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Forest Ecology and Management 118 (1999) 11–29

Forest Ecology  
and  
Management

# Population structure in old-growth and managed northern hardwoods: an examination of the balanced diameter distribution concept

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Accepted 22 August 1998

## Abstract

Silvicultural guidelines for uneven-aged management have traditionally been based on the regulation of ‘balanced’ stand structures that allow for periodic yields at regular intervals while providing adequate growing space for multiple cohorts. To evaluate certain assumptions behind the ‘balanced’ diameter distribution concept, we investigated differences in the size structure, canopy recruitment, and growing space allocation among 31 old-growth, managed uneven-aged (selection), and even-aged northern hardwood stands in north-central Wisconsin and adjacent western Upper Michigan. The frequency of stands meeting criteria for balanced uneven-aged structure was substantially affected by whether diameter distributions were plotted for all crown classes combined (traditional approach) or whether the distributions included only trees with crowns exposed overhead to skylight. While all 10 old-growth stands and 11 of the 15 selection stands met the traditional criteria for balanced structure, only 50% and 27%, respectively, met the more stringent criteria for balanced structure that included evidence of substantial gap sapling recruitment. Both negative exponential and rotated sigmoid diameter distributions were found among individual old-growth and selection stands. However, all old-growth stands classified as balanced (based on exposed canopy trees) had rotated sigmoid diameter distributions for all species pooled and for sugar maple only. Negative exponential distributions were also observed in some ‘balanced’ stands, but only among the selection stands. Aggregate crown area distributions in old-growth and selection stands with reasonably smooth reverse-J diameter distributions provided support for a modified interpretation of the equal area allocation hypothesis. While the aggregate exposed crown area occupied by each size class tended to be lower for small trees than for medium and large trees, total crown area distribution for trees with partially or fully exposed crowns did approximate a nearly uniform distribution. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Diameter distributions; Growing space allocation; Old-growth forests;  $q$ -ratios; Stand structure; Uneven-aged management; Negative exponential; Rotated sigmoid; Northern hardwood forests; Stand dynamics; Sustainable forestry

## 1. Introduction

A commonly accepted minimum standard for uneven-aged management is that it provides periodic

harvests of merchantable timber while maintaining growing space for at least three age classes within each stand (Smith, 1962). If stand structure is carefully regulated to approach a ‘balanced’ condition, it is theoretically possible to achieve constant yields, equal to the periodic growth of the stand, at regular intervals

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(Meyer, 1952). While there are no compelling biological, social, or economic reasons for managing each stand for perfect ‘even flow’ of timber (Gould, 1984; Smith et al., 1997), wide fluctuations in harvest intensity are usually avoided in order to maintain a high proportion of crown cover in mature trees. It is therefore common for foresters to use balanced stand structure guidelines as approximate target conditions when marking individual stands.

The earliest guidelines for developing balanced stand structure were based on diameter distributions of managed uneven-aged or unmanaged old-growth stands presumed to be near equilibrium. De Liocourt (1898) and Meyer and Stevenson (1943) reported that the steeply descending diameter distributions in such stands were well fit by a negative exponential distribution, which is characterized by a constant ratio ( $q$ -factor) in the number of trees between successive size classes. In the United States, residual diameter distributions defined by constant  $q$ -factors are widely used in formulating uneven-aged management prescriptions (Frank and Blum, 1978; Marquis, 1978; Leak et al., 1987; Guldin, 1991; Lamson and Smith, 1991; Murphy et al., 1991).

Balanced stand structure has also been defined in reference to the amount of growing space allocated to each age class. By conceptualizing an uneven-aged stand as a mosaic of small even-aged patches, Smith (1962) and Assmann (1970) explained the steeply descending ‘reverse-J’ diameter distribution of uneven-aged stands as the summation of a series of unimodal diameter distributions of different cohorts, with the density of progressively older cohorts reduced as a consequence of self-thinning within each patch. Smith (1962), Nyland (1996), and the Society of American Foresters (1994) have all defined a balanced distribution as one in which each cohort occupies an approximately equal amount of growing space. Nyland (1996) is more explicit in defining growing space to be the ground area or horizontal crown area occupied by each cohort, although the same interpretation appears to be implicit in Smith’s (1962) discussion (e.g. Fig. 14.5, p. 485).

Evidence in recent years has revealed some unanticipated difficulties and complications in the use of the early criteria for balanced stand structure (see also review in O’Hara, 1996), suggesting that it may be useful to reexamine some of the original assumptions.

The negative exponential model presupposes equal mortality rates among size classes, which Goff and West (1975) regarded as biologically unrealistic. When plotted on semi-logarithmic axes, diameter distributions of old-growth northern hardwood and hemlock-hardwood stands can have ‘rotated sigmoid’ curve shapes that differ markedly from the straight line (constant attrition) expected under the negative exponential model (Goff and West, 1975; Lorimer and Frelich, 1984). Simulations by various authors have suggested that there are other sustainable distributions besides the negative exponential, and neither the negative exponential nor equal allocation of growing space among cohorts appears to give maximum yields or optimal economic returns (Adams and Ek, 1974; Bare and Opalach, 1988; Kaya and Buongiorno, 1989; Erickson et al., 1990). Equal allocation of growing space among cohorts, in fact, is largely hypothetical and has not been demonstrated by field data. O’Hara (1996), in one of the rare instances where growing space allocation was actually measured, found that few multi-aged ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stands had evidence of equal allocation of growing space (assessed by leaf area index).

Finally, steeply descending reverse-J diameter distributions have been reported in a variety of mixed-species stands that are either even-aged or were otherwise cut heavily in the early 20th century (Oliver, 1978; Muller, 1982; Lorimer and Krug, 1983; Hornbeck and Leak, 1992). While this observation does not necessarily indicate a problem in the interpretation of sustainability of uneven-aged stands, it raises important questions about how the structures of even- and uneven-aged stands differ, and whether sustained even flow requires any particular initial age structure.

The purpose of this study is to evaluate the diameter distributions and growing-space allocation in a set of old-growth and managed northern hardwoods stands in light of the traditional criteria for balanced stands. Northern hardwood forests of the upper Great Lakes region are especially suitable for evaluating some of the issues mentioned above because, unlike some other regions and forest types, large tracts of old-growth forest are available for study, the natural disturbance regime is dominated by diffuse, low-intensity disturbances leading to broadly uneven-aged stands (Frelich and Lorimer, 1991a, b; Frelich and Graumlich, 1994; Parshall, 1995), and the most com-

mon regime in managed stands is the selection system using the balanced stand structure guidelines of Arbogast (1957). As a result, it is not difficult to find uneven-aged stands (both managed and old-growth), some of which can be expected to meet the prevailing criteria of balanced stands. In making these comparisons, we propose to address three questions: (1) How do old-growth, even-aged, and managed uneven-aged (selection) stands differ in size structure and canopy recruitment? (2) Do the existing old-growth and managed stands better fit the negative exponential or rotated sigmoid model? and (3) Do either the old growth or managed uneven-aged stands support the equal area allocation hypothesis?

## 2. Study areas

Thirty-one northern hardwood and hemlock-hardwood stands were selected for study on mesic sites in northeastern Wisconsin and adjacent western Upper Michigan. An effort was made to select stands with uniform soil and site characteristics within each forest type using available multi-factor ecological classification systems developed for the Sylvania Wilderness

Area and the Ottawa National Forest, and floristic forest habitat type classifications for the region (Coffman et al., 1983; Spies and Barnes, 1985; Kotar et al., 1988). Overstory species composition was also similar across the different management histories (Table 1). All northern hardwood and hemlock-hardwood study stands had been classified as forest habitat type *Acer-Tsuga-Dryopteris* (ATD) (Coffman et al., 1983; Kotar et al., 1988), although a few plots were transitional between the ATD habitat type and the *Acer-Viola-Osmorhiza* (AViO) or the *Acer-Tsuga-Maianthemum* (ATM) type. Most stands were located on the Winegar terminal moraine complex, an area where a deep layer of sandy glacial drift was deposited over iron-rich Precambrian bedrock. Disintegrating glacial ice created an irregular rolling topography in this sandy drift (Albert, 1995). Elevations range from approximately 500–550 m. Upland soils in this region are predominantly loamy sand to sandy loam in texture and are classified as well-drained coarse-loamy Typic Haplorthods or moderately-well-drained Alfic Fragorthods (Hole, 1976; Spies and Barnes, 1985). The continental climate is characterized by extremely cold winters, with heavy snowfall and warm humid summers. Mean January temperature is  $-12.2^{\circ}\text{C}$  and

Table 1  
Mean overstory species composition by treatment history

	Northern hardwood			Hemlock-hardwood	
	Old-growth	Selection	Even-aged	Old-growth	Selection
Basal area, all dbh classes ( $\text{m}^2/\text{ha}$ )	34.4	25.5	32.3	37.5	28.0
Species composition of trees $\geq 11$ cm dbh	Percent of basal area ( $\pm$ std. dev.)			Percent of basal area ( $\pm$ std. dev.)	
Sugar maple	69.6 ( $\pm 15.5$ )	69.3 ( $\pm 20.5$ )	64.5 ( $\pm 22.8$ )	41.2 ( $\pm 16.3$ )	39.3 ( $\pm 19.0$ )
Red maple	0.0 ( $\pm 0.0$ )	6.3 ( $\pm 11.8$ )	5.8 ( $\pm 9.9$ )	0.5 ( $\pm 0.6$ )	0.0 ( $\pm 0.0$ )
Yellow birch	9.9 ( $\pm 6.7$ )	6.5 ( $\pm 6.0$ )	4.9 ( $\pm 5.6$ )	17.6 ( $\pm 12.4$ )	11.5 ( $\pm 11.3$ )
White ash	0.3 ( $\pm 0.8$ )	2.2 ( $\pm 7.0$ )	4.0 ( $\pm 11.2$ )	0.0 ( $\pm 0.0$ )	1.7 ( $\pm 2.3$ )
Basswood	13.8 ( $\pm 10.5$ )	5.5 ( $\pm 5.1$ )	11.3 ( $\pm 11.0$ )	4.9 ( $\pm 6.1$ )	2.2 ( $\pm 2.1$ )
Eastern hemlock	5.3 ( $\pm 6.1$ )	6.4 ( $\pm 8.4$ )	2.6 ( $\pm 4.0$ )	32.5 ( $\pm 7.5$ )	42.9 ( $\pm 11.1$ )
Other conifer spp.	0.6	0.7	0.5	1.0	0.5
Other hardwood spp.	0.5	3.1	6.4	2.3	1.9
No. of stands sampled	6	10	6	5	4

mean July temperature is 18.6°C. Precipitation averages 85 cm per year (Albert et al., 1986; Lac Vieux Desert weather station, National Climatic Data Center, Asheville, NC, 1993).

Unmanaged old-growth stands were located in the Sylvania Wilderness Area on the Watersmeet District of the Ottawa National Forest. Sylvania is a large tract of natural forest that has had little past cutting other than removal of scattered white pine (*Pinus strobus* L.) near the turn of the century (USDA, 1964). Ten old-growth stands >20 ha were selected, including six upland northern hardwood stands heavily dominated by sugar maple (*Acer saccharum* Marshall) and four mixed hemlock-hardwood stands, in which eastern hemlock (*Tsuga canadensis* L.) composed >30% of the basal area for trees >2 cm dbh.

Selection forests included in the study had to meet certain criteria typifying uneven-aged management in the region (e.g., Arbogast, 1957; Tubbs, 1977b), including previous single tree selection harvests on an 8–15-year cutting cycle, a residual basal area stocking target exceeding 16.1 m<sup>2</sup> ha<sup>-1</sup>, and a maximum residual tree diameter >45 cm dbh. While some study stands were essentially uncut primary forest prior to uneven-aged management, the majority were second-growth stands that had been cut at the turn of the century, but were being converted to a regulated uneven-aged stand structure. Ten managed northern hardwood stands and five hemlock-hardwood stands were selected for study. The time interval since the most recent harvest ranged from 3–13 years in the 15 selection stands, with a mean of 6.9 years. No other criteria were used in the screening of stands for sampling, and the degree to which any of the old-growth or selection stands approached a balanced structure was not known in advance.

A previous study in second-growth northern hardwoods managed by the selection system indicated that although cohorts dating to the early 20th century are often numerically dominant, the stands typically do have multiple cohorts, with some trees ranging from 100–250 years of age (Cole and Lorimer, 1994). Both old-growth and selection stands tend to have nearly linear trends between diameter and age, although there is substantial scatter (Tubbs, 1977a; Singer and Lorimer, 1997; Lorimer and Frelich, 1998). In a previous study of old-growth stands in Sylvania and other Michigan sites, all 15 old-growth stands with smooth

reverse-J diameter distributions were found to be broadly uneven-aged, with trees ranging from <20 to >200 years. Fifteen of the 17 old-growth stands with multimodal or irregular descending diameter distributions were also broadly uneven-aged (Frelich and Lorimer, 1991b, 1998 and unpublished data). Because the general uneven-aged character of these stands has been demonstrated in previous work, sampling for ages was not repeated in the present study.

The six even-aged stands (60–80 years old) selected for comparison contain primarily pole and mature trees (11–45 cm dbh) but include some scattered residual trees of an older age class. Stands have had no history of thinning treatments, and were essentially unmanaged since stand initiation. Even-aged hemlock-hardwood stands are uncommon in the region and were not included in this study. The 31 stands sampled in the study included 22 northern hardwood stands (six old-growth, 10 selection, and six even-aged), and nine hemlock-hardwood stands (four old-growth, five selection).

### 3. Methods

#### 3.1. Field procedures

Within each study stand, a point was randomly located to serve as plot center (minimum 200 m from stand edge), and then a single 30 × 100 m plot was established with the long axis oriented east-west. Species, dbh, and crown class were recorded for all trees (>2 cm dbh) within the entire 0.3 ha plot. The six crown classes used were similar to the Kraft classification system devised for even-aged stands (Smith et al., 1997), but were primarily intended to distinguish between trees receiving overhead skylight (i.e., dominant, codominant, intermediate, gap sapling) and those that were not (i.e., overtopped, understory sapling).

Additional height and crown measurements were collected for trees within the central 10 × 100 m transect of the 0.3 ha plot. Total tree height was measured using a clinometer or height pole. Radii of the 'exposed' portion of each tree crown (the portion not overtopped by branches of taller competitors) were measured along four cardinal compass directions, using a clinometer to locate points directly

beneath the crown edge. The projection area ( $\text{m}^2$ ) of the exposed portion of each crown (referred to as 'exposed crown area') was used as one of the indicators of two-dimensional growing space occupied by each tree and was calculated as the sum of the four quarter ellipses (NE, SE, SW, NW) defined by these exposed crown radii. Data on total crown projection area were collected from a random subset of 12 stands (two to three stands in each of five forest type-management history combinations) in order to derive regression equations for estimating total crown projection area of trees in all other stands. Total crown radii were measured with a tape along four cardinal directions from the center of the crown to the dripline. The total crown projection area (referred to as 'total crown area') was then calculated as the sum of the four quarter ellipses (NE, SE, SW, NW) defined by these total crown radii.

### 3.2. Analytical procedures

#### 3.2.1. Criteria for balanced and unbalanced structures

Following the general criteria used in earlier studies such as Meyer and Stevenson (1943) and Eyre and Zillgitt (1953), we defined stands as having a balanced structure only if all of the broad size classes (saplings, poles, and sawtimber) were well represented. A balanced structure was required to have minimum full stocking ( $>12 \text{ m}^2/\text{ha}$  of basal area) based on the stocking chart of Erdmann (1986), and at least  $3.5 \text{ m}^2/\text{ha}$  of basal area in sawtimber ( $>25 \text{ cm dbh}$ ). Because economically optimal diameter distributions often do not include large sawtimber (Adams and Ek, 1974; Kaya and Buongiorno, 1989), balanced stands were not required to have a minimum large-sawtimber component. The diameter distribution (4 cm classes) also had to have a descending trend to compensate for expected mortality, with no major irregularities that could lead to fluctuating yields. For objectivity and repeatability, we set numerical criteria for basal area allocation among size classes. Two different classifications of curve shape were conducted, with the first or traditional approach including trees of all crown classes. The diameter range was divided into five equal intervals or quintiles. A balanced diameter distribution was defined as having  $>3\%$  of the stand basal area in the 1st

quintile,  $<67\%$  in two adjacent central quintiles, and  $>12\%$  in the 5th quintile. With these criteria, only fairly smooth reverse-J distributions were accepted as balanced. Stands not meeting criteria for balanced structure were classified as unimodal if the diameter distribution had  $<3\%$  of the stand basal area in the 1st quintile,  $>67\%$  in two adjacent central quintiles, and  $<20\%$  in the 5th quintile. The remaining stands were classified as irregular uneven-aged stands.

The second classification posed more stringent criteria for balanced stands, based on the assumption that a balanced uneven-aged stand should have actual evidence of canopy gaps in various stages of regrowth. With the model of Smith (1962) (Fig. 14.5), in which each cohort has approximately equal growing space, the diameter distribution of the stand should follow a reverse-J curve even if the understory (suppressed) trees are omitted (see actual examples in Lorimer, 1985 and Lorimer and Frelich, 1998). We therefore set up analogous criteria for balanced, irregular, and unimodal curves using aggregate exposed crown area (ECA) to judge dispersion among size classes, but with understory trees omitted. A balanced diameter distribution was defined as having  $>3\%$  ECA in saplings (2.0–10.9 cm dbh),  $<67\%$  ECA in two adjacent central quintiles, and  $>20\%$  ECA in the 5th quintile. Diameter distributions approximating unimodal curves were defined as having  $<2\%$  of ECA in saplings,  $<4\%$  of the ECA in the 1st quintile,  $>67\%$  of ECA in two adjacent central quintiles, and  $<30\%$  of ECA in the 5th quintile. All stands that did not meet criteria for either reverse-J or unimodal curve shapes were classified as irregular. Stands that were classified as balanced by these more stringent criteria were further examined to verify that separate distributions of the most dominant species (sugar maple or hemlock) met the same criteria.

We emphasize that these are modest criteria that can only help identify stands that appear to be sustainable based on current structure and are unlikely to undergo widely fluctuating yields. These criteria cannot demonstrate that any particular stand has reached a true steady state in either species composition or volume production, an issue that would be very difficult to prove and which would require growth and mortality measurements extending over 50–100 years or more.

### 3.2.2. Regression fits to negative exponential and rotated sigmoid models

Using linear regression techniques (Leak, 1996), we evaluated how well diameter distributions from various stands fit both negative exponential and rotated sigmoid curves. In all regressions, the dependent variable was the logarithm of the number of trees in each 5 cm (2 in.) diameter class (including all species and crown classes). Initially, the diameter class midpoint was used as the single explanatory variable in checking the fit of each stand to the negative exponential distribution. The slope coefficient of this regression was used to calculate the least squares estimate of the  $q$ -factor ( $q$  equals the square of the antilog of the slope coefficient). Further regressions were run using various combinations of the diameter class midpoint, the midpoint squared, and the midpoint cubed as explanatory variables. Following Leak (1996), the presence of rotated sigmoid curves was determined by testing for a significant reduction in the sums of squares given the addition of the squared and cubic terms, in conjunction with a difference in sign between the coefficients of the two terms.

### 3.2.3. Estimation of growing space allocation

We defined growing space allocation in line with the traditional concept (Smith, 1962; Nyland, 1996) to be the aggregate two-dimensional crown area occupied by each class of trees. Crown area, however, was calculated and analyzed in three alternative ways: (1) total crown projection area (as in Seymour and Kenefic, 1998); (2) total crown projection area for trees with fully or partially exposed crowns only; and (3) projection area of only the exposed portions of tree crowns (as in Smith, 1962, p. 472). Although the equal area allocation hypothesis is usually defined in reference to age cohorts, we analyzed area allocation in reference to equal diameter classes to make the analysis more comparable to the diameter frequency distributions and because stand management decisions are normally made on the basis of diameter rather than age classes. Given that diameter-age correlations in northern hardwoods are usually close to being linear (Frothingham, 1915; Tubbs, 1977a; Singer and Lorimer, 1997; Lorimer and Frelich, 1998), it is likely but not certain that similar conclusions would apply to allocation among age classes.

Distributions of aggregate total or exposed crown area for each dbh class were developed from direct measurements of exposed crown radii in the  $10 \times 100$  m center transect of all plots (1513 trees), and total crown radii in the intensively sampled 12 stand subset (1358 trees). Regression equations used to estimate total and exposed crown area from tree diameter, species, and crown class are listed in Table 2. Equations for sugar maple were used for other minor species for which a separate equation is not listed.

These regression equations were also used to generate an estimate of growing space allocation under the Arbogast (1957) guidelines for balanced stand structure. The proportions of trees with exposed crowns in each 2.5 cm dbh class of the Arbogast distribution were assumed to be the same as those observed in our 15 selection study stands. Regression estimates of exposed and total crown area per tree for each diameter class were calculated using the diameter class midpoint in the equations. Aggregate crown area estimates across the size range were then calculated from the density estimates for the number of canopy and understory trees in each size class and from the estimates of crown area per tree.

## 4. Results

### 4.1. Frequency of stands meeting balanced diameter distribution criteria

Frequency of stands meeting criteria for balanced uneven-aged structure was substantially affected by whether diameter distributions were plotted for all crown classes combined (traditional approach) or whether the distributions included only trees with crowns exposed to skylight (i.e., only those trees that would be visible from a low-altitude aerial photo). All 10 old-growth stands met the traditional criteria for balanced structure. Only half of them met the more stringent criteria that included evidence of substantial gap sapling recruitment, which requires reverse-J diameter distributions for trees with exposed crowns. The outcome, however, differed in northern hardwood and hemlock-hardwood stands. Most of the old-growth northern hardwood stands, but none of the hemlock-hardwood stands, met the more stringent

Table 2

Regression equations used in estimation of total and exposed crown area. Prior to ln transformation, TCA and ECA values were increased by 1.0 to avoid negative values in small trees for these dependent variables

Eq. No.	Dependent variable	Equation <sup>a</sup>	R <sup>2</sup>	MSE	p	n
	<i>Total crown area</i>		0.83	0.14	<0.001	1165
[1]	Sugar maple	$\ln(\text{TCA}+1) = -0.975 + 1.336 \ln(D) + 1.438(cc_1) + 1.527(cc_2) + 1.781(cc_3) + 1.516(cc_4) - 0.342 \ln(D) \times (cc_1) - 0.443 \ln(D) \times (cc_2) - 0.551 \ln(D) \times (cc_3) - 0.472 \ln(D) \times (cc_4)$				
[2]	E. Hemlock	$\ln(\text{TCA}+1) = 0.861 + 0.786 \ln(D)$	0.53	0.18	<0.001	60
[3]	Yellow birch	$\ln(\text{TCA}+1) = 0.233 + 0.982 \ln(D)$	0.79	0.22	<0.001	34
[4]	Basswood	$\ln(\text{TCA}+1) = 0.686 + 0.799 \ln(D)$	0.81	0.16	<0.001	11
[5]	White ash	$\ln(\text{TCA}+1) = -1.830 + 1.544 \ln(D)$	0.79	0.19	<0.001	10
[6]	Other conifer	$\ln(\text{TCA}+1) = 0.319 + 0.774 \ln(D)$	0.84	0.07	<0.001	9
	<i>Exposed crown area</i>					
[7]	Sugar maple	$\ln(\text{ECA}+1) = -1.028 + 1.266 \ln(D) + 0.952(cc_2) + 0.326(cc_6) - 0.581 \ln(D) \times (cc_2) - 0.199 \ln(D) \times (cc_4)$	0.77	0.31	<0.001	1215
[8]	E. Hemlock	$\ln(\text{ECA}+1) = 0.577 + 0.666 \ln(D) - 0.237 \ln(D) \times (cc_4)$	0.34	0.64	<0.001	104
[9]	Yellow birch	$\ln(\text{ECA}+1) = -1.068 + 1.267 \ln(D) - 0.510(cc_4)$	0.79	0.40	<0.001	70
[10]	Basswood	$\ln(\text{ECA}+1) = -2.344 + 1.478 \ln(D)$	0.76	0.24	<0.001	58
[11]	White ash	$\ln(\text{ECA}+1) = -3.589 + 2.017 \ln(D) + 3.363(cc_2) + 14.702(cc_4) - 1.120 \ln(D) \times (cc_2) - 5.656 \ln(D) \times (cc_4)$	0.78	0.32	<0.001	58
[12]	Other conifer	$\ln(\text{ECA}+1) = -7.061 + 2.681 \ln(D)$	0.68	0.41	0.012	8

<sup>a</sup>Variables: TCA = total crown projection area (m<sup>2</sup>); D = stem diameter (cm) at breast height (1.4 m); ECA = exposed crown area; cc<sub>i</sub> = dummy variables for various crown classes (1 – understory sapling; 2 – gap sapling; 3 – overtopped; 4 – intermediate; 5 – codominant; 6 – dominant); Dummy variable cc<sub>i</sub> = 1 for trees that are crown class *i*; otherwise cc<sub>i</sub> = 0.

Table 3

Number of individual stands meeting different criteria for balanced structure and the number of stands with diameter distributions fitting negative exponential and rotated sigmoid models

	Northern hardwood			Hemlock-hardwood	
	Old-growth	Selection	Even-aged	Old-growth	Selection
No. of stands sampled	6	10	6	4	5
<i>Number of stands classified as 'balanced'</i>					
Traditional approach (all crown classes)	6	7	2	4	4
Exposed crowns only	5	4	0	0	0
<i>Number of stands fitting different models</i>					
All species combined					
Rotated sigmoid	6	5		1	3
Negative exponential (or other)	0	5		3	2
Sugar maple only					
Rotated sigmoid	6	2		2	3
Negative exponential (or other)	0	8		2	2
Stands changing classification (sugar maple only vs. all species pooled)	0	3		1	2

criteria for balanced structure (Table 3). Gap saplings in old-growth hemlock-hardwood stands occupied only 1.1% of the aggregate exposed crown area of the stand, much lower than levels of gap sapling occupancy of 6.5% in old-growth northern hardwoods. When suppressed trees were omitted, the diameter distributions of the old-growth northern hardwood stands largely retained the reverse-J curve form (as in Fig. 1(a)), whereas those in the hemlock-hardwood stands became either flat (as in Fig. 1(b)) or broadly unimodal.

Among the 15 managed uneven-aged stands, 70–80% met traditional criteria for balanced structure, with the rest classified as irregular or unimodal (Table 3). Inclusion of criteria for gap sapling recruitment again reduced the proportion of stands qualifying as balanced, in this case to 40% for northern hardwood stands and 0% for hemlock-hardwood stands. Diameter distributions for trees with exposed crowns were highly variable in form. Of the 15 selection stands, eight had smooth or irregular descending curves and seven were either strictly unimodal or largely unimodal with gap saplings restricted to the smallest (2–6 cm) diameter class (as in Fig. 1(c)).

The group of even-aged stands had highly variable curve shapes when all crown classes were included in the diameter distributions, with a third having fairly

smooth reverse-J curves which met the criteria for balanced stand structure (as in Fig. 1(f)), a third having irregular reverse-J curves, and a third having unimodal distributions (as in Fig. 1(e)). The effect of imposing minimum gap sapling criteria had the most dramatic effect on the even-aged stands, with all six stands being 'transformed' into fairly symmetric, unimodal curves after the suppressed trees were omitted (Fig. 1(e) and (f)). Gap saplings occupied only 0.8% of the aggregate exposed crown area in the even-aged stands.

#### 4.2. Comparisons of actual stand structure with management targets

Fig. 2 shows how the distribution of basal area among five broad size groupings (sapling, pole, small, medium, and large sawtimber) compare with the balanced stand-structure guidelines of Arbogast (1957). We classified a stand as failing to meet the management target if the existing basal area in any size category was in deficit by more than 3 m<sup>2</sup>/ha. For the stands managed by the selection system, the conclusion was similar to that reached in the traditional analysis of diameter distribution shape—that 70% of the northern hardwood stands and 80% of the hemlock-hardwood stands closely approached the Arbogast guidelines. The stands failing to meet the

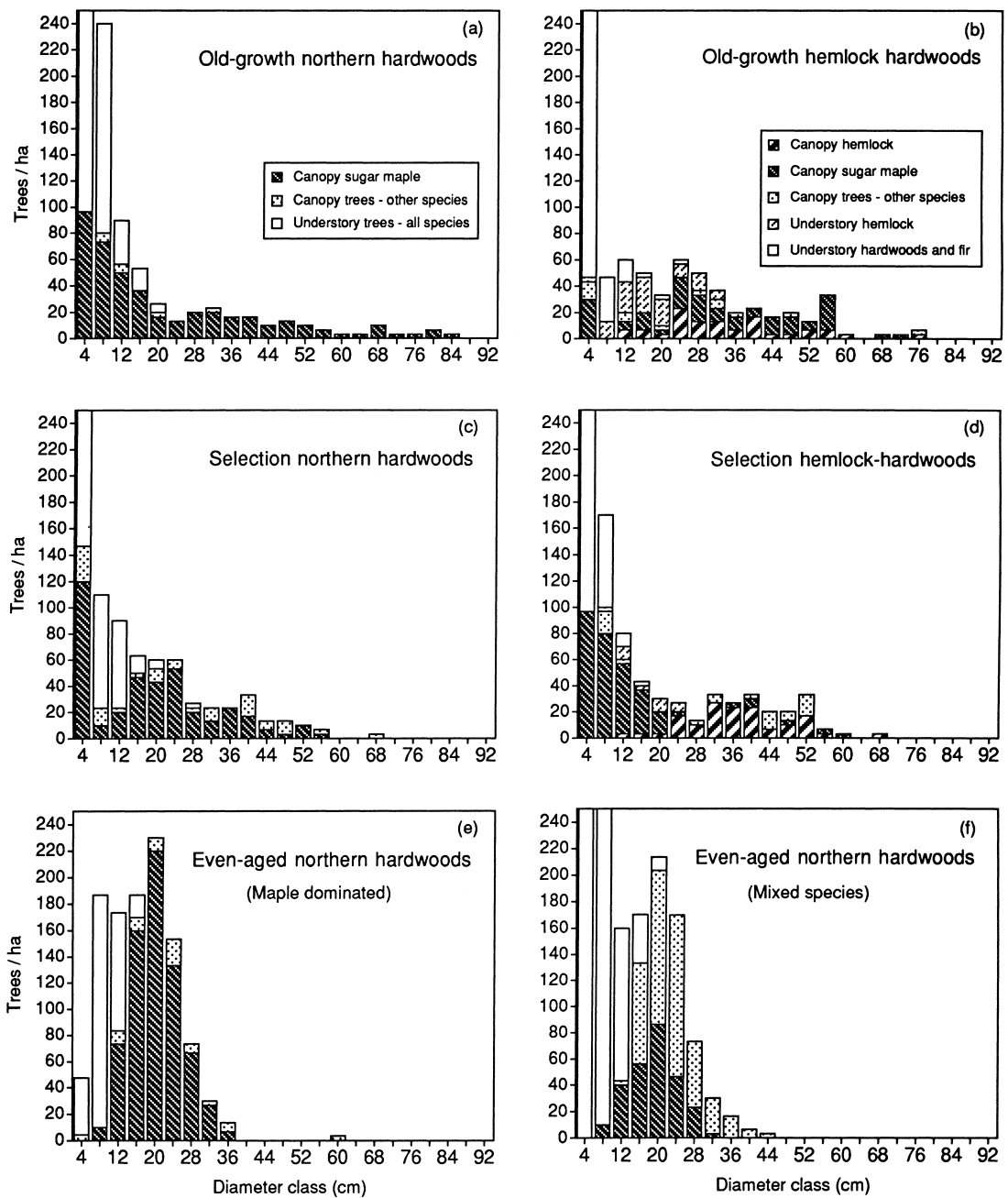


Fig. 1. Representative diameter distributions from individual old-growth, selection, and even-aged stands displaying trees with exposed crowns (canopy) separately from understory trees. The ‘canopy’ category includes gap saplings. In this and other figures, diameter class midpoints are shown. Note that bar patterns in (a), (c), (e), and (f) follow the northern hardwood legend displayed in (a).

guidelines were those which had highly irregular or unimodal diameter distributions. When pooled as a group, the northern hardwood and hemlock-hardwood

stands came very close to the Arbogast targets, suggesting that aggregate stand structure at the landscape level is well regulated.

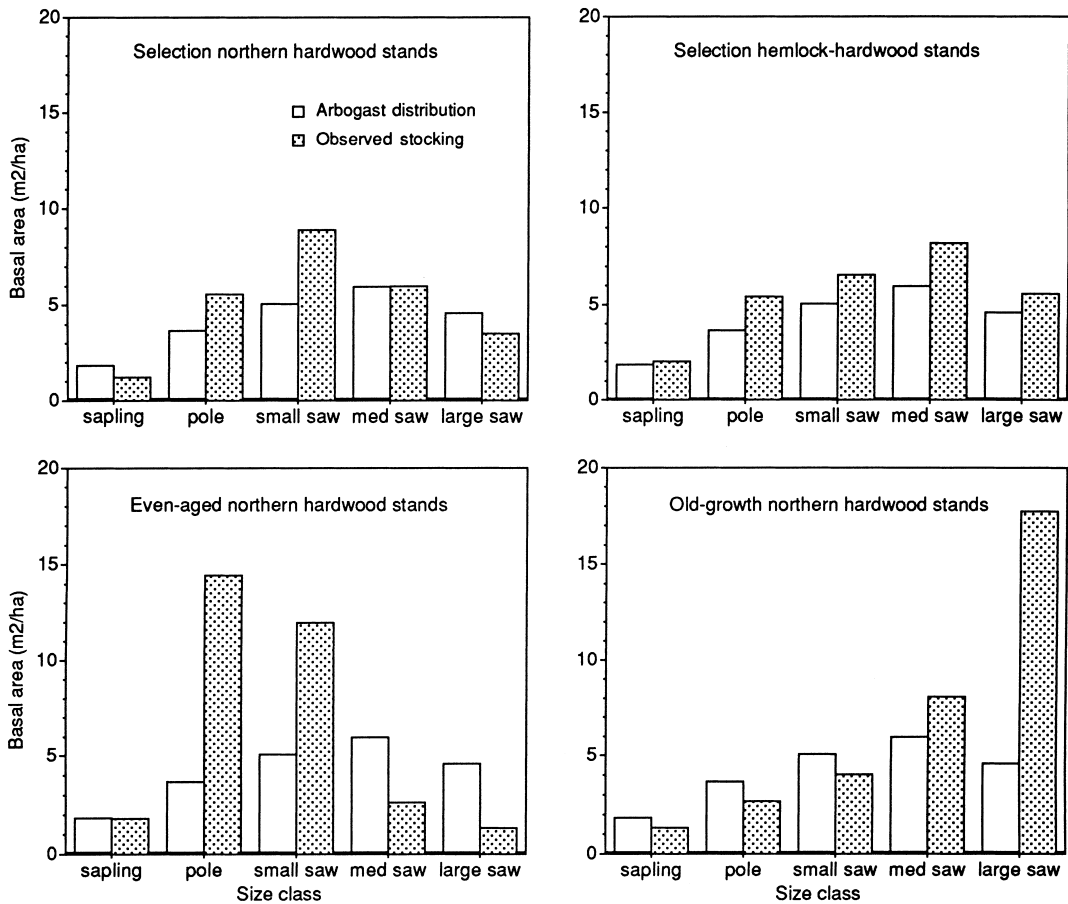


Fig. 2. Distributions of basal area stocking among five broad size classes for stands of different management histories, compared to the Arbogast (1957) guidelines for 'balanced' stand structure in managed uneven-aged northern hardwoods. All species and crown classes are combined, and each graph shows pooled data for all stands in that management history category. Size class boundaries are 4.5–11.4 cm dbh for saplings, 11.4–24.1 cm dbh for poles, 24.1–36.8 cm dbh for small sawtimber, 36.8–49.5 cm dbh for medium sawtimber, and >49.5 cm dbh for large sawtimber.

Even-aged stands, as might be expected, deviated substantially from the Arbogast guide in having large excesses of basal area in the pole and small sawtimber classes, and substantial deficiencies in the medium and large sawtimber (Fig. 2). The sapling class is close to the Arbogast target, although as pointed out previously, nearly all of these saplings are suppressed beneath the main canopy rather than growing in gaps.

Old-growth stands, on the other hand, had a large excess of basal area in large-diameter trees relative to the Arbogast guidelines, and slight deficits in saplings, poles, and small sawtimber.

#### 4.3. Quantitative diameter distribution models

When plotted on semilogarithmic axes, diameter distributions in old-growth northern hardwood stands were predominantly rotated sigmoid in form (Fig. 3). As shown in Table 4,  $q$ -ratios for the aggregate stand data had a very high value of 6.1 in the 5–10 cm dbh class, decreasing to about 1.1 in the middle of the distribution, and increasing to a mean of 1.3 in the classes >50 cm dbh. The old-growth hemlock-hardwood stands showed similar but weaker trends, with  $q$ -ratios of aggregate data progressing from a high of 3.1

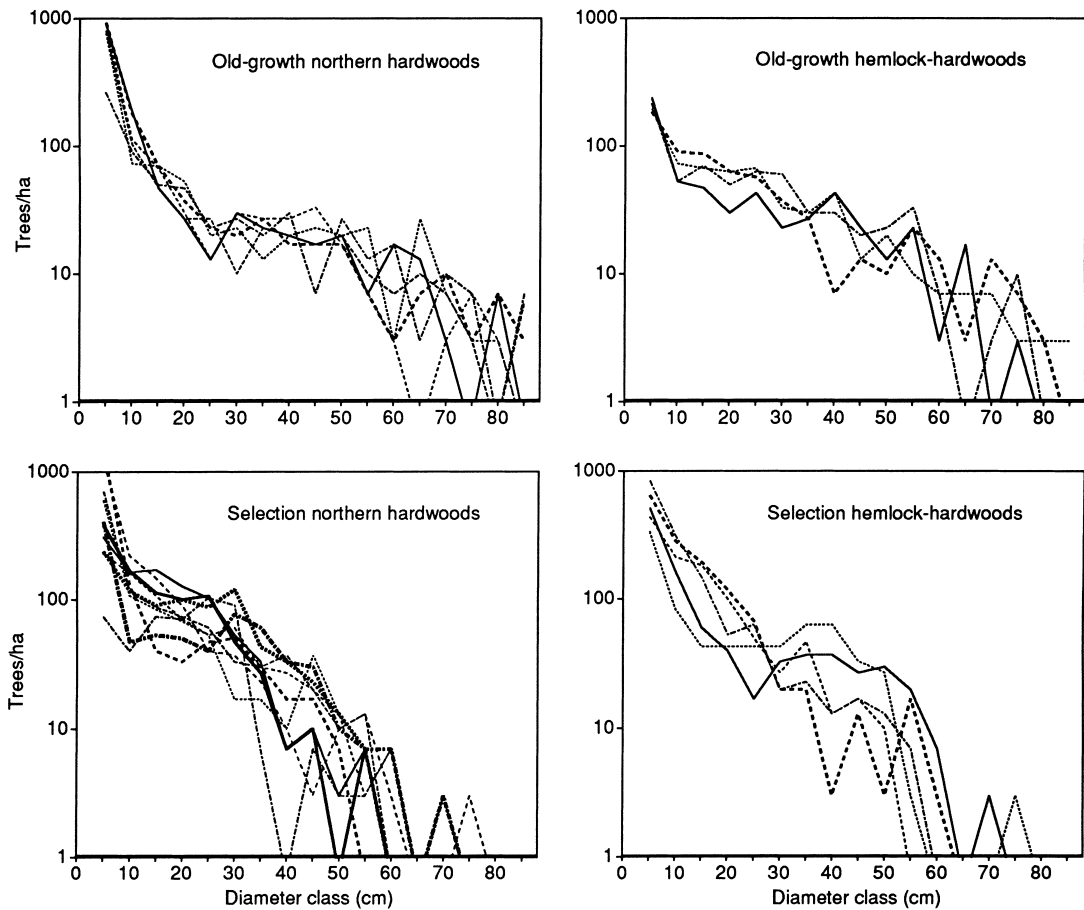


Fig. 3. Diameter distributions (all species combined) from individual old-growth and selection stands plotted on semi-logarithmic axes to show the variation in curve shapes.

in the 5–10 cm class to low mean values of 1.1 in the 10–50 cm class, rising to an intermediate mean value of 1.7 in the classes >55 cm dbh. Diameter distributions in selection stands were similar but more compressed, again with higher  $q$ -ratios near the ends of the distribution and lower ones near the middle (Table 4).

Analysis of individual stands, however, revealed substantial variation in the form of total-species diameter distributions among both the old-growth and selection stands. When the statistical criteria of Leak (1996) were applied, approximately one-third (nine of 25 stands) were significantly sigmoid in form. In the remaining stands, the addition of the  $\text{dbh}^2$  and  $\text{dbh}^3$  terms to the regression did not result in a significant reduction in sum of squares for error, suggesting insufficient evidence to reject the null hypothesis of

a straight-line (negative exponential) fit. Because Leak's (1996) statistical criteria do not take the pattern of residuals directly into account, however, four old-growth and two selection stands were classified as negative exponential even though they had clear rotated sigmoid tendencies, with slopes for the middle size classes (25–50 cm dbh) not significantly different from zero in all six cases. When these six stands were reclassified as rotated sigmoid distributions, the revised classification resulted in 70% of the old-growth stands with rotated sigmoid curves (including all six northern hardwood stands), and about half of the selection stands with rotated sigmoid curves (Table 3).

The diameter distributions of sugar maple, which had the highest fraction of stand basal area in most of

Table 4  
Estimates of individual q-ratios between successive 5 cm diameter classes for both old-growth and selection stands of each forest type

DBH class (cm)	Northern hardwood						Hemlock-hardwood					
	Old-growth			Selection			Old-growth			Selection		
	q-ratio <sup>a</sup> (mean)	SE	q-ratio <sup>b</sup> (aggregate)	q-ratio (mean)	SE	q-ratio (aggregate)	q-ratio (mean)	SE	q-ratio (aggregate)	q-ratio (mean)	SE	q-ratio (aggregate)
5–10	6.52	(±1.11)	6.12	4.35	(±0.91)	4.08	3.28	(±0.56)	3.06	2.84	(±0.35)	2.63
10–15	2.22	(±0.41)	2.13	1.40	(±0.23)	1.31	1.01	(±0.09)	1.00	1.88	(±0.27)	1.68
15–20	1.67	(±0.17)	1.59	1.23	(±0.07)	1.24	1.34	(±0.11)	1.31	1.75	(±0.29)	1.77
20–25	1.91	(±0.23)	1.83	1.20	(±0.14)	1.13	0.89	(±0.09)	0.90	1.60	(±0.30)	1.47
25–30	1.08	(±0.34)	0.86	1.45	(±0.26)	1.19	1.61	(±0.21)	1.50	1.98	(±0.57)	1.67
30–35	1.11	(±0.19)	1.05	2.82	(±1.20)	1.94	1.34	(±0.24)	1.35	0.80	(±0.08)	0.75
35–40	1.04	(±0.14)	1.00	2.65	(±0.61)	1.66	1.58	(±0.81)	0.92	2.65	(±0.95)	1.46
40–45	1.59	(±0.59)	1.18	1.15	(±0.26)	1.03	1.78	(±0.57)	1.76	1.03	(±0.28)	1.22
45–50	1.01	(±0.23)	0.94	2.78	(±0.74)	2.08	1.15	(±0.24)	1.05	1.81	(±0.56)	1.28
50–55	2.14	(±0.30)	1.80	1.97	(±0.66)	1.25	0.93	(±0.36)	0.74	4.34	(±1.95)	1.75
55–60	2.28	(±0.98)	1.33	1.50	(±0.53)	2.03	3.81	(±1.33)	3.00	4.00	(±0.63)	2.86
60–65	1.81	(±0.79)	0.82				2.97	(±1.48)	1.08			
65–70	1.80	(±0.72)	1.53				1.64	(±1.13)	1.19			

<sup>a</sup>The mean q-ratio for that size class among all individual stands.

<sup>b</sup>The q-ratio for that size class when data from all stands in that management history group are pooled.

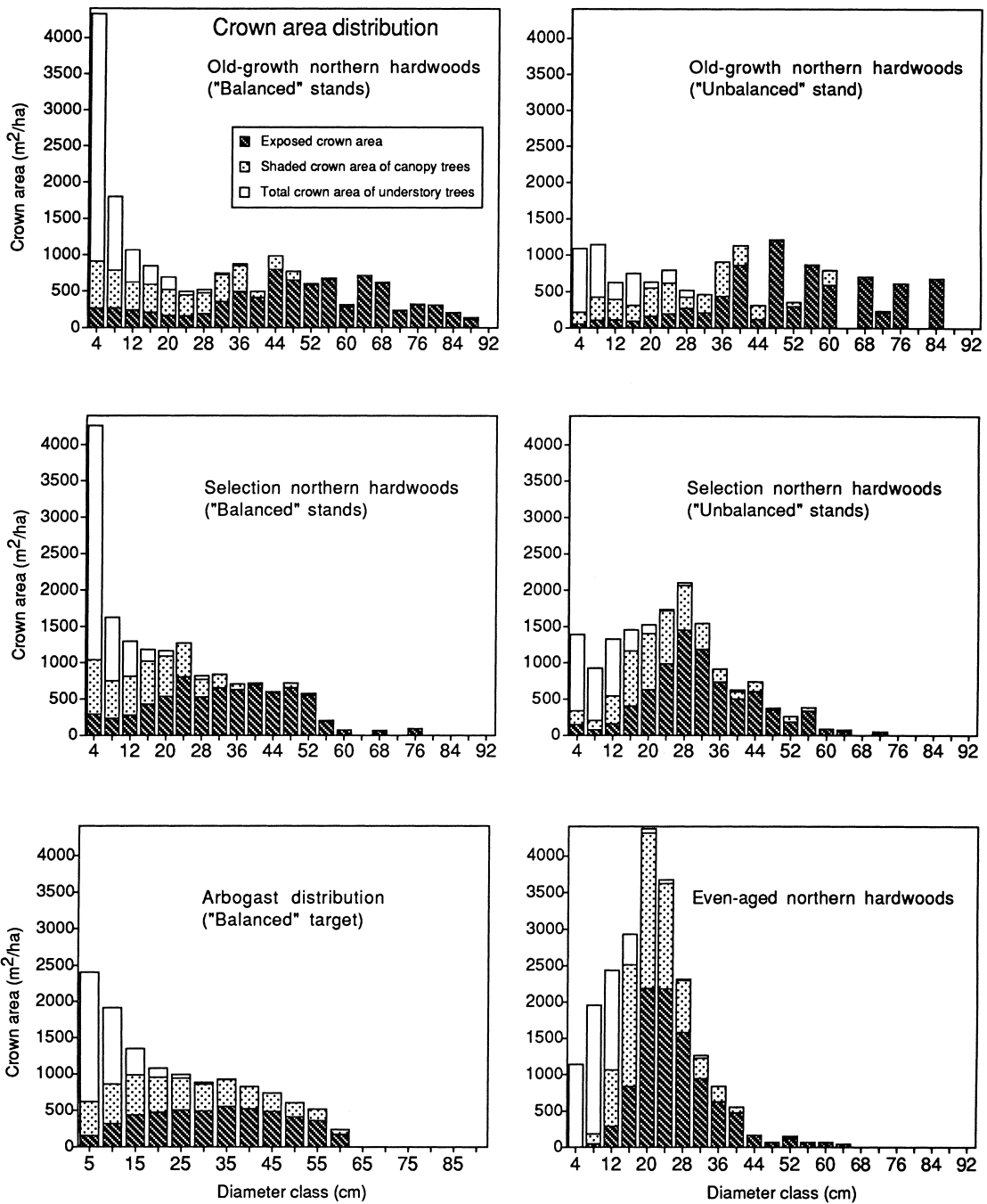


Fig. 4. Crown area distributions for both 'balanced' and 'unbalanced' stands showing the allocation of growing space among size classes in terms of the aggregate amount of exposed and total crown area in each diameter class. Each graph shows pooled data for all stands in that management history category, and all species are combined. The 'canopy' category includes gap saplings.

the stands, were often different from the diameter distributions of all species combined. Applying the same criteria of Leak (1996) to sugar maple in all 25 old-growth and selection stands resulted in six stands changing classification between rotated sigmoid and negative exponential. In four of these cases, the distribution was negative exponential for sugar maple alone but rotated sigmoid for all species combined, while for two stands the distribution was rotated sigmoid for sugar maple and negative exponential for all species combined. The net result was 13 stands with a rotated sigmoid population of sugar maple and 12 stands with a negative exponential population of sugar maple. The hemlock-hardwood stands followed a similar pattern to the entire group, with approximately equal number of stands in each category. But for northern hardwoods, all of the old-growth stands were still rotated sigmoid, while 80% of the selection stands were now negative exponential (Table 3).

#### 4.4. Allocation of growing space among size classes

Histograms of aggregate exposed crown area in each dbh class indicate that none of the stands in the different management history categories had evidence of equal allocation of growing space among size classes, if growing space is defined to be two-dimensional and non-overlapping (Fig. 4). That is, if the aggregate crown projection area that would be visible in a low-altitude aerial photo, analogous to the 'cone diagram' of Smith (1962) (p. 485), is plotted by dbh class, the resulting distributions differ substantially from a uniform distribution. Even among stands recognized as balanced based on presence of a reverse-J curve and meeting the more stringent criteria of exposed crown area distribution among quintiles (including our regression-generated reconstruction of crown area in the Arbogast distribution), lower amounts of exposed crown area are present in the smaller size classes (<36 cm dbh in old-growth stands and <24 cm dbh in selection stands). Histograms of total crown area for all crown classes, including suppressed understory trees, have an irregular descending distribution, with larger amounts of crown area in the smaller size classes.

However, when *total* crown area is plotted by size class for all trees having fully or partially exposed crowns (indicated by both types of stippling in Fig. 4),

the resulting histograms for stands previously recognized as balanced are close to a uniform distribution over a rather broad range of size classes (from 2–70 cm dbh in old-growth northern hardwoods and from 2–54 cm in the selection northern hardwoods). The latter distributions show aggregate total crown area for all trees with at least partially exposed crowns, but include the portions of the crowns that would not be visible in a low-altitude aerial photo because of crown overlap. Data for individual old-growth stands followed the same trends as in the aggregate stand data shown in Fig. 4. Individual selection stands, however, tended to have bimodal distributions, and the relatively uniform distribution shown in Fig. 4 is a result of irregularities being smoothed out when the data are pooled.

## 5. Discussion

### 5.1. Criteria for balanced diameter distributions

In the group of 31 stands investigated in this study, all of the old-growth stands and 70–80% of the stands managed by the selection system met our 'traditional criteria' for balanced structure, based on presence of a reverse-J curve form, residual stand basal area greater than the specified threshold, absence of major irregularities in the distribution, and minimum allocation of basal area among each of the quintiles of the distribution. However, the traditional approach based on analysis of all species and all crown classes pooled (as in Meyer and Stevenson, 1943) may give an overly optimistic assessment of the degree to which stands have achieved a balanced structure. While guidelines such as those of Arbogast (1957) implicitly assume the presence of canopy gaps in different stages of regrowth as a result of past harvests, such features are not explicitly taken into account. When we explicitly included such requirements, as assessed by a reverse-J diameter distribution for trees with exposed crowns, the frequency of balanced stands dropped to 50% of old-growth stands and 27% of managed uneven-aged stands.

The pitfalls of interpreting pooled-species diameter distributions have been more commonly recognized. In the case of mixed-species stands, the size distribution of each component species must of course be

examined separately to determine if there is evidence that the population of each species is being sustained. By these criteria, none of the hemlock-hardwood stands in our study could be considered currently balanced or sustainable since hemlock shows little or no recruitment of saplings and small poles.

Several authors have also noted how pooled size distributions of different species in an even-aged stand can be combined to give a misleading impression of an uneven-aged stand, because the total-species distribution in such cases often approaches a reverse-J curve (Hough, 1932; Oliver, 1978; Muller, 1982). Less commonly recognized is the tendency for some individual species in even-aged stands to have reverse-J diameter distributions as well. In our case, the size distributions of sugar maple in a third of the even-aged stands were reverse-J in form and met our quantified 'traditional' criteria for balanced uneven-aged stands. As in the earlier study of Lorimer and Krug (1983), we found that these cases were stands that had mixed-species overstories with a substantial proportion of midtolerant tree species such as basswood (*Tilia americana* L.) and white ash (*Fraxinus americana* L.). Size distributions of even-aged stands with canopies heavily dominated by sugar maple, on the other hand, were strongly unimodal in form (cf. Fig. 1(e) and (f)).

These variations in the structure of even-aged stands may be related to greater light transmission through crowns of midtolerant species, as demonstrated by Horn (1971) and Canham et al. (1994) using canopy photography. Beneath even-aged, maple-dominated canopies, attrition of large understory saplings of sugar maple is likely to be high because of low understory light intensities. Dahir (1994), for example, found 11-year mortality rates of sugar maple and hemlock saplings in excess of 40%, even in old-growth forests with frequent gap formation. We hypothesize that the higher understory light intensities under mixed canopies with midtolerant species allow larger numbers of sugar maple saplings to survive and 'accumulate' in the understory, creating a steep left 'tail' in the size distribution (Fig. 1(f)). The high attrition rate of understory saplings beneath maple-dominated canopies results in limited numbers of survivors at any one time (Fig. 1(e)) and trims the left tail of the distribution, keeping it more symmetric.

We suggest that diameter distributions which differentiate between suppressed understory trees and gap saplings, and plotted for individual species, can give a more realistic portrayal of the degree to which a stand has approached a balanced uneven-aged structure and avoid many of the complications discussed above. In the case of the even-aged stands, for example, all of the interpretive difficulties were resolved by plotting the diameter distribution of sugar maple with suppressed trees omitted (Fig. 1(e) and (f)). The resulting strongly unimodal curves are then easily distinguished from the reverse-J curves obtained by applying the same criteria to balanced, uneven-aged stands (Fig. 1(a)–(d)).

Since the diameter distributions of some even-aged stands meet traditional criteria of balanced stands (and in fact closely resemble size distributions in industrial uneven-aged stands with a 45 cm maximum diameter), it is reasonable to question whether gap recruitment should be a criterion of sustainability. Stands such as those in Fig. 1(f) could perhaps be managed as if they were already uneven-aged even if they are not, and gap structure would gradually develop anyway as harvests are made. Such a point may be valid from a strictly population perspective. However, as Erdmann (1986) has noted, the over-topped saplings in even-aged stands have led a 'hard life,' spending many decades under a marginal energy budget. As a result, they are often poorly formed, have broken tops, internal stem decay, and numerous dormant epicormic buds. Erdmann (1986) estimated that only 2% of the understory trees in even-aged northern hardwood stands had the potential to become grade-1 crop trees, using the criteria of Boyce and Carpenter (1968). For this reason, Erdmann suggested that uneven-aged management of even-aged stands should involve a 'conversion' process, in which large understory trees are removed and canopy gaps created to stimulate better quality regeneration.

## 5.2. Quantitative models of balanced diameter distributions

Previous investigators have reached differing conclusions on whether equilibrium population structure of shade-tolerant hardwood species is better described by negative exponential or rotated sigmoid distributions (Goff and West, 1975; Muller, 1982; Lorimer and

Frelich, 1984; Leak, 1996). These studies are not always directly comparable, however, because of differing methodology. Studies have differed in the size (and perhaps heterogeneity) of the study sites, whether species are plotted individually or pooled, and whether complete or truncated distributions are presented. As suggested by our findings in this study, any of these features can change the outcome.

Even when complete diameter distributions of individual species are examined on fairly small and homogeneous tracts, the distributions may be either negative exponential (Muller, 1982), rotated sigmoid (Lorimer and Frelich, 1984), or both (this study). As Leak (1996) has suggested, there may be a variety of equilibrium or sustainable population structures depending on species and site. It may also be the case that few or none of the stands that have been examined in this and previous studies are close enough to a true steady state to allow reliable inferences about equilibrium structure based on field data. The main relevance to timber management, aside from interpretation of underlying population dynamics, is whether fairly abrupt changes in the slope of the distribution in the pole and medium sawtimber classes are to be interpreted as normal features of a balanced stand (rotated sigmoid model) or whether they signal the presence of deficit and surplus classes (negative exponential model).

In this study, all of the old-growth northern hardwood stands had rotated sigmoid diameter distributions for all species pooled and for sugar maple only. The structure of these stands makes biological sense in light of mortality trends observed on similar tracts. Based on 11-year permanent plot records in old-growth stands, Dahir (1994) found a U-shaped mortality-size trend, with highest mortality in small and large trees. However, mortality rates were nearly constant over a fairly broad range from 18–66 cm dbh. Simulations of steady-state conditions verified that rotated sigmoid distributions would develop for sugar maple under this type of mortality function (Lorimer and Frelich, 1984). In both simulated as well as observed diameter distributions, however, it is probably not coincidental that distributions of log number of trees vs. dbh are close to a straight line or negative exponential fit between the limits of 15–70 cm dbh (see also Leak, 1996).

Negative exponential distributions were also observed among balanced stands in this study, but only among the managed uneven-aged stands. It is not known to what extent the pattern of cutting and gap creation alters growth and mortality trends relative to that in an old-growth forest and whether it represents a different equilibrium regime. However, the selection stands can be viewed as a kind of ‘forced equilibrium’, since repeated cutting across the range of size classes is needed to maintain the target structure and prevent a ‘demographic bulge’ that would develop if cutting were to cease or to be confined to the largest classes (Roach, 1974; Leak, 1996).

### 5.3. *The equal area allocation hypothesis*

Our analysis of old-growth and managed stands with reasonably smooth reverse-J diameter distributions provides support for a modified interpretation of the equal area allocation hypothesis. While the aggregate exposed crown area occupied by each size class tends to be lower for small trees than for medium and large trees, total crown area distribution for trees with partially or fully exposed crowns does approximate a nearly uniform distribution. The difference is probably attributable in part to lateral crown expansion of gap border trees into the canopy gaps, a phenomenon described in various studies of gap dynamics (Trimble and Tryon, 1966; Hibbs, 1982; Runkle and Yetter, 1987). In fact, Smith (1962) (p. 472) already anticipated that lateral crown expansion of border trees would reduce the canopy space occupied by saplings and small poles even in a perfectly regulated stand, and so it is reasonable to regard our findings as support for Smith’s (1962) interpretation of the equal area allocation hypothesis.

Another likely factor in influencing the form of the exposed crown area distribution of balanced stands that has not received much attention is the size and age distribution of trees within individual canopy gaps. In his simplified textbook presentation of the equal area hypothesis, Smith (1962) describes each gap as becoming occupied by a new even-aged cohort of seedlings with a bell-shaped size distribution. Our observations in both managed and old-growth stands, however, suggest that frequently a canopy gap becomes occupied by a highly heterogeneous assemblage of advance regeneration of different heights and

ages. A study in old-growth hemlock-hardwoods showed that the tallest gap ‘saplings’ shortly after gap formation, and the ones presumably most likely to capture the gap, were formerly overtopped trees already averaging 60% of mean canopy height and averaging from 65–149 years of age (Dahir and Lorimer, 1996). This process would tend to allocate more growing space to large saplings and small poles at the expense of seedlings and small saplings. Because of the frequently poor stem quality of overtopped trees, however, many foresters in Wisconsin have adopted a policy of cutting existing large saplings in gaps in order to favor smaller and more vigorous regeneration. Such a policy would be expected to shift the growing space allocation in managed stands more in the direction of the equal allocation described by Smith (1962).

The divergence between our findings and those of O’Hara (1996), who found no evidence for equal growing space allocation in multi-aged ponderosa pine, may be related in part to differences in population structure between very shade-tolerant species in a humid region and intolerant species in a drier climate. O’Hara’s (1996) use of leaf area index as a measure of growing space occupancy is also likely to lead to different conclusions, since a cohort of large trees will have a higher leaf area index than a cohort of smaller trees, even if they occupy the same amount of ground area. We agree with O’Hara (1996) that other distributions beside the negative exponential or equal growing space allocation among cohorts may be sustainable and perhaps more productive, and that it may be possible to allocate less growing space to younger cohorts than has been the case in traditional uneven-aged management. However, on our sites, both old-growth and selection stands are often structured in such a way that trees in smaller size classes occupy more total crown projection area than trees in medium or larger classes, even though they are allocated a smaller amount of canopy space in gaps. Thus, whether intentionally planned that way or not, the existing structure of balanced selection stands closely resembles the structure of old-growth stands. The main exception is the reallocation of growing space formerly occupied by trees >60 cm dbh in a more or less uniform manner to the size classes below that threshold.

## Acknowledgements

This project was supported by the Bureau of Forestry, Wisconsin Department of Natural Resources, the Connor Hardwood Research Fund, and the School of Natural Resources, College of Agriculture and Life Sciences, University of Wisconsin-Madison. We gratefully acknowledge the U.S. Forest Service, Wisconsin Land Commission, and Nicolet Hardwoods Corporation for permission to install sample plots. Helpful comments on the manuscript were received from two anonymous reviewers.

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