NRC Research Press

ARTICLE

Dynamics of the diameter distribution after selection cutting in uneven- and even-aged northern hardwood stands: a long-term evaluation

Sarita Bassil, Ralph D. Nyland, Christel C. Kern, and Laura S. Kenefic

Abstract: Selection cutting is defined as a tool for uneven-aged silviculture. Dependence on diameter distribution by forestry practitioners for identifying stand conditions has led to misuse of selection-like cuttings in even-aged northern hardwood stands. Our study used several long-term data sets to investigate the temporal stability in numbers of trees per diameter class in uneven-aged northern hardwood stands treated with single-tree selection and in 45-year-old second-growth stands treated with selection-like cuttings. We analyzed data from New York, Michigan, and Wisconsin to determine changes through time in number of trees across 2.5 cm diameter classes, shifts in the shape and scale of the three-parameter Weibull function used to describe the diameter distributions, and dynamics of associated stand attributes. Findings showed that single-tree selection cutting created and sustained stable diameter distributions and uniformity of conditions through consecutive entries in uneven-aged stands. By contrast, these characteristics varied through time in the second-growth stands that had been treated with selection-like cuttings. Analysis also showed that the Weibull shape and scale parameters for stands under selection system migrated towards those of the recommended target diameter distribution in the uneven-aged stands. These parameters diverged from the target with repeated use of selection-like cuttings in the second-growth even-aged stands.

Key words: structural stability, single-tree selection, diameter distribution, northern hardwood stands, long-term study.

Résumé : La coupe de jardinage est considérée comme un outil de la sylviculture inéquienne. L'utilisation de la distribution des diamètres par les praticiens forestiers pour déterminer l'état des peuplements a conduit à une mauvaise application de coupes ressemblant au jardinage dans les peuplements équiennes de feuillus nordiques. Notre étude a utilisé plusieurs jeux de données à long terme pour analyser la stabilité temporelle du nombre d'arbres par classe de diamètre dans des peuplements inéquiennes de feuillus nordiques traités par jardinage par pied d'arbre, ainsi que dans des peuplements de seconde venue âgés de 45 ans qui ont été traités à l'aide d'une coupe ressemblant au jardinage. Nous avons analysé des données provenant des états de New York, Michigan et Wisconsin afin de déterminer les changements temporels du nombre d'arbres par classe de diamètre de 2,5 cm, les changements de forme et d'échelle de la fonction de Weibull à trois paramètres utilisée pour décrire la distribution des diamètres, et la dynamique des autres attributs des peuplements. Les résultats ont montré que le jardinage par pied d'arbre créait et maintenait des distributions diamétrales stables et une uniformité des conditions par des entrées consécutives dans les peuplements inéquiennes. Par contre, ces caractéristiques ont varié au fil du temps dans les peuplements de seconde venue traités à l'aide d'une coupe ressemblant au jardinage. L'analyse a également montré que les paramètres de forme et d'échelle de la fonction de Weibull des peuplements jardinés se dirigeaient vers les cibles de distribution diamétrales recommandées pour les peuplements inéquiennes. Ces paramètres ont divergé de la cible à la suite de l'utilisation répétée de coupes ressemblant au jardinage dans les peuplements équiennes de seconde venue. [Traduit par la Rédaction]

Mots-clés : stabilité structurale, jardinage par pied d'arbre, distribution diamétrale, peuplements de feuillus nordiques, étude à long terme.

Introduction

Selection system in the United States

Conceptually, the selection system creates and maintains a consistent diameter distribution, a high degree of vertical structural diversity, and stable stand conditions over space and time. In addition, the selection system improves the quality, vigor, and growth of residual trees and enhances important habitat components and visual qualities within treated stands. When correctly applied within uneven-aged communities, it also provides sustainable yields and consistent revenues at regular time intervals over multiple cutting cycles (Nyland 2016). Further, the selection system ensures continued access to many nonmarket values and other ecosystem services (Guldin 1996).

In northern hardwood forests of the United States (US), early experiments compared growth and mortality among old-growth stands treated with a variety of partial cuttings. Results from the Lake States suggested stocking and diameter distribution goals to sustain high levels of sawtimber production in uneven-aged stands (Eyre and Zillgitt 1953) and a marking guide for the selec-

Received 6 June 2019. Accepted 21 August 2019.

S. Bassil and R.D. Nyland. State University of New York College of Environmental Science and Forestry, 1 Forestry Drive, Syracuse, NY,13210 USA.
C.C. Kern. USDA Forest Service, Northern Research Station, 5985 Highway K, Rhinelander, WI, 54501 USA.
L.S. Kenefic. USDA Forest Service, Northern Research Station, 54 Government Road, Bradley, ME, 04411 USA.
Corresponding author: Sarita Bassil (email: sbassil@syr.edu).

tion system in uneven-aged northern hardwoods (Arbogast 1957). Later, Gilbert and Jensen (1958) and Leak et al. (1969) proposed a similar approach for uneven-aged silviculture in New England. Subsequent research explored the effects from different combinations of residual stand density, maximum tree size, diameter distribution, and length of cutting cycle on structural, compositional, and growth responses of multi-aged northern hardwood stands (Crow et al. 1981; Hansen and Nyland 1987; Orr et al. 1994; Gronewold et al. 2012). All showed the flexibility that managers had for adapting the target diameter distribution and cutting interval to address different management objectives and production goals.

Within former old-growth northern hardwood stands of the upper Lake States managed with a series of selection cuttings, Tubbs (1977) found a close correlation between tree height, diameter, and age. Kenefic and Nyland (1999) also demonstrated a correlation between diameter, height, and age among trees in a northern hardwood stand with a history of selection cutting in New York. In stands such as these, the diameter distribution could serve as a functional surrogate for age and height distributions and could be used to guide uneven-aged silviculture, with the goal of creating a stand structure that remains stable and can be periodically re-established over multiple cutting cycles. That consistency results from sufficient upgrowth of residual trees to compensate for mortality and removals, with periodic recruitment into the smaller size classes (Nyland 2016; Lundqvist 2017). Under those circumstances, a graph of features such as median diameter, tree density, and residual basal area plotted across multiple cutting cycles would show a horizontal sawtooth pattern, demonstrating temporal consistency (Nyland 2016). This has been associated with a reverse-J-shaped diameter distribution in uneven-aged stands (Meyer 1952), especially if the proportion of trees in the different size classes resembles that recommended by Eyre and Zillgitt (1953) (see Hansen and Nyland 1987).

Broadening the options

While much of the early research into northern hardwood silviculture focused on old-growth and other uneven-aged stands, appropriate methods for other conditions remained untested. So, by the mid-20th century, the U.S. Forest Service (hereafter referred to as Forest Service) began exploring silvicultural options for second-growth northern hardwood communities that had regenerated after heavy cutting between the late 19th and early 20th centuries. By definition (Helms 1998), second-growth forests such as these are comprised of relatively young trees that regenerated after a major disturbance. In northern hardwoods, they usually have an important shade-tolerant component with a wide range of diameters. In addition, areas that regenerated after heavy exploitative harvests often included some older unmerchantable residuals with larger diameters. Forest Service studies of the 1950s evaluated cutting strategies similar to the popular uneven-aged guidelines by Eyre and Zillgitt (1953) and Arbogast (1957), but applied in 45-year-old second-growth northern hardwood stands with a simplified age structure but wide range of diameters (Erdmann and Oberg 1973; Strong et al. 1995; Leak and Gove 2008; Kern et al. 2014). They cut across the size classes to maintain a reverse-J-shaped distribution like that recommended by Eyre and Zillgitt (1953) and Arbogast (1957), while also removing a component of large trees to brighten the understory and promote regeneration.

Though age can correlate with tree size in uneven-aged northern hardwoods managed by the selection system (Tubbs 1977; Kenefic and Nyland 1999), small trees of shade-tolerant species in even-aged stands grow slowly and remain alive in subordinate crown positions for decades. That can result in a reverse-J-shaped diameter distribution in which stem density decreases progressively from small to large size classes. However, these stands usually have a low degree of vertical structural diversity, with increasing height to the main canopy layer as the cohort ages (Nyland 2016).

Reports by Assmann (1970) for oaks (*Quercus* spp.) in Europe, Marquis (1991) for Allegheny hardwoods, Clatterbuck (1993) for oaks on the Cumberland Plateau, and Nyland (2016) for other forest community types in the US indicate that growth of intermediate and overtopped trees in single-cohort stands will not increase appreciably after release by cutting. If so, they would not likely move up in size sufficiently to replenish stocking of larger diameter classes as necessary for successful selection system silviculture. Consequently, mistakenly using strategies appropriate to uneven-aged silviculture might lead to unfavorable outcomes with respect to structural and timber production goals for young second-growth stands having a predominant even-aged component. For that reason, we opted to call this "selection-like cutting".

Some research options

For northern hardwoods, most studies relied on relatively short-term remeasurement data to assess structural changes (Leak 1996; Leak and Sendak 2002; Schwartz et al. 2005; Neuendorff et al. 2007; Gronewold et al. 2010). Others used computer simulations that compared responses to different alternatives for management (e.g., Hansen 1987). Many relied on visual approximation of the shape of a curve depicting the number of trees across the diameter classes based on a normal or logarithmic scale (Leak 2002) or on criteria reflecting conceptualized perspectives (Leak 1996; Janowiak et al. 2008). Alternately, more rigorous assessments might use a probability density function such as the two- and three-parameter Weibull function introduced by Bailey and Dell (1973). It is highly flexible, easy to interpret, and involves uncomplicated computations (McGarrigle et al. 2011; Diamantopoulou et al. 2015).

Our objective was to assess long-term changes in the diameter distribution of uneven-aged stands treated with single-tree selection system cutting based on guidelines by Eyre and Zillgitt (1953) and Arbogast (1957) and to compare the findings with changes in 45-year-old second-growth stands treated with selection-like cuttings. We defined stability as a condition in which the stand has sufficient trees at the end of a cutting cycle for managers to recreate the initial diameter distribution by removing surpluses above the target number in any size class (Adams and Ek 1974; Nyland 2016). Our general hypothesis is that correctly applying single-tree selection cuttings in uneven-aged stands results in long-term structural stability, while applying selection-like cutting in young second-growth stands results in temporal instability of the diameter distribution and some associated stand attributes. We explored this through several lines of investigation. Specifically, we expected that forest inventory metrics such as standing basal area, tree density, and median tree size would serve as useful surrogates for stand stability. They should show reasonable uniformity through time in stable stands and vary across time in unstable ones. Further, we expected that the distribution of trees by diameter class through multiple cutting cycles would remain consistent (stable) after selection cuttings and become unstable with selection-like cuttings. Lastly, we expected that parameters of the three-parameter Weibull curve representing the diameter distributions in stands treated with selection cutting would stabilize towards those of the target distribution, whereas ones for second-growth stands treated with selection-like cutting would not.

Materials and methods

Study sites

To address our hypotheses, we used long-term empirical data from two control (uncut) and 29 treated northern hardwood stands at locations in New York, the Upper Peninsula of Michigan, and northern Wisconsin (Table 1). New York data came from the

Table 1. Characteristics of stands used in this study.

Site[a]	No. of stands	No. of sample points or plots by stand	Stand name	Area of stands (ha)	Treatment
Wisconsin					
AEF	1	15	AEF control	3.0	Control
	3	15	ARG60, ARG75, ARG90	3.0, 3.0, 3.0	Selection-like
New York					
CSH	6	6 to 53	E13B, E13C, E13D, H1SQ55, H1SQ70, Secord	5.3, 2.4, 1.2, 2.0, 4.0, 4.0	Single-tree selection
HF	8	11–57	GBMTA2, GBMTA3, GBMTA4, JUNA1, JUNA2, OMR1, OMR2, OMR3	4.0, 4.0, 7.7, 2.0, 2.4, 1.6, 3.6, 7.3	Single-tree selection
Michigan					
DEF	1	1	DEF control	3.6	Control
	2	1	OMD1, OMD2	4.0, 5.3	Single-tree selection
DEFN	10	31 to 42	D3020, D5005, D7005, D9005, D5010, D7010, D7010, D5015, D7015, D9015	12.1 to 18.2	Single-tree selection

[a]Sites: AEF, Argonne Experimental Forest; CSH, Cuyler and Secord Hill State Forests; DEF, Dukes Experimental Forest old study; DEFN, Dukes Experimental Forest new study; HF, Archer and Anna Huntington Wildlife Forest.

silviculture research program at the State University of New York College of Environmental Science and Forestry. Those for Michigan and Wisconsin were from research plots established and maintained by the Forest Service's Northern Research Station.

New York

The New York stands lie on Cuyler Hill and Secord Hill State Forests (CSH) in the Southern Tier and Archer and Anna Huntington Wildlife Forest (HF) in the central Adirondacks. All are uneven-aged and started in a multi-aged condition (Bohn 2005; R.D. Nyland, unpublished data). They have the sugar maple – beech – yellow birch vegetation type (SAF Type 25; Eyre 1980). The dominant species is sugar maple (*Acer saccharum* Marsh.), with varying amounts of American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britt.). Exact composition varies between the Southern Tier and Adirondack sites (Bohn 2001, 2005). All had at least one single-tree selection cutting between 1973 and 1992 and were remeasured at least four times (Table 2). The cuttings followed the strategy and guidelines described in Eyre and Zillgitt (1953) and Arbogast (1957). They left different levels of residual basal area from one stand to another, with numbers of trees across the diameter classes based on the target distribution from the guidelines. Maximum diameters ranged from 51 to 68 cm.

Inventories at irregular time periods included the diameter of trees at breast height (DBH, at 1.37 m) for any with DBH ≥ 2.54 cm and falling within variable-radius plots at the intersections of 30.5 × 30.5 m gridlines at CSH and 40.2 × 40.2 m gridlines at HF. Trees were selected for inclusion in the sample plots using a BAF-10 English prism.

Wisconsin

Wisconsin plots are located on the Argonne Experimental Forest (AEF) in the northern part of the state and are dominated by sugar maple. At the beginning of the Forest Service study, stands consisted of 45-year-old second-growth northern hardwoods that originated after commercial clearcutting in around 1905 (Erdmann and Oberg 1973). Across the diameter distribution, most trees of all sizes had the same age, except for some scattered remnants from past high-grading (Erdmann and Oberg 1973; Strong et al. 1995). Based on these published descriptions, we conclude that these stands were predominantly even-aged. As described by Erdmann and Oberg (1973) and Strong et al. (1995), the experiment evaluated treatments resembling a single-tree selection system as described by Eyre and Zillgitt (1953) and Arbogast (1957) in these second-growth stands. Hereafter, we call them selection-like treatments. They included a 10-year cutting cycle initiated during 1951–1952 (Table 2), following the target diameter distribution recommended by Arbogast (1957) and leaving a specified residual density. We used data from the light (20.7 m²·ha⁻¹ residual basal area stocking, rBA), medium (17.2 m²·ha⁻¹ rBA), and heavy (13.8 m²·ha⁻¹ rBA) cutting treatments. Data came from 0.04 ha circular plots (Table 1) remeasured at 5-year intervals between 1951 and 2006 and included species and diameter for all trees with DBH ≥ 11.5 cm.

Michigan

Michigan stands are located on the Dukes Experimental Forest (DEF) in Michigan's Upper Peninsula. Stands were described as old growth in the early 1900s, with light selective harvesting in the late 19th century that left predominantly sugar maple and varying amounts of yellow birch, American beech, and red maple (*Acer rubrum* L.) (Eyre and Zillgitt 1953; Crow et al. 1981). Trees in the preharvest stands ranged from new germinants to more than 360 years old, with most sawtimber trees being more than 200 years old (Eyre and Neetzel 1937; Tubbs 1977). Data for the present study came from two experiments at DEF. The first, established between 1926 and 1932, included one replication of a reserve (control) unit and nine different treatments as described by Eyre and Zillgitt (1953). We used data from the control unit and two units classified as "Overmature and Defective" (OMD1 and OMD2) in the original experiment. These old-growth uneven-aged stands were treated with single-tree cutting across the diameter classes and left a residual stocking of 12–13 m²·ha⁻¹. Remeasurement data included DBH of trees 5.0 cm and larger, gathered from square 0.4 ha (OMD2) and 0.8 ha (OMD1 and control) permanent sample plots (Table 1) at 5-year intervals until 1966 and reinventoried in 2007 (Table 2). The second experiment (referred to as DEFN hereafter) in 1951 evaluated responses of uneven-aged northern hardwood stands after single-tree selection cutting following guidelines by Arbogast (1957). It left different levels of stocking (6.9, 11.5, 16.1, and 20.7 m²·ha⁻¹ rBA) with 5-, 10-, 15-, or 20-year cutting cycles (Crow et al. 1981). These stands were part of the old-growth forest described above but had a "light improvement cut" in the 1940s. They were considered uneven-aged in 1951 (Crow et al. 1981). We used data for diameter of trees with DBH of 11.5 cm and larger collected from 0.08 ha circular, fixed-area plots (Table 1) at 5-year intervals between 1952 and 1973 (Table 2).

Data management

We reconciled field data from different locations to ensure uniformity of format among plots. Data were then used to develop a stand table for each experimental unit. Because experiments at the New York and Lake States locations used different sampling techniques, we converted all data to unit area values to ensure consistency among stands when fitting the diameter distributions. Following findings by Ducey (2000), we used the exact

Table 2. Treatment details for stands at different sites used in this study.

Site[a]	Stand name	Years treated	Total time (years)
Wisconsin			
AEF	AEF control	—	0, 4, 9, 14, 19, 24, 29, 34, 39, 40, 44, 49, 50, 54
	ARG60, ARG75, ARG90	1952, 1962, 1972, 1982, 1992, 2002	4, 9, 14, 19, 24, 29, 34, 39, 40, 44, 49, 50, 54
New York			
CSH	E13B, E13 C, E13 D	1973, 1994, 2013	0, 6, 11, 15, 18, 21, 28, 32, 36, 43
	H1SQ55	1980	16, 21, 25, 29, 36
	H1SQ70	1980, 2005	17, 19, 21, 25, 36
	Secord	1990	0, 5, 9, 11, 15, 19, 26,
HF	GBMTA2, GBMTA3, GBMTA4	1987	1, 9, 18, 29
	JUNA1, JUNA2	1988	1, 7, 17, 28
	OMR1, OMR2, OMR3	1986	2, 9, 19, 30
Michigan			
DEF	DEF control	—	1, 6,10, 15, 20, 26, 30, 36
	OMD1	1927, 1962, 1986	1, 5, 10, 15, 20, 26, 31, 34, 39, 80
	OMD2	1932, 1952, 1962	1, 5, 10, 15, 20, 24, 30, 34, 75
DEFN	D3020	1952	5, 10, 15, 21
	D5005, D7005, D9005	1952, 1957, 1962, 1967	5, 10, 15, 21
	D5010, D7010, D7010	1952, 1962	5, 10, 15, 21
	D5015, D7015, D9015	1952, 1967	5, 10, 15, 21

Note: Total time represents remeasurement in number of years since the first treatment in treated stands and since the first measurement after the beginning of the experiment in control stands.

[a]Sites: AEF, Argonne Experimental Forest; CSH, Cuyler and Secord Hill State Forests; DEF, Dukes Experimental Forest old study; DEFN, Dukes Experimental Forest new study; HF, Archer and Anna Huntington Wildlife Forest.

diameter instead of diameter class for better accuracy when computing the unit area values.

We composited the data across replicated experiments at AEF, DEF, and DEFN and assessed them by treatment and study site. We used only trees with DBH of 11.5 cm and larger. With the older study at DEF, some plots only had diameters for trees ≥ 24.0 cm during some remeasurements. To supplement this, we used inventories from previous or later years to interpolate missing data. We grouped all trees into 2.5 cm DBH classes with midpoints (e.g., 12.5 for 11.5–14.0 cm) ranging between 12.5 and 70.0 cm. Then, based on a preliminary review of the field measurements, we used a common upper maximum diameter class of ≥70.0 cm to standardize the data.

A remeasurement period was designated in two ways. The first (total time) was the number of years since the first cutting in treated stands and since the first measurement in control stands. The second, for treated stands only, was the number of years after a cutting, with each successive treatment counted as the beginning of a new cutting cycle. Remeasurements occurred at irregular intervals and did not always cover entire cutting cycles. In some cases, an inventory described conditions a few years after cutting or prior to the next one. Other inventories were done at the beginning or end of a cutting cycle (Tables 1 and 2).

Statistical analysis

Forest inventory metrics

With this study, we looked for ways to statistically evaluate stability of the diameter distributions in the stands under the selection system and those cut with selection-like methods, both at any given time and through time. As a first step, we visually described the temporal patterns of basal area, stem density, and median diameter in the treated stands and controls. We also fit linear and quadratic regressions including all remeasurements to represent the variation in attributes through time using the residual maximum likelihood (REML) method and PROC MIXED in SAS 9.4M1 (SAS Institute Inc., https://support.sas.com/documentation/cdl/en/statug/63962/HTML/default/viewer.htm#statug_mixed_sect008.htm) and tested for significance of the slope coefficients of the best model to confirm stability inferences ($\alpha = 0.05$). Stability would be suggested by attributes and slopes that remained uniform (not significantly different) over time. Unstable structures would have attributes and slopes that varied significantly over time.

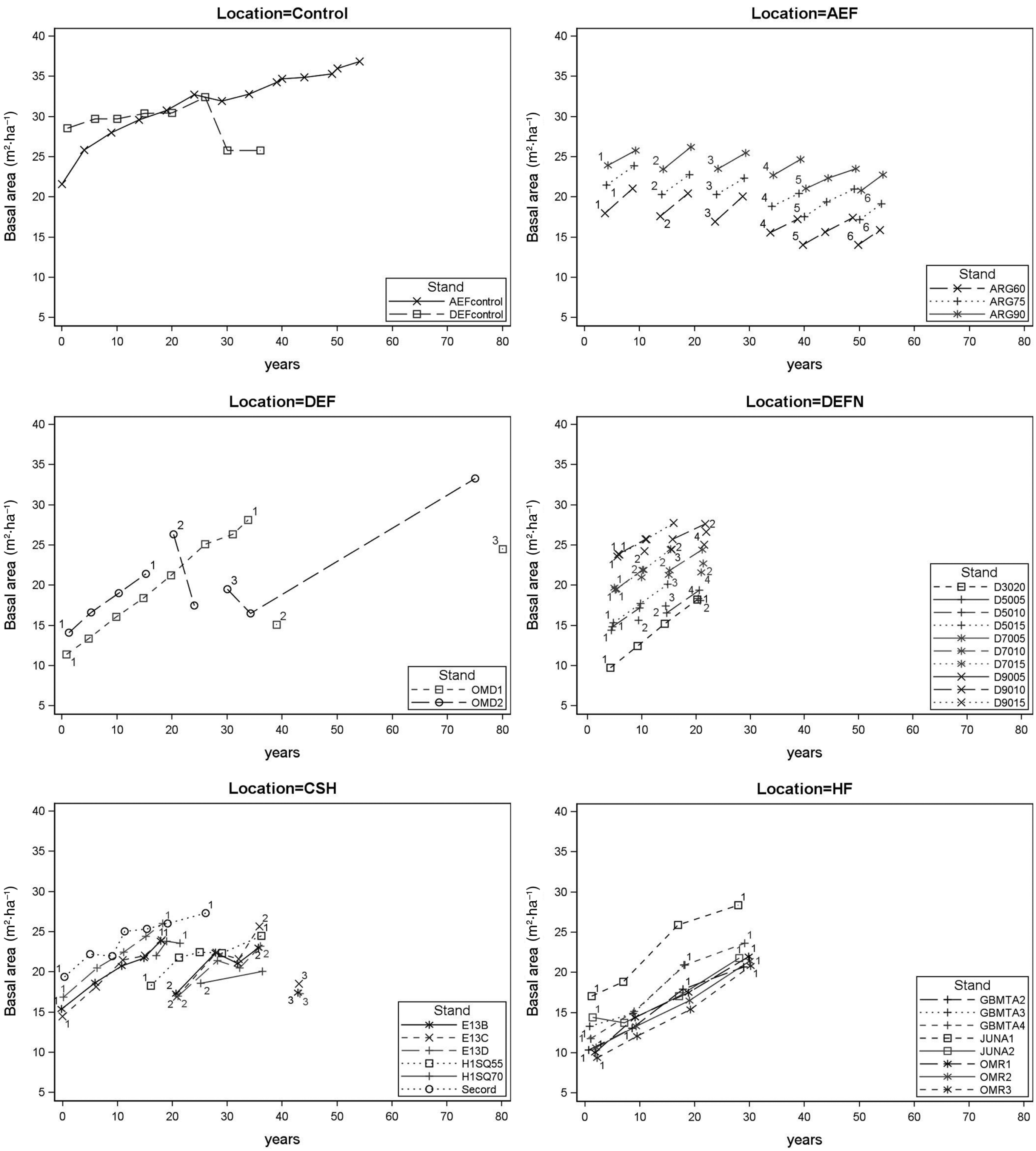
Diameter distribution through time

For this analysis, we used a Kolmogorov–Smirnov (K–S) two-sample test to compare the distributions for tree density by size class between remeasurements. We employed the maximum deviation statistic D to test the null hypothesis H_0: $F_1(x) = F_2(x)$ for all x (suggesting no significant difference in tree density across all DBH classes and reflecting the stability of the stand diameter distribution over time) and the alternative hypothesis H_1: $F_1(x) \neq F_2(x)$ for at least one x (suggesting a significant difference in tree density for one or more of the 2.5 cm DBH classes between remeasurements, and reflecting the instability of the stand diameter distribution over time). For this, we used PROC NPAR1WAY (SAS 9.4M1). For all locations, we calculated the tree density per hectare by 2.5 cm DBH classes to build plots of the empirical distribution and tested the maximum deviation at a level of significance of $\alpha = 0.05$ to validate the presence or absence of a significant difference among the compared diameter distributions through time in each stand.

Probability distribution function

The next step consisted of identifying a probability distribution function that fit the data and analyzing the dynamics of its parameters through time. We hypothesized that the shape and scale parameters of a fit distribution would stabilize and resemble the theoretical values of the Arbogast-recommended (Arbogast 1957) distribution, suggesting a stable condition through consecutive cutting entries. We used PROC UNIVARIATE (SAS 9.4 M1) to fit left-truncated Gamma and three-parameter Weibull distributions to the proportion of trees per hectare in the different 2.5 cm DBH classes and the maximum likelihood method to estimate the parameters. The location parameter (α) was constrained to 10.0, 11.4, and 12.5 for the three-parameter Weibull distribution, and the location parameter was fixed at 10.0 for Gamma distribution. Goodness-of-fit statistics (Anderson–Darling test and Cramér–von Mises test) were used to select the best model. They showed that the three-parameter Weibull with α fixed at 11.4 performed the best.

Fig. 1. Dynamics of basal area through time in all stands of the five study locations and the control stands. Stands in each site are presented by different line patterns and marker symbols. Lines between consecutive cycles are not joined, and the beginning and end of each cycle are determined by the numbers around the markers, while the number of years represents the total time since the first measurement. At the beginning of the experiments, stands at location AEF were second-growth with even-aged characteristics, while the other stands were uneven-aged.

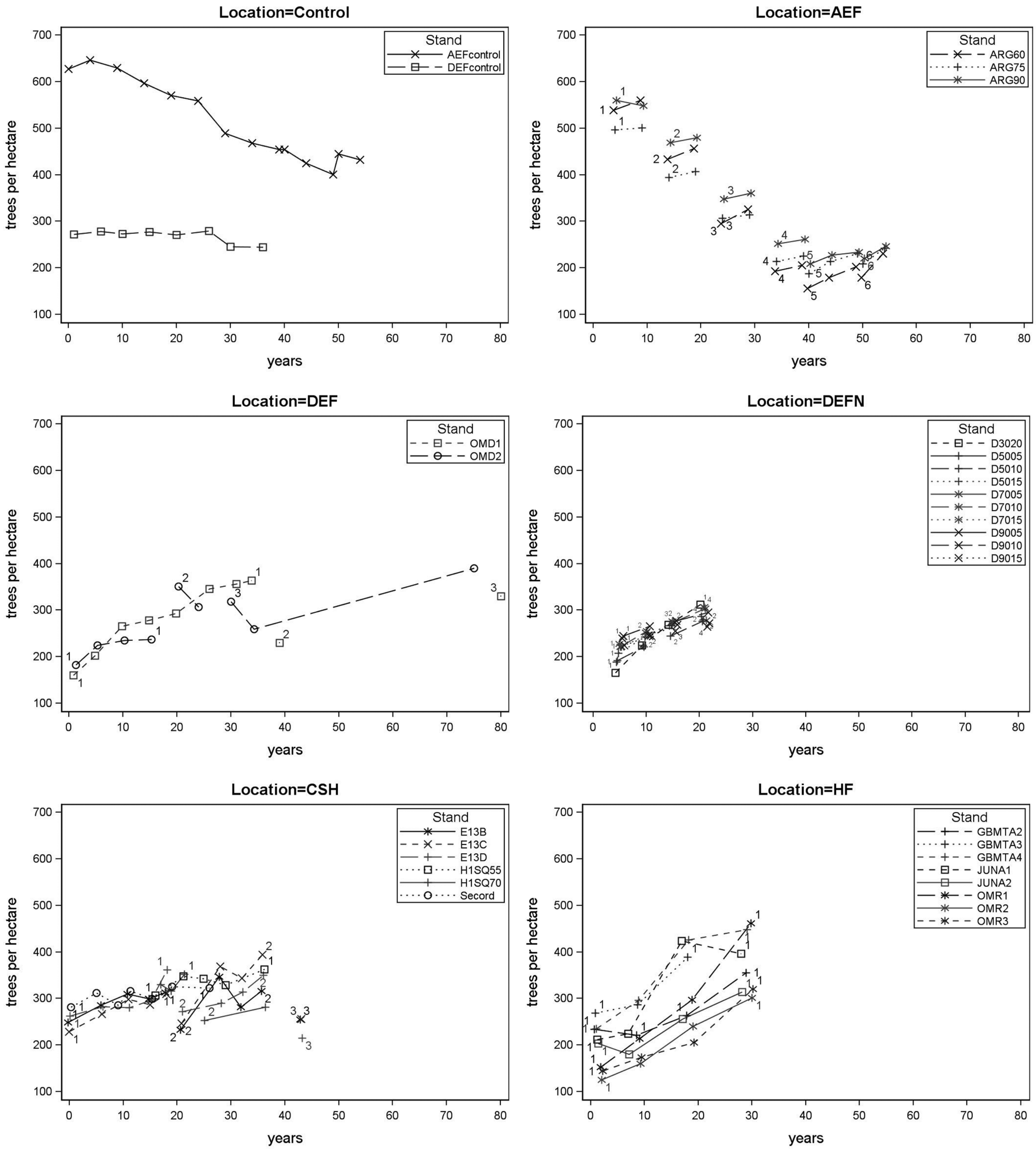


Results

Forest inventory metrics

Figures 1, 2, and 3 show changes based on an iteration of measurements for stand attributes listed in Table 1. Curves for controls showed different dynamics between the second-growth (AEF) and uneven-aged (DEF) stands. Conditions remained relatively consistent through time at the DEF control, except for a drop in the three attributes at 30 years. Field sheets show that this resulted from the natural mortality of multiple trees, including one with DBH larger than 40 cm. In subsequent years, the attributes

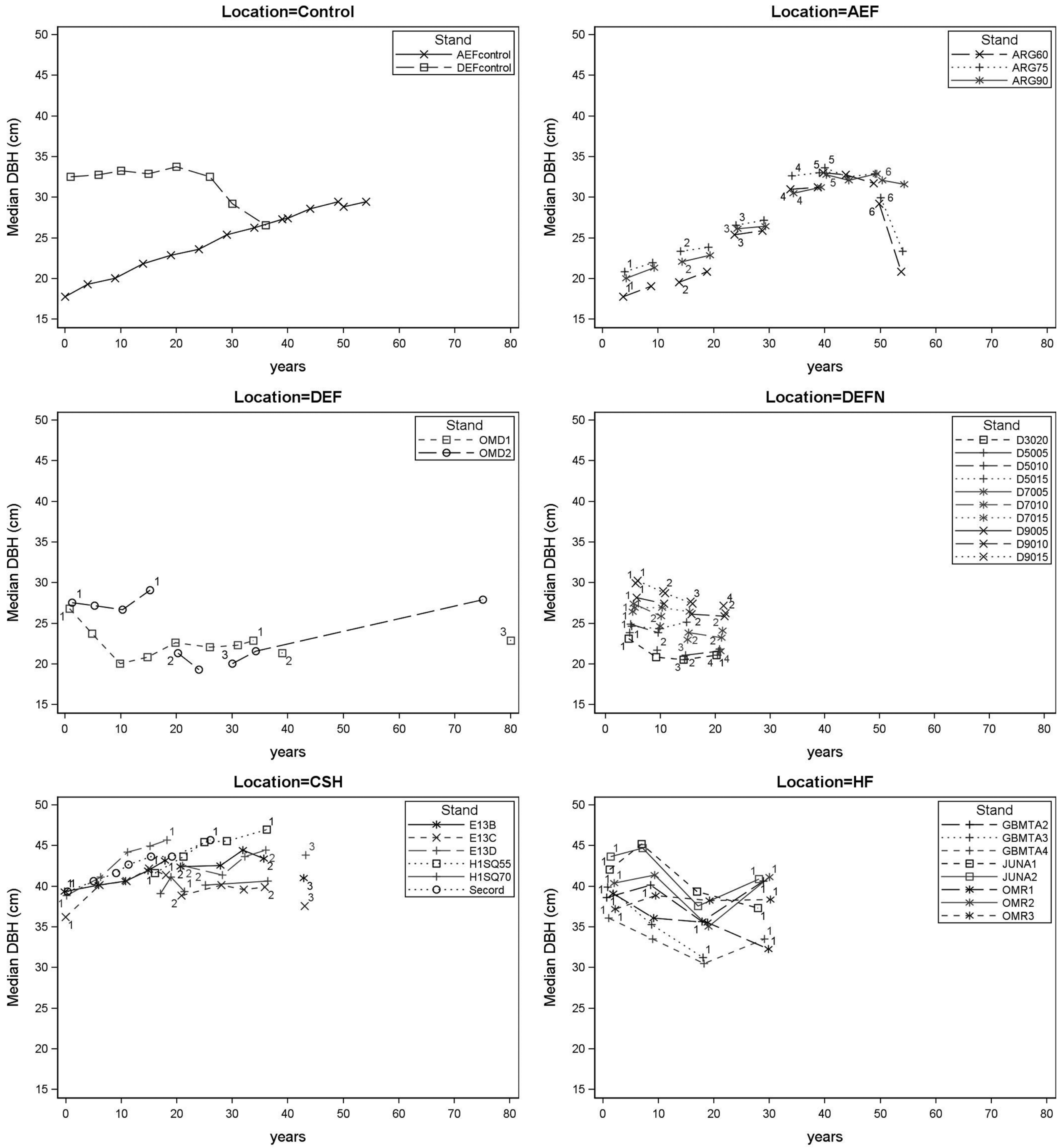
Fig. 2. Dynamics of tree density through time in all stands of the five study locations and the control stands. Stands in each site are presented by different line patterns and marker symbols. Lines between consecutive cycles are not joined, and the beginning and end of each cycle are determined by the numbers around the markers, while the number of years represents the total time since the first measurement. At the beginning of the experiments, stands at location AEF were second-growth with even-aged characteristics, while the other stands were uneven-aged.



stabilized again through the next remeasurement. At the AEF control, median diameter and basal area steadily increased through time, while tree density decreased. For treated stands, basal area, total tree density, and median diameter changed little through time in DEF, DEFN, CSH, and HF. They varied through time at AEF, with the pattern changing in the fifth cutting cycle (Figs. 1, 2, and 3).

Results from the regression analysis fitted to all remeasurement data in each stand (Table 3) confirm the significant variation of the three attributes through time at AEF and their consistency

Fig. 3. Dynamics of median diameter at breast height (DBH) through time in all stands of the five study locations and the control stands. Stands in each site are presented by different line patterns and marker symbols. Lines between consecutive cycles are not joined, and the beginning and end of each cycle are determined by the numbers around the markers, while the number of years represents the total time since the first measurement. At the beginning of the experiments, stands at AEF were second-growth with even-aged characteristics, while the other stands were uneven-aged.



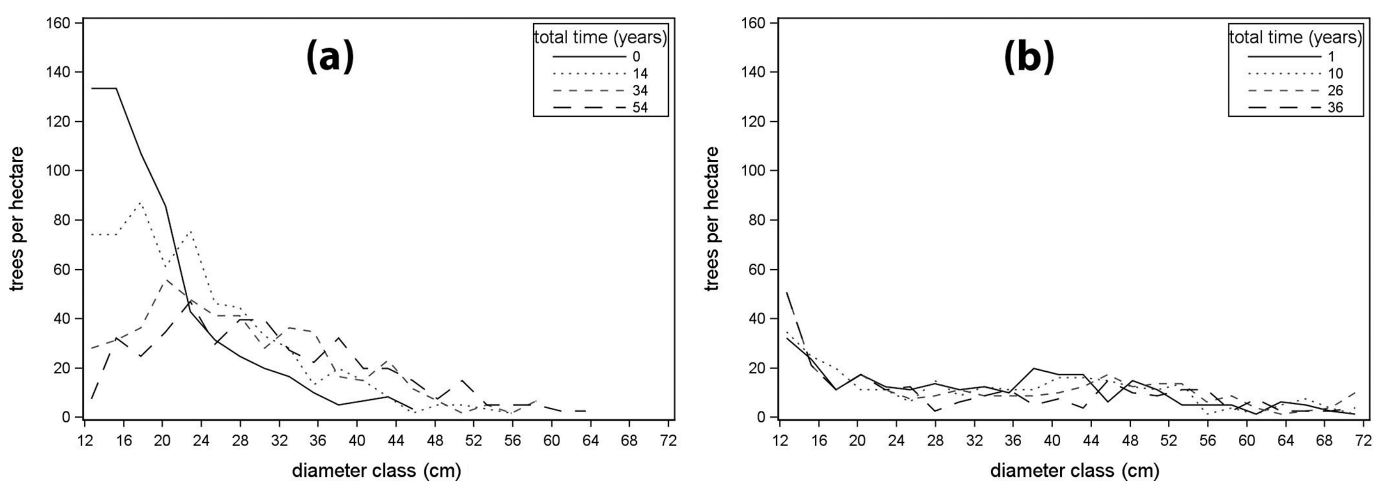
at the other sites. For basal area through time, linear models provided the best fit (Fig. 1; Table 3). The slope was significantly negative for all treated stands at AEF, indicating a decrease in stocking for these second-growth stands. For the others, including the AEF control, the models had positive slopes, indicating increasing basal area through time in uneven-aged and uncut second-growth stands. For stem density, a negative, linear slope was significant for all stands at AEF, indicating declining numbers of trees over time (Fig. 2; Table 3). Other stands had mostly non-significant positive slopes, suggesting that the number of stems

Table 3. Results of the regression analysis for the variation of the stands attributes through time.

	Basal area			Density			Median diameter		
Stand	AIC[L]	Slope	AIC[Q]	AIC[L]	Slope	AIC[Q]	AIC[L]	Slope	AIC[Q]
ARG60	56.4	**−0.09**	66.6	135.0	**−8.02**	131.5	75.9	**0.25**	78.9
ARG75	53.4	**−0.08**	63.9	128.9	**−6.18**	123.8	72.3	**0.20**	75.5
ARG90	51.4	**−0.06**	61.7	128.0	**−7.53**	125.6	52.1	**0.28**	60.0
AEF control	54.7	**0.23**	56.7	121.7	**−4.69**	126.4	29.1	**0.22**	32.5
D3020	5.2	**0.53**	14.3	22.6	**9.08**	20.3	14.2	−0.12	17.1
D5005	9.7	**0.26**	17.2	23.0	**6.27**	23.3	14.1	−0.17	14.6
D5010	13.9	0.25	19.9	16.8	**5.18**	21.2	14.2	−0.23	19.5
D5015	16.4	0.19	19.1	23.0	**4.46**	19.5	15.0	−0.15	19.3
D7005	10.6	0.11	16.3	9.9	**4.90**	16.8	8.5	**−0.30**	14.1
D7010	13.0	**0.28**	19.5	20.5	**5.01**	22.7	11.5	**−0.27**	17.7
D7015	16.2	0.22	19.1	23.2	**3.68**	22.6	13.0	−0.17	15.9
D9005	6.2	**0.09**	16.0	14.7	**1.57**	20.0	9.3	**−0.18**	16.5
D9010	11.8	**0.21**	18.9	18.7	**3.09**	21.6	9.8	**−0.15**	17.2
D9015	14.9	0.19	18.4	22.4	**3.07**	22.4	8.0	**−0.25**	9.7
DEF control	38.1	−0.07	42.4	56.6	−0.81	58.2	35.4	**−0.15**	34.7
E13B	51.1	0.06	55.2	92.2	0.31	94.0	38.8	0.07	42.2
E13 C	53.2	0.11	58.5	96.9	2.04	97.9	44.4	0.00	47.0
E13 D	54.0	0.00	59.2	95.3	0.03	95.5	45.2	0.07	52.1
GBMTA2	14.3	**0.38**	22.5	29.0	4.54	26.5	19.1	0.03	25.0
GBMTA3	11.9	0.45	0.0	17.8	7.14	0.0	9.1	**−0.51**	—
GBMTA4	15.8	**0.44**	23.0	29.6	**8.12**	29.9	18.5	−0.10	23.0
H1SQ55	17.7	**0.27**	24.0	34.4	2.09	35.9	15.2	**0.26**	20.5
H1SQ70	21.9	−0.18	26.7	39.1	−3.14	38.1	16.9	0.05	23.7
JUNA1	16.6	**0.45**	23.4	32.0	8.17	31.0	18.6	−0.24	24.6
JUNA2	16.5	0.29	21.9	28.2	4.69	29.1	19.6	−0.17	24.9
OMD1	61.5	0.15	68.4	101.1	1.69	102.6	45.9	−0.02	55.8
OMD2	51.8	**0.21**	61.3	84.6	**2.47**	88.9	52.1	−0.02	55.5
OMR1	14.1	**0.41**	22.3	28.0	**10.88**	27.7	14.9	**−0.22**	23.2
OMR2	11.4	**0.38**	20.5	23.6	**6.47**	27.4	20.3	−0.04	25.3
OMR3	12.7	**0.40**	20.7	28.2	**6.08**	28.1	14.1	0.03	22.2
Secord	24.3	**0.30**	30.9	50.4	1.43	53.5	14.8	**0.24**	24.1

Note: The regressions were fitted to all remeasurements within each stand. AIC[L] is AIC value for the fitted linear regression, and AIC[Q] is AIC value for the fitted quadratic regression. Boldface type indicates significant slope at $\alpha = 0.05$.

Fig. 4. Diameter distribution in the control stands at (*a*) Argonne Experimental Forest (AEF), being even-aged, and (*b*) Dukes Experimental Forest (DEF), being uneven-aged. The solid line represents the first measurement after the initiation of the study, the dashed line represents the last measurement, and other formats pertain to few selected remeasured periods in between the first and the last.

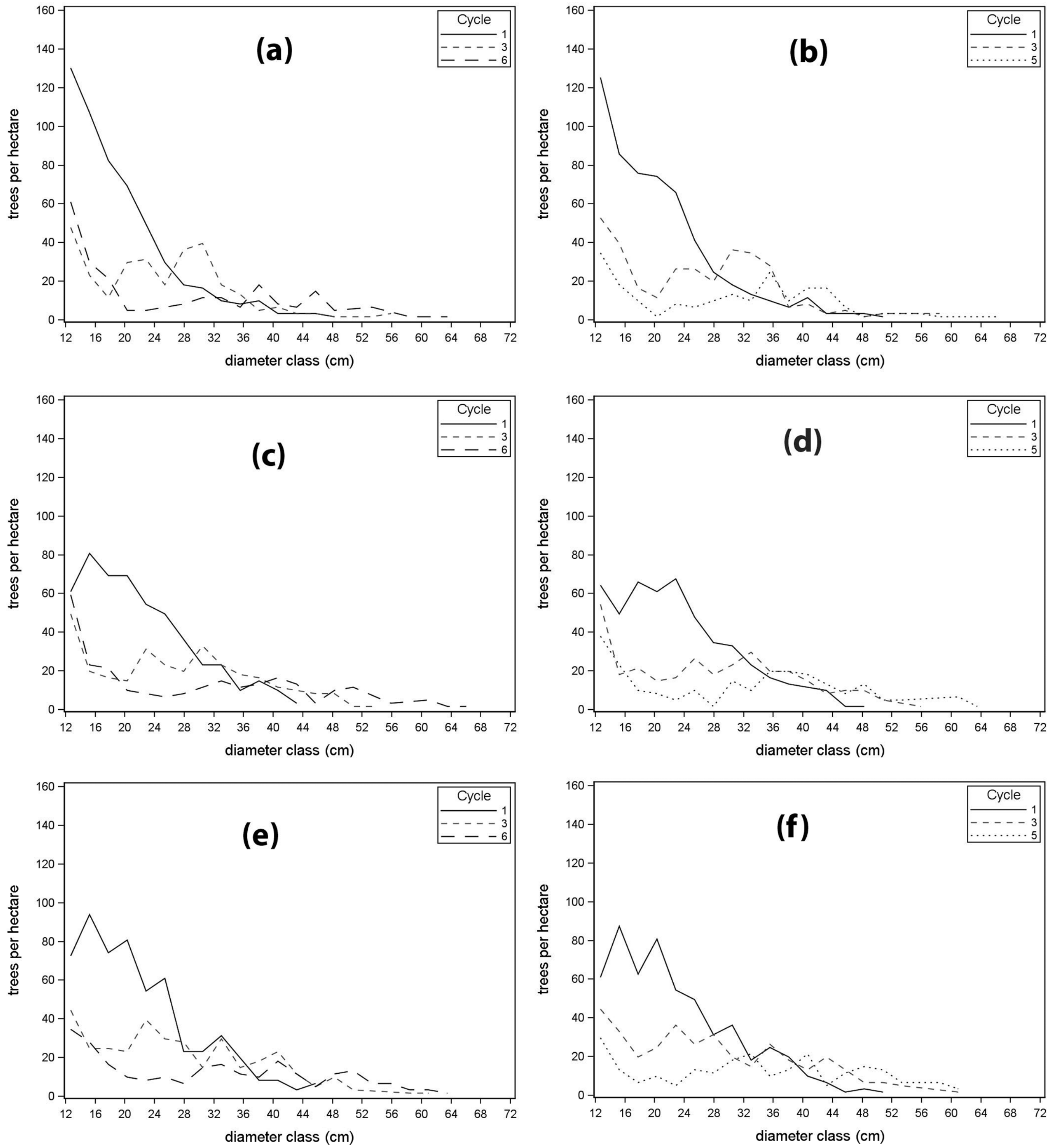


slightly increased over time (Fig. 2; Table 3). For median diameter, linear models fit better than the quadratic models (Fig. 3; Table 3). They had a significant positive slope at AEF, indicating an increasing tree size over time in these second-growth stands. At other sites, median diameter patterns were explained with a negative and nonsignificant slope, indicating a decrease or no change in tree size in the uneven-aged stands.

Diameter distribution through time

Changes in the diameter distributions for the control stands at DEF and AEF (Fig. 4) reveal a dissimilarity in stand dynamics. The diameter distribution at DEF remained largely consistent over 36 years, except for some minor changes. By contrast, at AEF, the diameter distributions changed appreciably. They had a right-skewed distribution for the inventory at the beginning of the

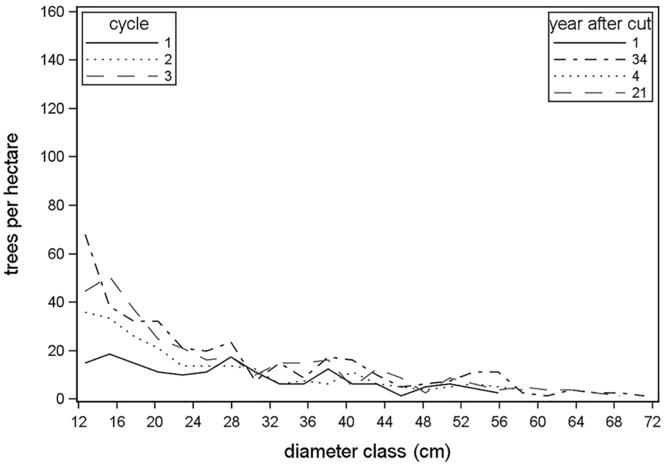
Fig. 5. Diameter distribution in selected cutting cycles at the first remeasurement after cut (year 4 after cut) in even-aged stands (*a*) ARG60, (*c*) ARG75, and (*e*) ARG90 and the last remeasurement after cut (year 9 after cut) in the same stands, (*b*) ARG60, (*d*) ARG75, and (*f*) ARG90.



experiment (designated as year 0) and became approximately unimodal by the remeasurement at year 54. Also, the height of the diameter distribution curves decreased due to a drop in the proportion of trees in small- and mid-diameter classes. A K–S two-sample test for the control plots compared the distributions at the same periods as the treated ones at all locations. Tests for DEF control showed no significant difference between all pairs of compared distributions. Those for AEF control showed a significant difference for the distributions between years 4 and 14 ($p = 0.0283$) but no statistically significant difference in the proportion of trees across the diameter classes among subsequent years.

The diameter distributions in the precut ARG60, ARG75, and ARG90 stands (Fig. 5) initially had a reverse-J shape that remained so after the first cutting. They began to diverge to a unimodal form

Fig. 6. Diameter distribution at various selected times of the three cutting cycles in uneven-aged stand OMD1 at DEF.



following the second cutting. After that, the unimodal shape shifted to the right through time. Also, the numbers of smaller trees in the left tail of the diameter distributions decreased gradually after the second cutting to just before the fifth cutting, suggesting inadequate recruitment of new age classes. A new left tail then formed between the fifth and sixth cuttings and became more pronounced thereafter. Yet the K–S two-sample test for these stands showed no significant difference when comparing diameter distributions at various periods within each of the six cutting cycles. For ARG60 and ARG75, the maximum deviation was significant for the change in distributions among the second, third, and fourth cutting cycles due to the formation and progression of the mid-diameter peak and between distributions of the fifth and sixth cutting cycles due to reforming of the left tail. Yet progression of the peak and development of a left tail at ARG60 and ARG75 were not large enough to cause a significant difference among distributions for later time periods. For ARG90, a significant deviation appeared only within the inventory data for the first measurement and after treatment in second and third cutting cycles and is related to the shape and amplitude of the peak.

Diameter distributions for both OMD1 (Fig. 6) and OMD2 (Fig. 7) did not appear noticeably different between cycles and became more stable through time. Also, the left tail of the reverse-J curve developed more within the first cutting cycle at OMD1. It took a second entry in OMD2 for a left tail to fully develop. The K–S two-sample test showed no significant difference for all comparisons within and among cutting cycles in OMD1. For OMD2, it showed a significant maximum deviation between inventories at year 1 and year 45 of the third cutting cycle due to an increase in number of trees between the 27.5 cm and 37.5 cm diameter classes by the year-45 inventory. These classes had deficiencies at the beginning of the same cutting cycle. Also, a significant difference was found between distributions of the first and second cutting cycles at different time intervals. The graphs suggest that this might relate to better development of the left tail after the second cutting in OMD2.

For all stands at DEFN, CSH, and HF (see Supplementary data),[1] characteristics of the diameter distribution dynamics and rate of stabilization depended on the degree of irregularities in the original precut diameter distribution, the number of entries, and the time intervals between cuttings. In general, all stands developed and maintained relatively consistent diameter distributions through time, and the structures morphed to a more pronounced reverse-J shape due to development of a left tail. Also, the distributions became less irregular and smoother through time, with fewer deficiencies and excesses across the diameter classes. In addition, the K–S two-sample test between diameter distributions within the same cycle and between two consecutive cycles mostly showed no statistical significance in maximum deviations for any stand.

Based on the dynamics of stand attributes and changes in the diameter distributions over time, stands treated with selection system all moved towards stability. By contrast, the three AEF second-growth stands treated with selection-like cutting show unstable structural conditions.

Probability distribution function

Figure 8 (*b*, scale parameter) and Fig. 9 (*c*, shape parameter) show the changes through time for the Weibull distributions, along with reference lines for the target distribution as recommended by Arbogast (1957) and Eyre and Zillgitt (1953). The three-parameter Weibull equation is

$$g(y) = (c/b)((y - a)/b)^{c-1}\exp\{-((y - a)/b)^c\}, \quad y \geq a, \ \ b > 0, \ \ c > 0$$

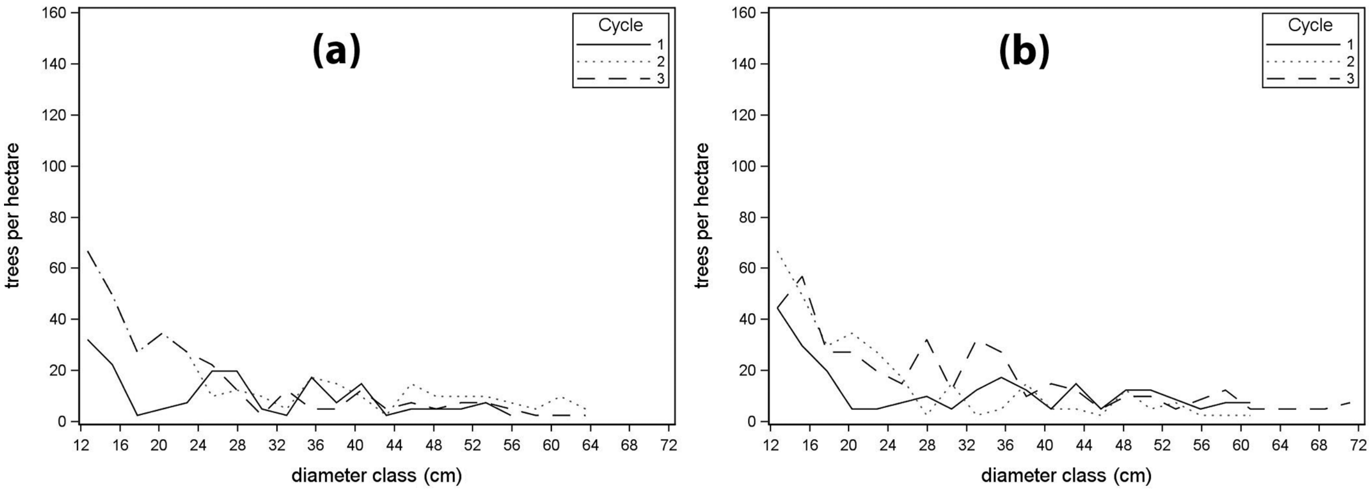
where a, b, and c are the location, scale, and shape parameter, respectively, and x is the DBH. When describing a diameter distribution, the location parameter (a) represents the smallest possible diameter, the sum of the scale parameter (b) and the location parameter is the 63rd percentile of the diameter distribution, and the parameter (c) reflects the shape of the fitted curve. A reverse-J curve would have $c < 1$. A normal curve would have $c = 3.6$ and an exponential distribution results in $c = 1$, and a bell-shaped curve with skewness would have $1 < c < 3.6$ or $c > 3.6$ (Bailey and Dell 1973).

Parameters b and c at DEF control remained relatively stable through time, with values similar to or higher than those for the Arbogast (1957) distribution (hereafter referred to as reference values). For AEF control, parameter b initially had a value lower than the reference, increased steadily over time, and eventually surpassed the reference. Parameter c started with a value higher than the reference and moved away from it over time.

Treated stands at AEF and DEF showed different dynamics through time for both the scale and shape parameters (Figs. 8 and 9). In the uneven-aged stands at DEF, the shape parameter b remained stable, approximating the reference value. The scale parameter c decreased slightly after the first cut and then stabilized at or similar to the reference value. In the second-growth stands at AEF treated with selection-like cutting, parameter b initially was smaller than the reference value. It increased for the first four cutting cycles, surpassed the reference value of 5.947, and then decreased to approach (ARG90) or resemble (ARG60 and ARG75) the reference value during the sixth cutting cycle. Parameter c started larger than the reference value, did not change for the first three cutting cycles, increased for the fourth cutting cycle, started decreasing at the beginning of the fifth cutting cycle, and then became similar to the reference value (ARG90) or below the limit of $c = 1$ (ARG60 and ARG75). At DEFN, the value of parameter b stabilized with each consecutive entry, but at different levels among treatment intensities. It approached the reference value for the lower levels of residual stocking and their longer cutting cycles. All treatments at DEFN created and maintained c similar to the reference value, except for D5015, where c exceeded the reference value following the first entry. It converged to a reference value at the end of the first cutting cycle.

[1]The graphs for the diameter distributions for all stands at DEFN, CSH, and HF are presented in the Supplementary material available with this article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2019-0204.

Fig. 7. Diameter distribution at (*a*) one year after each of three cuttings and (*b*) years 15, 4, and 45 of cutting cycles 1, 2, and 3, respectively, in uneven-aged stand OMD2 at DEF.



Among stands treated with the selection system in New York (CSH and HF), the shape parameter *b* stabilized for each stand (Figs. 8 and 9), but the exact change in *b* and the required time before stabilizing varied among stands. The scale parameter *c* at all stands in NY, except OMR, remained relatively unchanged. They were similar to the reference values or fell between both reference lines. In some cases, they dropped below 1.

Discussion

All of the stands that we evaluated had precutting diameter distributions characterized by decreasing numbers of trees from the small to large size classes. Yet the stands at AEF were young (45-year-old) pole-sized second-growth stands comprised primarily of a single cohort, but with inclusions of some remnant trees left after past exploitive cutting (Erdmann and Oberg 1973). By contrast, stands at DEF, DEFN, CSH, and HF were multi-aged, with a history of partial harvesting (Eyre and Neetzel 1937; Tubbs 1977; Crow et al. 1981; Bohn 2005). Thus, based on current understanding about differences in the growth and dynamics between even- and uneven-aged stands, we expected to see dissimilarities develop through time in the diameter distributions and some associated stand attributes.

Changes in the median diameter, basal area, and tree density over 36 years in the control stands at DEF reflect dynamics related to a stability in those diameter distributions, as demonstrated by a lack of significant differences per the K–S two-sample test. Minimal fluctuations in the shape and scale parameters of the Weibull function fitted to these stands (Figs. 8 and 9) verified the structural stability. Conceptually, a similar dynamic should occur among other uneven-aged northern hardwood stands affected by selection system cutting, with the proportions of trees in all size classes fluctuating around relatively constant values due to balanced growth, mortality, and regeneration (Nyland 2016).

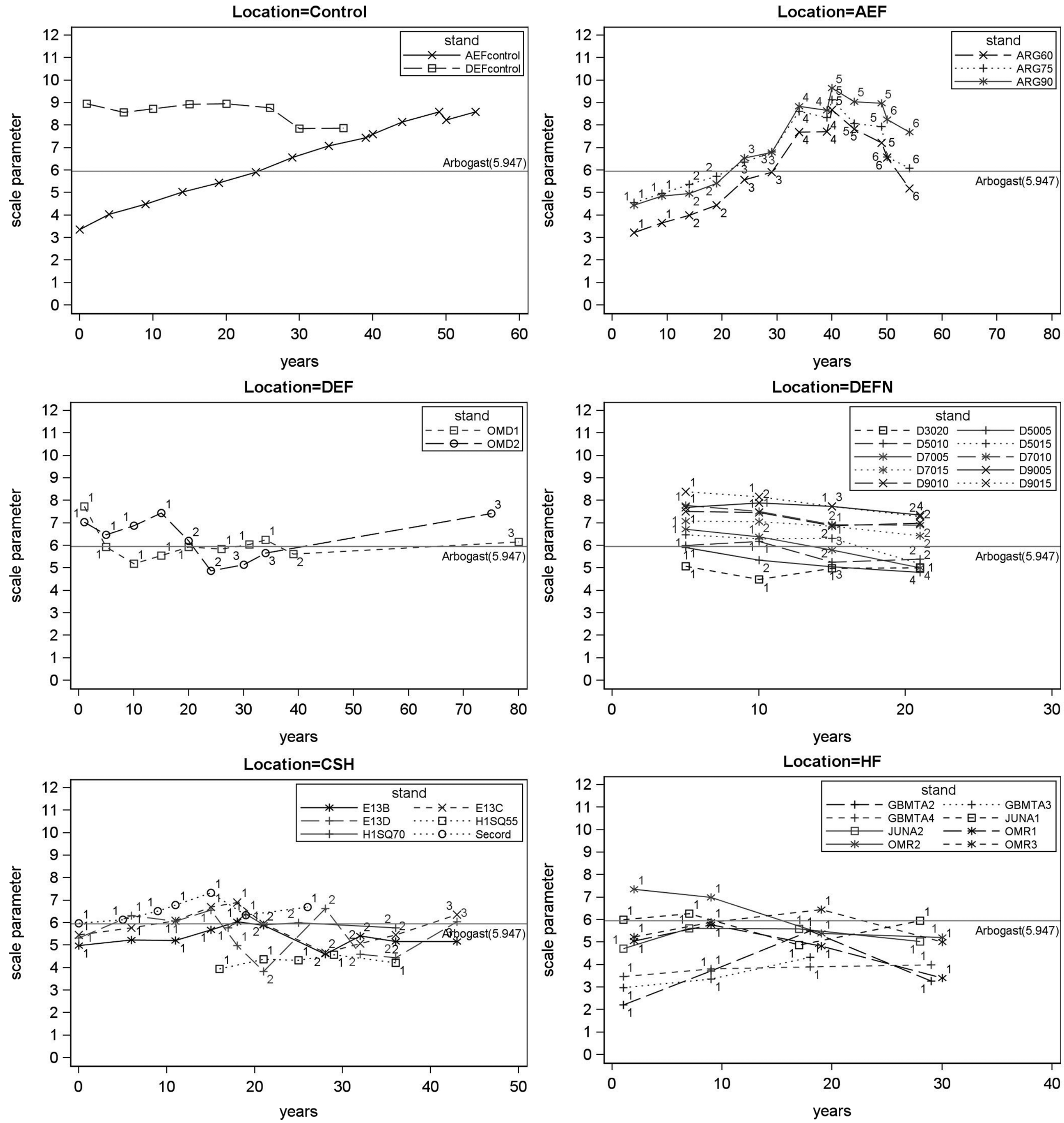
Development within the control stands at AEF typifies that of single-cohort stands in which trees become larger, intertree competition leads to appreciable mortality among smaller and less vigorous individuals, and the number of trees decreases through time (Nyland 2016). This becomes manifest in the change of the diameter distribution from the initial reverse-J curve to a bell-shaped curve, a continuous decrease in the height of the diameter distribution curve, and an extension of the right tail (Marquis 1986). Consistent with such changes in even-aged stands, the median diameter and basal area of plots at AEF also increased, while the number of trees decreased. Such dynamics confirm that a single cohort likely dominated the 45-year-old second-growth stands used for the experiment at AEF. A lack of significance in the K–S two-sample tests for consecutive remeasurements, except between inventories at years 4 and 14, results from a gradual change in the diameter distribution (Fig. 4), and while the distributions changed distinctly through the first 54 years at the AEF control, they showed relatively small differences for 36 years at the DEF control. These long-term shifts within the AEF control also likely resulted in an overall increasing trend in the shape and scale parameters.

While the control plots showed changes consistent with natural differences between uneven- and even-aged stands, the managed ones illustrate how cutting influences the change in a diameter distribution. Past studies have shown that single-tree selection cutting within uneven-aged northern hardwood stands improves the diameter growth of trees in the smaller size classes (Eyre and Zillgitt 1953; Orr et al. 1994; Bédard and Majcen 2003), with increases in saplings and a greater growth rate among poles than for trees of sawtimber sizes (Eyre and Zillgitt 1953; Kiernan et al. 2008). By contrast, partial cuttings in even-aged northern hardwood stands leads to greater rates of diameter growth in larger trees rather than smaller trees (Erdmann and Oberg 1973). Those differences between uneven- and even-aged stands would affect the structural dynamics through time.

The uneven-aged stands at DEF, DEFN, CSH, and HF all developed similarly through time, despite differences in residual basal areas and lengths of the cutting cycles and some irregularities in numbers of trees across the diameter distributions. Single-tree selection system cutting appears to have limited mortality among 12.5 to 70.0 cm trees and ensured adequate upgrowth across size classes to maintain a stable diameter distribution. Stands also had sufficient recruitment to sustain the 12.5 and 15.0 cm diameter classes through time (e.g., Figs. 6 and 7), as reflected in the development and subsequent maintenance of a left tail in the diameter distribution diagrams. This resulted in convergence and fluctuation of both the shape and scale parameters around the reference values (Figs. 8 and 9). Likewise, using the single-tree selection system in uneven-aged sugar maple – yellow birch – beech stands in Quebec increased the number of stems in most diameter classes (indicating adequate recruitment, survival, and upgrowth) and maintained the reverse-J-shaped diameter distribution through 10 years after selection cutting (Bédard and Majcen 2001, 2003).

Having proportions of trees across the diameter classes similar to those prescribed by Arbogast (1957) should ensure steadiness of the Weibull parameters through multiple cutting cycles. Records show that stands at DEFN had consistent recruitment over the

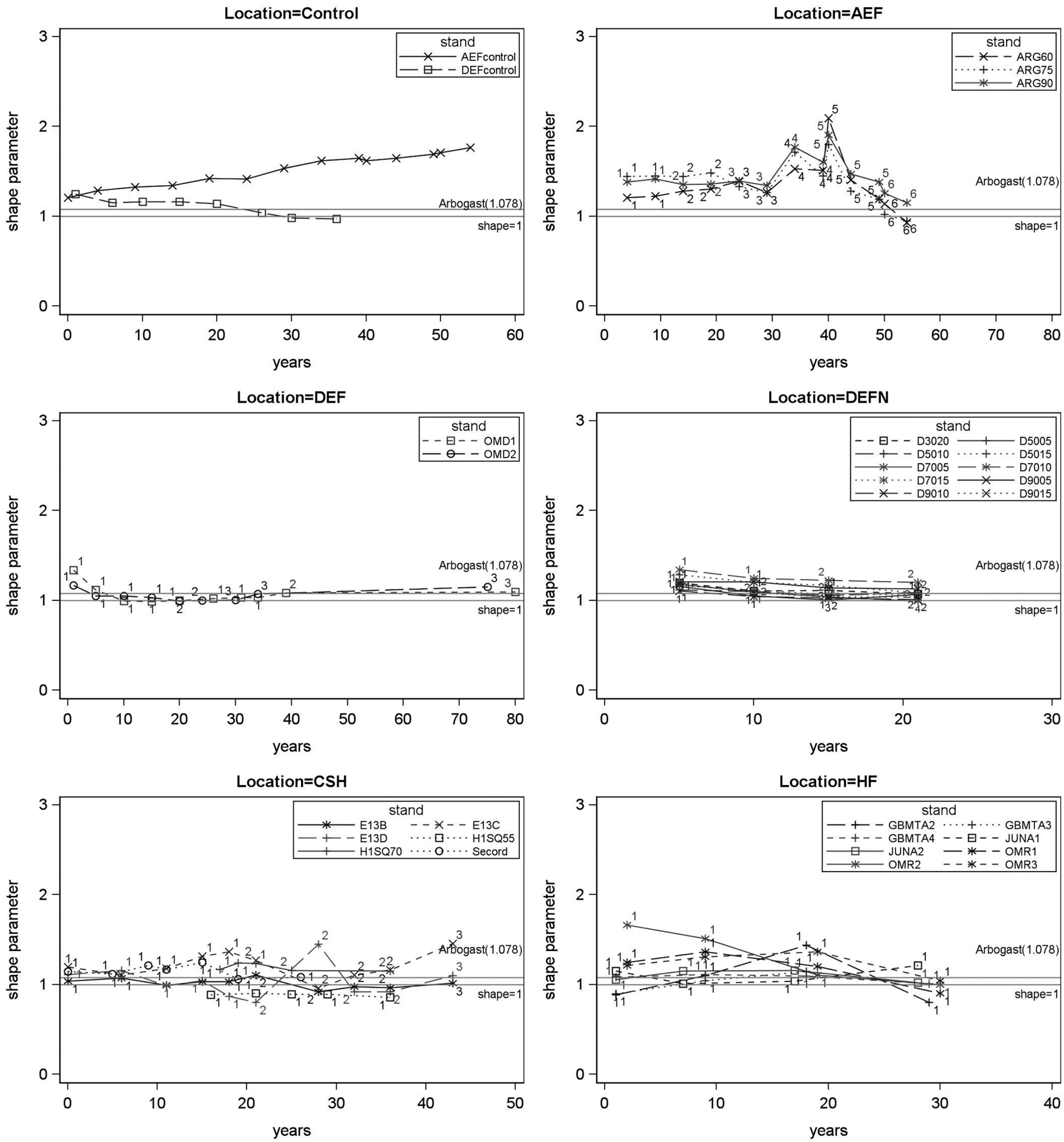
Fig. 8. Changes in the scale parameter of the truncated three-parameter Weibull function fitted to the proportion of trees in 2.5 cm diameter classes in all stands of the five study locations and the control stands. At the beginning of the experiments, stands at location AEF were second-growth with even-aged characteristics, while the other stands were uneven-aged. Stands in each site are presented by different line patterns and marker symbols. The number of the cycle is determined by the numbers around the markers, while the number of years represents the total time since the first measurement.



20 years of management (Crow et al. 1981). Similarly, the number of trees in the 15.0 cm diameter class remained adequate through 32 years of selection cutting in an uneven-aged northern hardwood woodlot in Michigan (Orr et al. 1994). Stabilization of the shape parameter around a value of 1 through consecutive entries verifies that the selection system did sustain a reverse-J-shaped distribution in the uneven-aged stands that we evaluated, leading to a more regular and smoother diameter distribution by managing the excesses and deficiencies across the size classes. The resulting structural stability also ensured consistency of the median diameter, tree density, residual basal area, and proportion of trees in different diameter classes.

The common theoretical saw-toothed shape for changes in tree density and residual basal area across multiple cutting cycles in

Fig. 9. Changes in the shape parameter of the truncated three-parameter Weibull function fitted to the proportion of trees in 2.5 cm diameter classes in all stands of the five study locations and the control stands. At the beginning of the experiments, stands at location AEF were second-growth with even-aged characteristics, while the other stands were uneven-aged. Stands in each site are presented by different line patterns and marker symbols. The number of the cycle is determined by the numbers around the markers, while the number of years represents the total time since the first measurement.



single-tree selection stands (Nyland 2016) was not obvious in our data, probably due to a lack of regular remeasurements immediately after cutting and (or) at the end of some cutting cycles. We also included stands with only a single cutting treatment. Yet the data reveal a tendency for all uneven-aged stands treated with single-tree selection system to develop a reverse-J-shaped distribution that can be recreated through repeated cutting cycles. We did observe differences among stands in the rate of change and the number of cutting treatments needed before an idealized diameter distribution developed. These likely reflect differences in initial stocking, the degree of irregularities in the precut diameter distribution (Arbogast 1957; Gilbert and Jensen 1958), and the cutting intensity (Eyre and Zillgitt 1953; Crow et al. 1981). For our study stands, establishing the target distribution required at least two entries (total time of 15 to 20 years), despite differences in the time intervals between subsequent treatments. This seems consistent with observations by Eyre and Zillgitt (1953), Arbogast (1957), and Bédard and Majcen (2003).

After 40 years of selection-like treatments in the second-growth AEF stands, Strong et al. (1995) found that all pole- and sawlog-sized trees had the same age, confirming their single-cohort status. Our assessments show that 54 years of selection-like cuttings at 10-year cutting cycles failed to create and maintain a stable reverse-J-shaped diameter distribution in these stands. This lack of structural stability through time was also reflected in the increasing shape and scale parameters of the Weibull distributions. It suggests that the strategy did not alter the growth dynamics common to single-cohort stands.

After a fifth entry, the median diameter in treated AEF stands began to decrease, while the basal area and tree density increased. These changes resulted from recruitment of a new cohort into the 12.5 and 15.0 cm diameter classes as shown by the development of the left tail. Both Weibull parameters also decreased after the fifth cycle due to changes in the smaller diameter classes, leading to a morphing of the structure back toward a reverse-J-shaped form. Potentially, the lower stocking and newly opened gaps during each entry throughout the 54-year period might maintain sufficient recruitment of additional cohorts to bring eventual structural stability to these stands, but that remains unclear from currently available data.

Changes in the diameter distributions, associated stand attributes, and both Weibull parameters contradict earlier suggestions that selection-like cuttings at a 10-year cycle would maintain a reverse-J-shaped structure in the second-growth stands at AEF (Erdmann 1987), with the size-class distribution recommended by Eyre and Zillgitt (1953) developing by the third entry (Erdmann and Oberg 1973). Instead, our findings agree with an earlier report that after 40 years, these stands had more stocking in sawtimber and less in poles than recommended in the Arbogast guide (Strong et al. 1995). Changes after the fifth cycle do support the observation by Smith and Miller (1987) that managers would need at least seven 10-year cycles of selection-like cutting to develop uneven-aged conditions in an even-aged stand.

We could not assess sustainability of the structure observed after the fifth entry in the plots at AEF. Yet, we suggest that to convert stands from an even-aged to an uneven-aged condition, managers might instead do a series of partial cuttings as suggested by Nyland (2003, 2016). They would remove the smallest trees at the first entry and open the canopy sufficiently for recruitment of a new cohort. With that treatment and each subsequent entry, they would retain adequate numbers of larger trees to maintain a desired level of stocking to ensure good growth among the standing trees, while also establishing an additional age class. Then managers could follow the Arbogast (1957) guidelines for northern hardwoods once an uneven-aged condition eventually developed (Nyland 2003, 2016). This might take at least four to five entries at 15- to 20-year intervals and a century of time (Crow and Metzger 1987; Erdmann 1987). Alternately, managers could combine patch cutting with thinning-from-below to maintain stand-level production while enhancing chances for regeneration of less shade-tolerant species (Kelty et al. 2003; Kern et al. 2017). Versions of an irregular shelterwood system (Raymond et al. 2009), or periodic progressive patch cutting (Nyland 2016), might also suffice to create multi-aged stands to eventually treat by some version of selection system.

Conclusion

Collectively, our findings support the notion that the diameter distribution in uneven-aged northern hardwood stands treated with single-tree selection system will remain stable through time. Yet the initial reverse-J-shaped diameter distribution found in young second-growth northern hardwood stands with an important single-cohort component will become unstable after selection-like cutting. The contrasting outcomes from the uneven-aged and second-growth stands likely result from differences in recruitment to the smaller diameter classes (<12.5 cm DBH) and dissimilar levels of postcutting growth of trees in the residual diameter classes, though that was not explicitly tested in the present study. The selection system led to temporal uniformity of the Weibull shape and scale parameters, median DBH, residual basal area, and number of trees in the uneven-aged stands that we evaluated. Findings also support the hypothesis that single-tree selection cutting can regulate distortions among the diameter classes, leading to a stable structure like that proposed by Eyre and Zillgitt (1953) and Arbogast (1957). By contrast, a strategy of selection-like cutting will likely result in unstable diameter distributions among young, second-growth stands predominantly comprised of a single cohort. Based on that evidence, we suggest using strategies other than cuttings resembling those used for single-tree selection system when managing second-growth northern hardwood stands similar to those studied here.

Acknowledgements

Funds for the research came from the Northeastern States Research Cooperative, with additional support and other contributions from SUNY College of Environmental Science and Forestry (ESF), and the U.S. Forest Service, Northern Research Station. We also acknowledge advice from E. Bevilacqua, D.H. Kiernan, and L. Zhang of SUNY ESF and A.W. D'Amato of the University of Vermont. J. Guldin of the U.S. Forest Service, Southern Research Station, and P.J. Smallidge of Cornell University also provided early reviews and suggestions. Five anonymous reviewers also offered useful suggestions that helped us to strengthen the manuscript.

References

Adams, D.M., and Ek, A.R. 1974. Optimizing the management of uneven-aged forest stands. Can. J. For. Res. **4**(3): 274–287. doi:10.1139/x74-041.

Arbogast, C., Jr. 1957. Marking guide for northern hardwoods under the selection system. USDA Forest Service Station Paper 56.

Assmann, E. 1970. The principles of forest yield study. *Edited by* P.W. Davis. *Translated by* S.H. Gardiner. Pergamon, Oxford. doi:10.1016/C2013-0-01587-3.

Bailey, R.L., and Dell, T.R. 1973. Quantifying diameter distributions with the Weibull function. For. Sci. **19**: 97–104.

Bédard, S., and Majcen, Z. 2001. Ten-year response of sugar maple–yellow birch–beech stands to selection cutting in Québec. North. J. Appl. For. **18**: 119–126. doi:10.1093/njaf/18.4.119.

Bédard, S., and Majcen, Z. 2003. Growth following single-tree selection cutting in Québec northern hardwoods. For. Chron. **79**: 898–905. doi:10.5558/tfc79898-5.

Bohn, K.K. 2001. Method for predicting American beech development in the understory of uneven-aged northern hardwood stands after cutting. M.Sc. thesis, State University of New York, College of Environmental Science and Forestry, Syracuse, New York.

Bohn, K.K. 2005. Residual spatial structure and implications for sawtimber production in uneven-aged northern hardwoods after selection system silviculture or diameter-limit cutting. Ph.D. thesis, State University of New York, College of Environmental Science and Forestry, Syracuse, New York.

Clatterbuck, W.K. 1993. Are overtopped white oak good candidate or management? *In* Proceedings of the Seventh Biennial Southern Silviculture Research Conference. *Edited by* J. Brissette. USDA Forest Service, GTR-SO-93. pp. 497–499.

Crow, T.R., and Metzger, F.T. 1987. Regeneration under selection system. *In* Managing Northern Hardwoods. *Presented at* the Silvicultural Symposium, SUNY ESF Faculty of Forestry, State University of New York College of Environmental Science and Forestry, Syracuse, New York. pp. 81–94.

Crow, T.R., Jacobs, R.D., Oberg, R.R., and Tubbs, C.H. 1981. Stocking and structure for maximum growth in sugar maple selection stands. USDA Forest Service, Res. Pap. NC-199.

Diamantopoulou, M.J., Ozcelik, R., Crecente-Campo, F., and Eler, U. 2015. Estimation of Weibull function parameters for modelling tree diameter distribution using least squares and artificial neural networks methods. Biosyst. Eng. **133**: 33–45. doi:10.1016/j.biosystemseng.2015.02.013.

Ducey, M.J. 2000. Prism cruising with diameter classes: theoretical considerations and practical recommendations. North. J. Appl. For. **17**: 110–115.

Erdmann, G.G. 1987. Methods of commercial thinning in even-aged northern hardwood stands. *In* Managing northern hardwoods. *Presented at* the Silvicultural Symposium, SUNY ESF Faculty of Forestry, State University of New York College of Environmental Science and Forestry, Syracuse, New York. pp. 191–210.

Erdmann, G.G., and Oberg, R.R. 1973. Fifteen-year results from six cutting methods in second growth northern hardwoods. USDA Forest Service, Res. Pap. NC-100.

Eyre, F.H. 1980. Forest cover types of the United States and Canada. Revised ed. The Society of American Foresters, Washington, D.C.

Eyre, F.H., and Neetzel, J.R. 1937. Applicability of the selection method in northern hardwoods. J. For. **35**(4): 353–358.

Eyre, F., and Zillgitt, W.M. 1953. Partial cuttings in northern hardwoods of the Lake States: twenty-year experimental results. USDA Forest Service, Technical Bulletin No. 1076.

Gilbert, A.M., and Jensen, V.S. 1958. A management guide for northern hardwoods in New England. USDA Forest Service, Station Pap. No. 112.

Gronewold, C.A., D'Amato, A.W., and Palik, B.J. 2010. The influence of cutting cycle and stocking level on the structure and composition of managed old-growth northern hardwoods. For. Ecol. Manage. **259**: 1151–1160. doi:10.1016/j.foreco.2010.01.001.

Gronewold, C., D'Amato, A.W., and Palik, B.J. 2012. Relationships between growth, quality, and stocking within managed old-growth northern hardwoods. Can. J. For. Res. **42**(6): 1115–1125. doi:10.1139/x2012-070.

Guldin, J.M. 1996. The role of uneven-aged silviculture in the context of ecosystem management. West. J. Appl. For. **11**: 4–12. doi:10.1093/wjaf/11.1.4.

Hansen, G. 1987. Choosing diameter distributions to aid in marking uneven-aged northern hardwood stands. *In* Managing northern hardwoods. *Presented at* the Silvicultural Symposium, SUNY ESF Faculty of Forestry, State University of New York College of Environmental Science and Forestry, Syracuse, New York. pp. 95–112.

Hansen, G.D., and Nyland, R.D. 1987. Effects of diameter distribution on the growth of simulated uneven-aged sugar maple stands. Can. J. For. Res. **17**(1): 1–8. doi:10.1139/x87-001.

Helms, J.A. 1998. The dictionary of forestry. Society of American Foresters, Bethesda, Md.

Janowiak, M.K., Nagel, L.M., and Webster, C.R. 2008. Spatial scale and stand structure in northern hardwood forests: implications for quantifying diameter distributions. For. Sci. **54**: 497–506.

Kelty, M.J., Kittredge, D.B., Jr., Kyker-Snowman, T., and Leighton, A.D. 2003. The conversion of even-aged stands to uneven-aged structure in southern New England. North. J. Appl. For. **20**: 109–116. doi:10.1093/njaf/20.3.109.

Kenefic, L.S., and Nyland, R.D. 1999. Sugar maple height–diameter and age–diameter relationships in an uneven-aged northern hardwood stand. North. J. Appl. For. **16**(1): 43–47. doi:10.1093/njaf/16.1.43.

Kern, C., Erdmann, G., Kenefic, L., Palik, B., and Strong, T. 2014. Development of the selection system in northern hardwood forests of the Lake States: an 80-year silviculture research legacy. *In* US Department of Agriculture Forest Service experimental forests and ranges research for the long term. *Edited by* D.C. Hayes, S.L. Stout, R.H. Crawford, and A.P. Hoover. Springer, New York. pp. 201–223.

Kern, C.C., Burton, J.I., Raymond, P., D'Amato, A.W., Keeton, W.S., Royo, A., et al. 2017. Challenges facing gap-based silviculture and possible solutions for mesic northern forests in North America. Forestry, **90**: 4–17. doi:10.1093/forestry/cpw024.

Kiernan, D.H., Bevilacqua, E., and Nyland, R.D. 2008. Individual-tree diameter growth model for sugar maple trees in uneven-aged northern hardwood stands under selection system. For. Ecol. Manage. **256**: 1579–1586. doi:10.1016/j.foreco.2008.06.015.

Leak, W.B. 1996. Long-term structural change in uneven-aged northern hardwoods. For. Sci. **42**: 160–165.

Leak, W.B. 2002. Origin of sigmoid diameter distributions. USDA Forest Service, Res. Pap. NE-718.

Leak, W.B., and Gove, J.H. 2008. Growth of northern hardwoods in New England: a 25-year update. North. J. Appl. For. **25**: 103–105. doi:10.1093/njaf/25.2.103.

Leak, W.B., and Sendak, P.E. 2002. Changes in species, grade, and structure over 48 years in managed New England northern hardwood stand. North. J. Appl. For. **19**: 25–27. doi:10.1093/njaf/19.1.25.

Leak, W.B., Solomon, D.S., and Filip, S.M. 1969. Silvicultural guide for northern hardwoods in the Northeast. USDA Forest Service, Res. Pap. RP-NE-143.

Lundqvist, L. 2017. Tamm Review: Selection system reduces long-term volume growth in Fennoscandic uneven-aged Norway spruce forests. For. Ecol. Manage. **391**: 362–375. doi:10.1016/j.foreco.2017.02.011.

Marquis, D.A. 1986. Thinning Allegheny hardwood pole and small sawtimber stands. *In* Guidelines for managing immature Appalachian hardwood stands. Society of American Foresters (SAF), Morgantown, W.Va. pp. 68–84.

Marquis, D.A. 1991. Independent effects and interactions of stand diameter, tree diameter, crown class, and age on tree growth in mixed-species, even-aged hardwood stands. *In* Proceedings of the Eighth Central Hardwood Forest Conference. *Edited by* L.H. McCormick and K.W. Gottshalk. USDA Forest Service, Gen. Tech. Rep. NE-148. pp. 442–458.

McGarrigle, E., Kershaw, J.A., Jr., Lavigne, M.B., Weiskittel, A.R., and Ducey, M. 2011. Predicting the number of trees in small diameter classes using predictions from a two-parameter Weibull distribution. Forestry, **84**: 431–439. doi:10.1093/forestry/cpr033.

Meyer, A.H. 1952. Structure, growth, and drain in balanced uneven-aged forests. J. For. **50**: 85–92.

Neuendorff, J.K., Nagel, L.M., Webster, C.R., and Janowiak, M.K. 2007. Stand structure and composition in a northern hardwood forest after 40 years of single-tree selection. North. J. Appl. For. **24**: 197–202. doi:10.1093/njaf/24.3.197.

Nyland, R.D. 2003. Even- to uneven-aged: the challenges of conversion. For. Ecol. Manage. **172**: 291–300. doi:10.1016/S0378-1127(01)00797-6.

Nyland, R.D. 2016. Silviculture: concepts and applications. 3rd. ed. Waveland Press, Inc.

Orr, B.D., Reed, D.D., and Mroz, G.D. 1994. Three basal area level harvest trials in uneven-aged northern hardwoods. North. J. Appl. For. **11**: 117–123. doi:10.1093/njaf/11.4.117.

Raymond, P., Bédard, S., Roy, V., Larouche, C., and Tremblay, S. 2009. The irregular shelterwood system: review, classification, and potential application to forests affected by partial disturbances. J. For. **107**: 405–413.

Schwartz, J.W., Nagel, L.M., and Webster, C.R. 2005. Effects of uneven-aged management on diameter distribution and species composition of northern hardwoods in Upper Michigan. For. Ecol. Manage. **211**: 356–370. doi:10.1016/j.foreco.2005.02.054.

Smith, H.C., and Miller, G.W. 1987. Managing Appalachian hardwood stands using four regeneration practices — 34-year results. North. J. Appl. For. **4**: 180–185. doi:10.1093/njaf/4.4.180.

Strong, T.F., Erdmann, G.G., and Niese, J.N. 1995. Forty years of alternative management practices in second-growth, pole-size northern hardwoods. I. Tree quality development. Can. J. For. Res. **25**(7): 1173–1179. doi:10.1139/x95-129.

Tubbs, C.H. 1977. Age and structure of a northern hardwood selection forest, 1929–1976. J. For. **75**: 22–24.