area of the old-growth stand was 123 ft^2/ac (28.2 m^2/ha), and the diameter distribution was reverse J-shaped (negative exponential) as evidenced by a close fit (adjusted $r^2 = 0.97$) of log (no. of trees) over dbh class; the q (ratio between numbers of trees in successive 2 in. dbh classes) equaled 1.39. Under all cutting methods, the diameter distributions after 35 yr fit the reverse J-shaped form only moderately well with adjusted r^2's of 0.81 to 0.95. An equal or better fit in most cases (adjusted r^2's of 0.91 to 0.98) was provided by log (no. of trees) over dbh^2, which reflects the tendency of the quotients between numbers of trees per dbh class to increase with dbh. None of the initial diameter distributions of the cut stands had rotated sigmoid characteristics, but five of the final diameter distributions had significant rotated sigmoid characteristics, and at least two others showed graphical sigmoid tendencies. Apparently, rotated sigmoid characteristics are caused by disturbance, perhaps coupled with successional trends toward increased tolerant softwoods. FOR. SCI. 42(2):160–165.

Additional Key Words: Diameter-distribution, negative-exponential, rotated-sigmoid, balanced-stand, q-distribution.

Diameter distribution (numbers of trees by dbh class) is an important component of uneven-aged silviculture. To maintain yields, forest managers must work toward a diameter distribution that will provide a continuous supply of trees, and one that will be both productive and economical. This paper describes the effects of a wide range in cutting intensities and strategies on the shape and level of diameter distributions in 10 northern hardwood stands at the beginning and end of a 35-yr period, compared to the distribution found in a comparable old-growth (never cut) stand. The purpose of the paper is to describe the effects of cutting disturbances on the development of diameter distributions. It does not address the effects of diameter distribution on stand productivity or quality development, or the feasibility of developing or maintaining certain distributions—questions that should be considered in choosing an optimum structural goal.

Meyer (1950) defined a balanced, uneven-aged forest as one where an essentially constant yield can be removed periodically while maintaining the structure and volume of the forest. This implies a certain constant residual diameter distribution and stand density after each cut and the return of the forest to a given distribution and density before each cut. In a large forested area where some stands are cut every year, the forestwide diameter distribution remains essentially constant. In any given stand, where cutting reoccurs on a 10-20 yr cycle, the density and perhaps the shape of the diameter distribution may vary appreciably between the before- and after-cut stand. Meyer suggested that old-growth forests in a fairly stable condition might provide examples of balanced diameter distributions useful for defining management objectives, and his work suggested that the reverse J-shaped (negative exponential) distribution could be a useful form.

In subsequent modeling studies, the balanced concept has been referred to as a sustainable, equilibrium, or steady-state structure (Adams 1976, Adams and Ek 1974, Chapman and Blatner 1991, Gove and Fairweather 1992, Hansen and Nyland 1987, Lorimer and Frelich 1984). All these terms apparently mean the same thing: a diameter distribution and density that will be maintained over time in an unmanaged

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stand through mortality, or a distribution and density that can be maintained forestwide through cutting (and mortality), or, at the stand level, a structure that can be reconstructed again and again at each stand entry with essentially constant yields from each cut.

Although Meyer's (1950) work demonstrated the utility of the reverse J-shaped form, many other apparently sustainable forms have been predicted through computer simulation (citations above), or defined through measurements of old-growth stands or managed stands (Crow et al. 1981, Eyre and Zillgitt 1953, Goff and West 1975, Schmelz and Lindsey 1965). This variety is not surprising since population theory suggests that there is an infinite number of balanced or sustainable structures, differing in age/diameter distribution and/or density (Keyfitz 1968). These structural differences are uniquely determined by birth rates and mortality schedules. In other words, a given stand/site combination subject to a certain mortality, cutting, and regeneration pattern should in theory produce a certain steady-state age/diameter distribution and density. Sustainable diameter distributions have one unique characteristic: the curve of numbers of trees over dbh is declining, or occasionally level, throughout its range. Bell-shaped, skewed bell-shaped, or distinctly bimodal forms cannot be sustained either naturally or through cutting regimes. A nearly level sustainable diameter distribution would represent a forest composed of wide-spaced plantations where there is no cutting until the final harvest and little natural mortality. Obviously, in most natural forests, natural mortality and cutting result in steeply declining segments.

Little is known about the causes of various structural developments. Goff and West (1975), working with hardwood-hemlock stands in Wisconsin, suggested that a rotated sigmoid form was a natural steady-state diameter distribution in unmanaged stands caused by lowered mortality and increased diameter growth of midsized trees just entering the upper canopy. This form is characterized by a plateau (nearly level or slight negative slope) in the mid-dbh classes of log (no. of trees) plotted over dbh class. Simulations by Lorimer and Frelich (1984) also indicated that rotated sigmoid forms were natural steady-state structures in unmanaged maple stands in upper Michigan. Schmelz and Lindsey (1965) believed that the rotated sigmoid form in midwestern old-growth hardwoods represented a temporary stage in recovery from an earlier disturbance that would be replaced by the negative exponential.

Based on cutting studies, recommended managed-stand residual structures for northern hardwoods in the Lake States have a slightly rotated-sigmoid form (Eyre and Zillgitt 1953). In Appalachian hardwoods, the negative exponential has proven to be a useful and apparently sustainable goal for managed stands (Trimble and Smith 1976). In managed stands, the recommendation generally is to attain the structural goal by cutting throughout all dbh classes. Roach (1974) argued that repeated cutting primarily in the larger size classes would result in the development of clearly nonsustainable diameter distributions such as extreme sigmoid (with positive slopes in the mid-dbh range), bimodal, or skewed bell-shaped forms depending on the intensity of the cut. This is a fairly common viewpoint among silviculturists practicing single-tree selection.

Methods

To provide some additional empirical evidence on the factors affecting structural development in uneven-aged stands, an analysis was made of structural change over a 35-yr period in 10 northern hardwood stands on the Bartlett Experimental Forest in New Hampshire that represented a wide range in residual density and diameter distribution. An old-growth northern hardwood stand (the Bowl) was used for comparison.

The ten Bartlett stands, averaging 44 ac (18 ha) in size, were part of a compartment management study on the Bartlett Experimental Forest. The Bowl stand, about the same size, is part of a nearby Research Natural Area that shows no evidence of any past logging. Initial density, diameter distribution (q = quotient between 2 in. classes), and species composition showed the normal range for northern hardwoods in the New England region (Tables 1 and 2). Beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), and yellow birch (*Betula alleghaniensis* Britton) were the main species with com-

Table 1. Characteristics of 10 stands on the Bartlett Experimental Forest, NH, that were cut in 1953–1965 and final-measured in 1992: basal area/ac in ft^2, *q*-ratio estimated by regression, softwoods in percent of trees per acre. Listed in order of increasing after-cut basal area.

	Basal area/ac			*q*-ratio			Softwood		Trees/ac	
Compartment	Initial	Aftercut	Final	Initial	Aftercut	Final	Initial	Final	Initial	Final
		(ft^2)					(%)		(no.)	
34	114	25	153	1.48	1.85	2.02	15	30	159	365
36	96	42	122	1.55	2.13	1.71	7	18	148	195
37	119	68	120	1.67	1.99	1.81	22	37	201	208
33	103	77	150	1.51	1.63	1.39	6	40	152	195
30	123	79	115	1.48	1.58	1.42	16	39	177	175
47	109	81	127	1.51	1.62	1.52	6	31	165	224
41	105	84	139	1.80	2.09	1.50	10	26	179	216
38	116	87	128	1.54	1.59	1.28	4	14	169	149
46	117	88	152	1.61	1.79	1.48	15	44	183	269
35	117	96	132	1.56	1.58	1.37	7	23	141	173
Bowl	123	—	—	1.39	—		0	0	157	

Table 2. Species percentages (common-name abbreviations) based on numbers of trees >5 0 in. dbh in initial (I) stand and >4.5 in. dbh in final (F) stands by compartments (C) and the Bowl (B).

	BE		YB		SM		RM		PB		WA		RS		EH		OTH	
C	I	F	I	F	I	F	I	F	I	F	I	F	I	F	I	F	I	F
34	35	28	21	6	10	8	7	7	8	7	3	9	4	1	11	29	1	5
36	49	57	13	13	17	6	5	3	5	0	1	1	2	0	5	18	3	2
37	27	21	12	9	8	5	12	11	11	10	1	0	10	8	12	29	7	7
33	49	28	14	13	18	11	5	4	4	1	3	2	1	8	5	32	1	1
30	25	29	22	13	11	10	13	5	7	1	5	1	5	6	11	33	1	2
47	48	39	17	13	16	12	4	3	7	2	1	0	1	0	5	31	1	0
41	40	42	17	12	16	10	8	4	7	1	1	0	2	3	8	23	1	5
38	48	42	12	17	29	24	4	2	2	1	0	0	4	14	0	0	1	0
46	42	24	15	12	11	14	8	1	6	2	3	3	2	1	13	43	0	0
35	28	28	26	16	17	18	13	9	5	1	4	2	4	3	3	20	0	3
B	48		17		22		0		0		0		1		0		12	

ponents of red maple (*Acer rubrum* L.), paper birch (*Betula papyrifera* Marsh.), white ash (*Fraxinus americana* L.), red spruce (*Picea rubens* Sarg.), and eastern hemlock (*Tsuga canadensis* [L.] Carr.).

The Bartlett stands had been lightly high-graded for softwoods in the late 1800s, and contained a wide range in tree size and age: up to more than 200 yr old and 34 in. (86.4 cm) dbh. These stands were initially inventoried in 1953 to 1956: 100% tallies by species and 2-inch (5.1 cm) dbh classes of all trees 5.0 inches (12.7 cm) and larger. The stands were partially cut (and sometimes TSI'd) between 1953 and 1965, and reinventoried immediately after. Diameter-limit cuts were applied in three stands down through the 10-inch (25 cm) dbh class (Compartment 34) or 13-inch (33 cm) dbh classes (Compartments 36 and 37); these cuts resulted, of course, in somewhat truncated distributions although not a complete elimination of trees above the diameter limit (Figure 1). The selection cuts in the other seven Bartlett compartments were directed toward goals of 80 ft^2/ac residual basal area (18.4 m^2/ha) with a q of 1.5 or a residual of 100 ft^2/ac with a q of 1.3. However, due to the necessity of removing high-risk and defective trees, the residual q's ranged from about 1.6 to over 2.0 (Table 1), but some marking took place throughout a range in dbh classes down to the 10 or 12 in. class or below (Figure 1). In 1992, the Bartlett stands were reinventoried again using a systematic grid of at least 30 twenty-factor prism points, classifying trees by 1 in. (2.54 cm) classes (trees 4.5 in. dbh and larger) and species. The average period between cutting and final measurement was 34.7 yr. The Bowl data were based on a one-time inventory in 1984 using 26 ten-factor prism points, classifying trees by 2 in. classes and species (trees 5.0 in. dbh and larger).

Analysis

Diameter distributions before and after cutting, and the final distribution in 1992, were fit with linear regression where the dependent variable was the log (base 10) of trees per acre and the independent variables were all combinations of the 2 in. dbh class midpoint, the midpoint squared, and the midpoint cubed. Midpoints for the before- and after-cut distributions, and the Bowl, were even integers (6, 8, 10, etc.); the midpoints for the final distributions were half-diameter decimals (5.5, 7.5, 9.5. etc.). Distributions in the Bartlett stands were fit up through the 24 in. (61.0 cm) or 23.5 in. (59.7 cm) class; trees above this size are beyond the usual management range and variable in occurrence. The Bowl distribution was fit up through the 28 in. class which still had more than 1 tree/ac.

The regressions using dbh midpoint provided least squares estimates of q, the constant quotient between numbers of trees by 2 in. classes in a reverse J-shaped (negative exponential) distribution; q equals the square of the antilog of the slope coefficient (Leak 1963). The regressions using the midpoint squared provide a logical functional form for distributions where the quotient increases with dbh class, a form of diameter distribution suggested by earlier work in northern hardwoods (Leak 1964). The presence of the rotated sigmoid form was determined by either of the following two tests:

1. A significant slope coefficient for the dbh-class midpoint squared plus a significant reduction in sum of squares for the midpoint cubed, coupled with a difference in sign for the two variables;
2. A significant slope coefficient for the dbh class midpoint plus a significant reduction in sum of squares by the addition of the midpoint squared and the midpoint cubed, coupled with a difference in sign between the latter two coefficients.

Significant reductions in sums of squares were tested by procedures outlined in Freese (1964).

Results

The results of these analyses can be summarized in a series of bullet statements that are reflected by the tabular and graphical summaries (Table 1, Table 3, Figure 1).

1. The regressions using dbh-class midpoint to estimate the q-ratio that characterizes a reverse J-shaped (negative exponential) distribution provided only a moderately good fit (adjusted r^2's of 0.81 to 0.98, Table 3) of the initial, after-cut, and final distributions.
2. Under heavy, diameter-limit cuttings (Compartments 34, 36, and 37), the after-cut distributions had a substantially higher q than the before-cut distributions, which reflects the fact that cutting was proportionally much higher in the

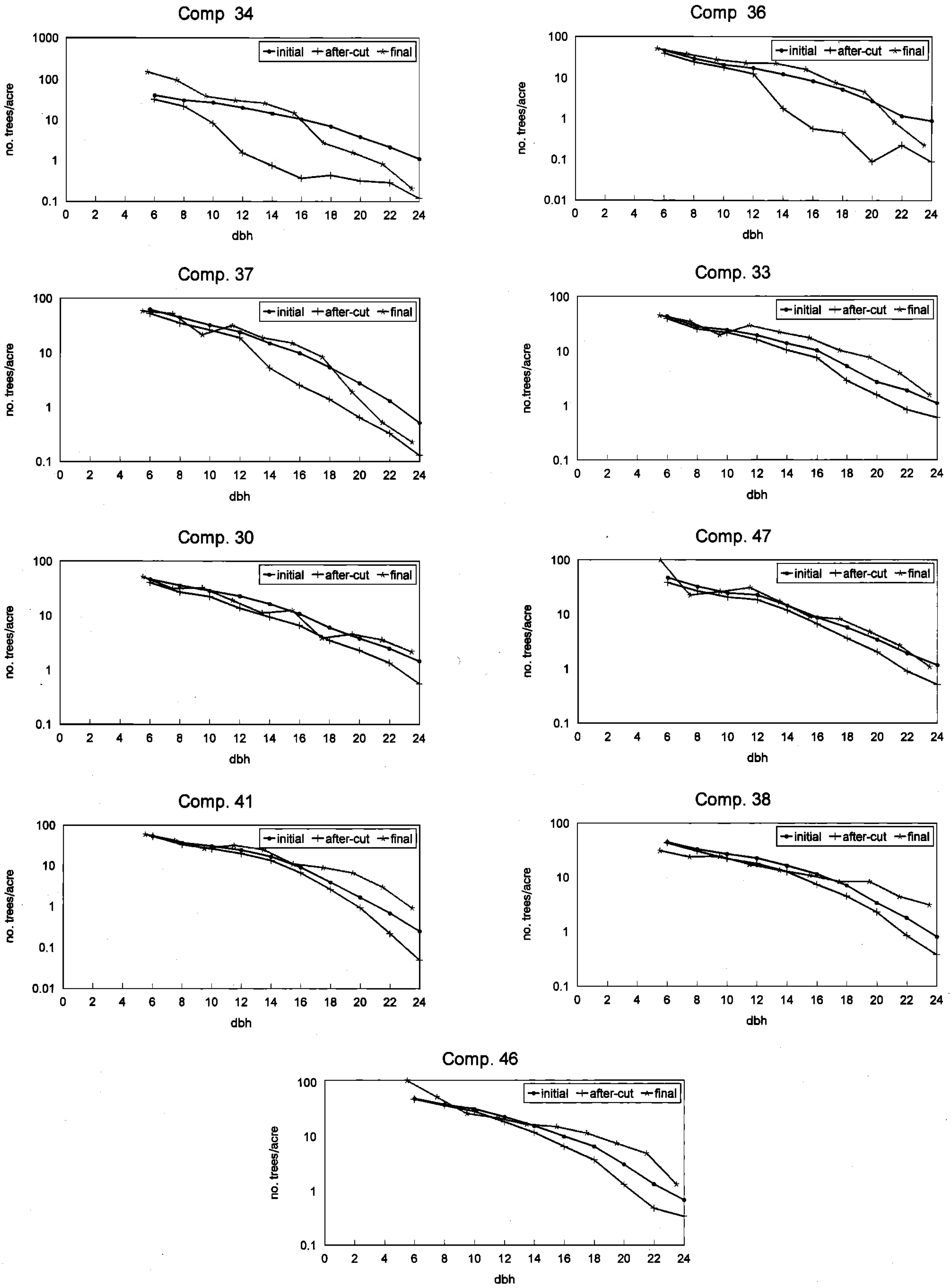

Figure 1. Graphs of no. of trees/ac on a log scale over dbh class midpoint for the initial, after-cut, and final diameter distributions for 10 stands on the Bartlett Experimental Forest shown in order of increasing after-cut basal area: Compartments 34, 36, 37, 33, 30, 47, 41, 38, 46, and 35. Diameter distribution of the Bowl (uncut old-growth) shown for comparison.

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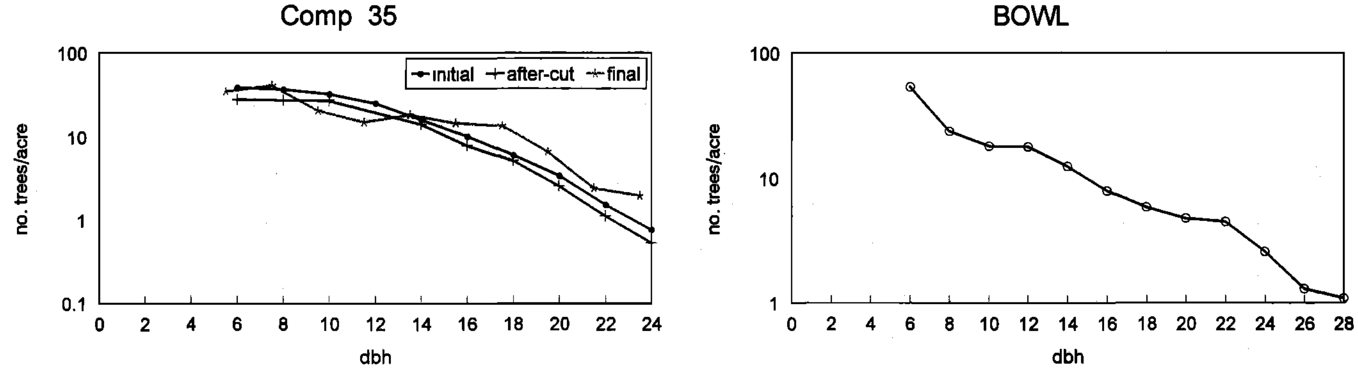

Figure 1. (continued)

larger dbh classes. Roach (1974) felt that repeated diameter cuts would result in the development over time of a normal or bimodal structure. Apparently, this does not occur after a single diameter-limit cutting in northern hardwoods in New Hampshire.

3. In all cases, except Compartment 34 (the most heavily cut), the *q* value was reduced over time from the after-cut value (Table 1). In stands with an after-cut basal area of 77 ft^2 (17.7 m^2/ha) or greater, the final *q* was about equal to or less than the initial. In stands with an after-cut basal area of 68 ft^2 (15.6 m^2/ha) or less, the initial-stand *q* value was not attained over a period as long as 35 yr.
4. Final basal area of all stands except Compartment 30 exceeded the initial basal area (Table 1). (Remember that the final basal area goes down to 4.5 in., which might account for an additional 5–6 ft^2 of basal area at most). The implication from these changes over time in basal area and *q* is that another cut might be made, similar to or heavier than the initial cut, in those stands with at least 77 ft^2/ac after-cut basal area from the previous entry. Examination of the actual diameter distributions (Figure 1) indicates that this is true: in fact, in several compartments (e.g., 33, 41, 38, 46, and 35) a substantial cut, primarily in sawtimber sizes, could have been made some years earlier, perhaps at 20 yr or so after the first cut—a more normal cutting cycle than the 35 yr measurement period in this study. Since most of the changes in the distributions over the study period were in the sawtimber sizes, the next cut could readily maintain, or lower, the current *q* ratio below that established through the initial cut.
5. Although the regression of log (no. of trees)/dbh provided a fairly good fit to the initial diameter distributions, the use of the dbh-class squared provided an equal or better fit to all of the initial Bartlett diameter distributions and most of the final ones (Table 3). Apparently, a quotient that increases with dbh is characteristic of many of these northern hardwood stands (Leak 1964). However, the diameter distribution in the Bowl (never cut) showed no improvement in fit by using dbh class squared. This suggests that the ultimate steady-state distribution in old-growth hardwoods in this area may be close to the negative exponential (constant *q* ratio).
6. None of the initial stands had significant rotated sigmoid characteristics. One of the after-cut distributions was sigmoid: heavily cut Compartment 34 (Table 3). Five of the final distributions tested significantly sigmoid, and two others (Compartments 34 and 35) showed graphical sigmoid tendencies (Figure 1). Since the initial distributions and the Bowl distribution were not sigmoid, I'll conclude that the rotated sigmoid form in these stands was caused by the disturbance from the first cut (similar to the conclusions of Schmelz and Lindsey 1965). Possibly, the sigmoid tendencies at Bartlett are related to the increasing component of tolerant softwoods (Table 1), especially hemlock, which is a very late successional species that tends to invade northern hardwoods on certain sites (Figure 2). This increase in the softwood component resulted in higher basal areas than usually found in northern hardwoods. This shift in species mix indicates that the Bartlett stands are still recovering from the early softwood removals in the late

Table 3. Adjusted r^2 values for regressions of log (no. trees/ac) over dbh class or dbh-class squared, and significance (0.05 or less) of the sigmoid tests for the initial (I), after-cut (AC), and final (F) stands. Compartments (C) listed in order of increasing residual basal area per acre (RBA).

		Dbh			Dbh^2			Sigmoid tests		
C	RBA (ft^2)	I	AC	F	I	AC	F	I	AC	F
34	25	0.95	0.89	0.95	0.99	0.77	0.98	NS	S	NS
36	42	0.96	0.92	0.81	0.99	0.87	0.92	NS	NS	S
37	68	0.96	0.98	0.85	0.99	0.98	0.94	NS	NS	S
33	77	0.96	0.96	0.86	0.99	0.99	0.94	NS	NS	S
30	79	0.97	0.98	0.95	0.99	0.99	0.92	NS	NS	NS
47	81	0.97	0.96	0.91	0.99	0.99	0.92	NS	NS	S
41	84	0.93	0.90	0.90	0.99	0.98	0.96	NS	NS	NS
38	87	0.93	0.94	0.96	0.99	0.99	0.98	NS	NS	NS
46	88	0.95	0.96	0.92	0.99	0.99	0.92	NS	NS	S
35	96	0.93	0.90	0.85	0.99	0.98	0.91	NS	NS	NS
Bowl	123	0.97			0.95			NS		

1800s All of the rotated sigmoid distributions had negative slopes in the mid-dbh classes except Compartment 35. This is the only compartment with a current distribution that might be regarded as nonsustainable: it is slightly bimodal, possibly with insufficient poletimber to maintain the sawtimber component. Unless something unusual happens, the trough at about 10 to 12 in. will tend to move into the larger sawtimber sizes. This compartment received the lightest cut and had the highest residual basal area after cutting (96 ft^2/ac). This finding is similar to that of Hansen and Nyland (1987) regarding the nonsustainability of high basal areas and low q's.

Conclusions

This study of long-term structural change in northern hardwood stands indicates that rotated sigmoid diameter distributions may be caused by disturbance, possibly accompanied by increases in the tolerant softwood component as these stands recover from early softwood removals. The reverse J-shaped form with constant q (negative exponential) provided a fairly good fit to the initial (before-cut) distributions and only a moderately good fit to the final distributions. The use of dbh-class squared provided a better fit to all of the initial Bartlett distributions and an equal or better fit to most of the final ones. In addition, five of the final distributions were significantly sigmoid while two others showed graphical sigmoid tendencies. Only one compartment, one that was lightly cut, showed some tendency toward a temporarily nonsustainable bimodal structure. However, heavy cutting concentrated in the upper dbh classes (i.e., diameter-limit cutting) results in a slow return to initial q levels and limited opportunities for a timely and comparable second cut.

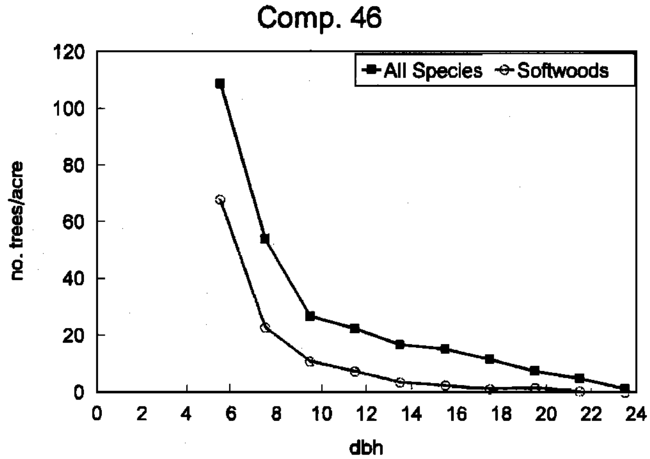

Figure 2. Final diameter distribution for Compartment 46, showing trees per acre by 2 in. classes for softwoods and all species.

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