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ARTICLE

Proportional basal area method for implementing selection silviculture systems in longleaf pine forests

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Abstract: Proportional basal area (Pro-B) was developed as an accurate, easy-to-use method for making uneven-aged silviculture a practical management option. Following less than 3 h of training, forest staff from a range of professional backgrounds used Pro-B in an operational-scale field study to apply single-tree selection and group selection systems in longleaf pine (*Pinus palustris* Mill.) stands. Field crews achieved precision levels often within 3%–5% of the 11.5 $m^2 \cdot ha^{-1}$ target residual basal area. By aggregating many diameter classes into only three diameter-class groups, Pro-B improves efficiency by requiring tree markers to remember only three fractions, while making a single pass through the stand. Trees of large size, specific species and with good form, broad crowns and cavities can be retained, while adjusting spacing to release residuals. Systematic quantification of marking trees for removal enables different individuals to obtain similar results. Early observations revealed encouraging levels of pine regeneration and stand development, along with continuing good volume growth rates of 3% per year. Although less certain until one or more cutting cycles are completed, these early tests indicate that a stable mature forest structure should develop, which is characterized by the presence of large trees and natural regeneration.

Key words: Pinus palustris Mill., multiaged silviculture, single-tree selection, group selection, Proportional-B.

Résumé : La surface terrière proportionnelle (ST-Pro) est une méthode précise et facile d'utilisation qui a été mise au point pour que la sylviculture inéquienne devienne une option pratique d'aménagement. Avec moins de trois heures d'entraînement, du personnel forestier provenant de divers milieux professionnels a utilisé ST-Pro dans le cadre d'une étude de terrain à l'échelle opérationnelle pour appliquer les systèmes de jardinage par pied d'arbre et par groupe à des peuplements de pin des marais (*Pinus palustris* Mill.). Les équipes de terrain ont souvent atteint des niveaux de précision variant entre 3 et 5 % de la valeur cible de surface terrière résiduelle qui était de 11,5 $m^2 \cdot ha^{-1}$. En regroupant plusieurs classes de diamètre en seulement trois groupes, la ST-Pro augmente l'efficacité en demandant aux marteleurs de ne retenir que trois fractions lors de leur passage unique dans le peuplement. Des arbres de grande taille, d'espèces particulières et ayant une belle forme, une large cime et des cavités peuvent être retenus tout en ajustant l'espacement entre les arbres résiduels. La quantification systématique des arbres marqués pour la récolte permet à différentes personnes d'obtenir des résultats similaires. Des observations préliminaires ont montré que la régénération en pin et le développement des peuplements montraient des signes encourageants tout en maintenant un bon taux de croissance en volume de 3 % par année. Bien que les résultats soient incertains jusqu'à ce qu'au moins un cycle de coupe soit complété, ces tests préliminaires indiquent qu'une structure stable de forêt mature devrait se développer, ce qui se caractérise par la présence de gros arbres et de régénération naturelle. [Traduit par la Rédaction]

Mots-clés : Pinus palustris Mill., sylviculture inéquienne, jardinage par pied d'arbre, jardinage par groupe, surface terrière proportionnelle.

Introduction

Ecosystem management emphasizing biodiversity conservation and long-term sustainability has, in recent years, increased interest in multi-aged structures that require practice of uneven-aged silviculture (O'Hara 1998). This trend in North America is parallel to the rising interest in continuous cover forestry in Europe (Mason et al. 1999) and worldwide emergence of retention forestry, which emphasizes creation of complex forest structures containing biological legacies through management that simulates natural disturbances in a landscape context (Gustafsson et al. 2012). The need for uneven-aged silviculture may be nowhere more urgent than in the pine forests of the southeastern United States, where even-aged methods for timber production have led to adverse consequences for other ecosystem values (Guldin 2006). Protecting native plant communities, maintaining continuous forest canopy, and facilitating development of large, old trees are among the desirable habitat features resulting when uneven-aged silviculture is applied in an adaptive management framework (Brockway et al. 2006). Uneven-aged silviculture also affords a major advantage in that natural regeneration is more or less continuous through time, as late-successional stand dynamics are emulated (Guldin 1996).

Despite an historical decline, longleaf pine (*Pinus palustris* Mill.) forests are highly valued for a variety of resources having ecological, economic, and cultural importance, and substantial interest has recently emerged in best management approaches for sustaining and restoring them (Brockway et al. 2005*b*; Van Lear et al. 2005). Although longleaf pine has been mostly managed with even-aged methods and was formerly thought to be too intolerant for uneven-aged silviculture (Croker and Boyer 1975), recent evidence suggests this to be a viable alternative (Farrar 1996; Palik et al. 1997; Brockway and Outcalt 1998; McGuire et al. 2001;

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Gagnon et al. 2003). Longleaf pine can grow in pure stands and also in association with numerous trees species across a wide range of site types, including slash pine (*Pinus elliottii* Engelm.) on flatwoods, loblolly pine (*Pinus taeda* L.), and shortleaf pine (*Pinus echinata* Mill.) on mesic uplands, and various hardwoods on xeric sandhills, mountains, and other site types (Boyer 1990). This natural variety indicates that no single prescription is appropriate for sustaining longleaf pine everywhere. Prudent managers will select approaches appropriate for their specific environment and management objectives, which can lead to (*i*) an overstory dominated by mature longleaf pine occurring as uneven-aged stands or even-aged patches across an uneven-aged landscape, with a lesser component of other tree species, (*ii*) a midstory that is generally absent or mostly composed of ascending longleaf pine in scattered, modestly-sized canopy gaps, and (*iii*) an understory with abundant longleaf pine seedlings and groundcover dominated by native grasses and forbs with lesser cover of shrubs and vines (Brockway et al. 2005*b*).

Research has fostered improved technology for the establishment, recovery, and maintenance of longleaf pine ecosystems (Jose et al. 2006). While there is a role for even-aged and uneven-aged approaches, even-aged methods are better developed than uneven-aged methods. Existing uneven-aged methods seem complicated and perhaps too constraining for longleaf pine management. The BDq method (Leak 1964; Marquis 1978) was recommended following early field tests for uneven-aged silviculture in longleaf pine, using a residual basal area (*B*) of 13.8 $m^2{\cdot}ha^{-1}$, a maximum diameter (D_{max}) of 50 cm, and a diameter distribution defined by a *q*-value of 1.44 for 5 cm diameter classes (Farrar 1996). However, the D_{max} in BDq does not encourage retaining large trees and the *q*-value of BDq fosters an artificial mathematical construct rather than the more dynamic ecological relationship preferable for longleaf pine stands. The volume control-guiding diameter limit (VCGDL) method (Farrar 1996; Guldin 1996) relies on marking volume rather than basal area, which we believe is more easily quantified. Thus, there may be opportunities to develop a way of tending uneven-aged stands by focusing on basal area and accommodating larger trees, while marking stands in a single pass.

Method based on proportional basal area

Recognition that *B* is the most important of these stand structure variables, resulted in deletion of the requirements to identify a D_{max} and adhere to a specific *q*-value. Basal area is biologically linked to the cross-sectional area of sapwood, hence, leaf area index and the total foliar display of the stand (O'Hara and Valappil 1999; O'Hara et al. 2001; O'Hara and Gersonde 2004). Basal area may also be used for expressing stand condition relative to stocking, competition, and prospects for regeneration success. Unless optimal timber production is desired, there is no need to set a tree-diameter size limit or a specific *q*-value, since basal area occurring in a small number of trees in the larger diameter classes can be compensated for through adjustments in the smaller diameter classes. A key consideration is accounting for the presence of trees in all diameter classes. Ease of measurement in the field makes apportioning basal area by diameter classes preferable to doing so for stem density. A method that apportions basal area across broad diameter classes will be easy to use. Thus, *B* was retained as the principal index for the Pro-B method. Rather than tallying individual trees for numerous 5 cm diameter classes, the many diameter classes were combined into three diameter-class groups, each representing a stage in stand development and potential product (<15 cm, 15–30 cm, >30 cm at dbh). Tree marking was also changed to simply mark the fraction of trees that should be removed in each diameter-class group. To attain the target stand structure, tree markers need to remember at most only three fractions that represent the rate of tree removal in each of the three diameter-class groups. This process systematically apportions residual basal area among diameter-class groups, thus the name arose as Proportional-B (for "proportional basal area"), or more simply Pro-B.

While even-aged silviculture of longleaf pine is well understood, less is known about the effects of uneven-aged silviculture. Although selection silviculture techniques can be used to mimic the natural stand replacement dynamics that occur in longleaf pine forests, it is less clear whether they can ensure that regeneration goals will be met. The primary objectives of this study were to quantify the effects of applying single-tree selection and group selection via Pro-B on (1) pine regeneration, (2) stand development, and (3) volume growth. Secondary objectives included (4) discerning accuracy of the Pro-B method for obtaining the target residual basal area and (5) observing the ease with which managers from a range of professional backgrounds could learn and apply Pro-B in the field. Analysis of changes in stand density, basal area, growth, regeneration, and the accuracy with which Pro-B can be applied should help managers determine whether Pro-B can be used as a practical field method for attaining the objectives of continuous cover forestry and retention forestry.

Methods

Study sites and management history

Flatwoods

The Goethe State Forest is located 24 km east of the Gulf of Mexico (29°13′N, 82°33′W), on the Lower Coastal Plain of the Florida peninsula. Temperatures in the humid subtropical climate range from a maximum of 33 °C in summer to a minimum of 5 °C in winter. Annual precipitation averages 1448 mm, arriving mostly from April to September. At 15 m above sea level, topography is nearly level and dominated by Smyrna fine sand (Aeric Alaquod), which is very deep, poorly-drained, low in organic matter and nutrients, and low in water-holding capacity (Slabaugh et al. 1996).

The overstory was dominated by longleaf pine, with lesser amounts of slash pine and very few hardwoods. Tree seedlings were few and mostly comprised of slash pine, longleaf pine, sweetgum (*Liquidambar styraciflua* L.), and oaks (*Quercus* spp. L.). Understory plants were dominated by shrubs, primarily saw-palmetto (*Serenoa repens* W. Bartram) and gallberry (*Ilex glabra* (L.) A. Gray), with lesser amounts of wax myrtle (*Myrica cerifera* L.), dwarf live oak (*Quercus minima* (Sarg.) Small), shiny blueberry (*Vaccinium myrsinites* Lam.), and fetterbush (*Lyonia lucida* (Lam.) K. Koch). Because of shrub dominance, the herbaceous layer was poorly developed, with wiregrass (*Aristida beyrichiana* Trin. & Rupr.), broomsedge bluestem (*Andropogon virginicus* L.), witchgrass (*Dichanthelium* spp. Willemet), and nodding fescue (*Festuca obtusa* (Pers.) E.B. Alexeev) the most prominent grasses.

These flatwoods were cutover about 100 years ago and then subjected to a 50 year period of fire exclusion, during which trees recovered and saw-palmetto expanded to now dominate the understory. Since 1992, active programs of prescribed burning on a 3 year cycle and timber harvest have been implemented to foster multiple-use management and restore the ecosystem. The most recent pretreatment prescribed fire was applied to the study area during April 2005. Stands received improvement cuts between 1997 and 2004. Overstory pines were 48–74 years in age, and site index ranged from 21 to 24 m at 50 years.

Uplands

The Blackwater River State Forest is located 48 km north of the Gulf of Mexico (30°47′N, 86°44′W), on the Middle Coastal Plain of the Florida panhandle. Average temperatures range from 27 °C in summer to 12 °C in winter. Annual precipitation averages 1651 mm, with about half arriving from June to September. At 61 m above sea level, topography is nearly level to gently inclined.

Soils include the Troup (Grossarenic Paleudult), Orangeburg (Typic Paleudult), Lucy (Arenic Paleudult), and Dothan (Plinthic Paleudult) series, which are deep, well-drained and sandy soils, low in organic matter and nutrients, and low to moderate in water-holding capacity (Weeks et al. 1980).

The overstory was dominated by longleaf pine, with a smaller component of hardwoods and slash pine. Tree seedlings were abundant in the understory, with southern red oak (*Quercus falcata* Michx.), bluejack oak (*Quercus incana* W. Bartram), post oak (*Quercus stellata* Wangenh.), persimmon (*Diospyros virginiana* L.), and longleaf pine most common. Dangleberry (*Gaylussacia frondosa* (L.) Torr. & A. Gray ex. Torr.), blueberries (*Vaccinium* spp. L.), blackberries (*Rubus* spp. L.), wax myrtle, gallberry, winged sumac (*Rhus copallinum* L.), and gopherapple (*Licania michauxii* Prance) were the most prominent shrubs. The herbaceous layer was well developed and species-rich, with wiregrass and broomsedge bluestem dominating the grasses, with lesser amounts of witchgrass, crowngrass (*Paspalum* spp. L.), lopsided Indiangrass (*Soghastrum secundum* (Elliott) Nash), and purpletop (*Tridens flavus* L.). The most common forbs were silverthread goldaster (*Pityopsis graminifolia* (Michx.) Nutt.), morning-glory (*Ipomea* spp. L.), milkpea (*Galactia volubilis* (L.) Britton), and noseburn (*Tragia urens* L.).

These uplands were occupied by second-growth longleaf pine that naturally regenerated following cutover of the original forest during the 1920s. Most of the overstory pines were about 66 years old, with the oldest being 80 years in age. Site index is 24 m at 50 years. This site has been managed with numerous prescribed fires since 1970, on a 3 year burning cycle. The most recent pretreatment prescribed fire was applied to the study area during December 2004. Improvement cutting during 1981 and 1991 and hurricane-salvage in late 2004 were followed by waves of natural regeneration that resulted in an uneven-aged structure.

Study design and experimental treatments

In June and July 2004, a randomized complete block study design was installed as three replications of the two silvicultural treatments (single-tree selection and group selection) plus three control stands (no harvest) at each site. During May 2005, treatments were randomly assigned within the three replications that were aggregated as blocks to topographically account for moisture gradient or spatial differences. The 9 plots (stands) are each 9 ha (300m × 300 m) and totaled 81 ha at each forest. Within each treatment plot, five 0.1 ha measurement subplots were randomly located, each 20m × 50 m with the long axis oriented in a north-south direction. In all treated stands, the forest matrix was tended by reducing basal area to 11.5 $m^2 \cdot ha^{-1}$ using Pro-B, and in group selection stands, three 0.1–0.2 ha gaps were then created in each 9 ha plot. Canopy gap width ranged from 1.4 to 2 times the height of adjacent dominant trees.

Applying the Pro-B method

Computing tree-marking guides

Pretreatment inventory data collected from each stand represented a 6% sample fraction and were the basis for computing tree-marking guides. These data were entered into the Pro-B Calculator, which is a Microsoft Excel-based computing tool developed during this study. This calculator has tabular fields for the input of stand inventory data and output of tree-marking guides and graphic displays of the pre-cutting and post-cutting forest structure. As quickly as the data are entered, the Pro-B Calculator populates the output graphs and tables, displaying tree-marking guides that need to be used for achieving the target. This calculator makes the computation of tree-marking guides much easier and provides practitioners with an opportunity to consider the projected results, in tabular and graphic formats, before deciding whether to proceed with field application or adjust the prescription.

A target residual basal area of 11.5 $m^2 \cdot ha^{-1}$ was specified for stands receiving the single-tree selection and group selection treatments. In both treatments, a dispersed pattern of trees was obtained by adjusting spacing among residuals. In the group selection treatment, three gaps of 0.1–0.2 ha in area were cut in locations already containing advanced regeneration or having an herb-dominated groundcover suitable for regeneration. This 11.5 $m^2 \cdot ha^{-1}$ target was selected to reflect the relative intolerance of longleaf pine and contrast this work to earlier selection research in southern pines, using 13.8 $m^2 \cdot ha^{-1}$ (Farrar 1996; Guldin and Baker 1998). Pro-B apportioned residual basal area in a ratio of 1:2:3, leaving the post-harvest stands with 1.91 $m^2 \cdot ha^{-1}$ in the small (<15 cm), 3.84 $m^2 \cdot ha^{-1}$ in the medium (15–30 cm), and 5.75 $m^2 \cdot ha^{-1}$ in the large (>30 cm) diameter-class groups. To obtain the target basal area in these stands, a tree removal rate (by diameter-class group) typically ranged from cut-one-of-four-trees (1/4) to cut-two-of-three-trees (2/3). Rarely, were lighter or heavier cutting rates indicated. For any given stand, the practitioner needed to keep in mind no more than three fractions (one for each diameter-class group) while making a single pass for tree marking. As with other selection methods, conducting commercial cutting in the <15 cm diameter-class group remains challenging. Our stands typically contained a basal area for trees <15 cm at dbh, which was less than the target for that small diameter-class group. However, when present in excess of the target, these smaller trees were marked and either harvested by the logger or run over by machinery.

Training workshops and field application

Outputs from the Pro-B Calculator were incorporated into a training booklet used to supplement oral instructions provided at two field workshops, held at the Goethe State Forest in February 2006 and Blackwater River State Forest in March 2006. Each indoor training session lasted less than three hours and presented (*i*) an overview of selection silviculture, (*ii*) fundamentals of the Pro-B method and computations, and (*iii*) field considerations. Following questions and discussion, each group was ready for Pro-B implementation in the field.

In the field, newly-trained practitioners arrayed themselves 20 m apart in a line along the edge of each stand and made a single pass through, covering their 20 m wide assigned lane and painting trees they identified for removal in accordance with the marking guides. Although the instructors were present, almost no coaching was needed. Practitioners (ranging from administrators to field foresters to wildlife biologists to recreation managers to GIS specialists) demonstrated substantial skill in marking stands to a high level of precision (often within 3%–5% error of the target). Therefore, our first secondary objective was met, that high accuracy in the field can be achieved when using the Pro-B method to mark to a target residual basal area. Their work yielded a remarkably uniform result for groups as large as a dozen or more. Along with the Pro-B numeric marking guides, they easily incorporated marking rules, such as (*i*) take the worst and leave the best trees, (*ii*) remove less desirable species, (*iii*) adjust spacing to release residual trees, and (*iv*) retain snags, live cavity trees and large trees with broad crowns that can benefit wildlife. Thus, in addressing our next secondary objective, we observed that managers from a range of professional backgrounds could easily learn and effectively apply Pro-B in the forest. In November and December 2006, marked trees were harvested by private logging contractors.

Measurements and analysis

In winter 2005, tree data were collected on all subplots to establish pretreatment stand conditions. Species was recorded and diameter of all trees greater than 2.5 cm at dbh was measured to the nearest mm. The total height of trees in a subsample representing the full range of size classes was also measured to the nearest 0.1 m, to establish the height–diameter relationships for longleaf pine and slash pine. Repeated posttreatment measurements of trees were then completed following the 2006, 2007, and 2008 growing seasons. Following the 2005 and 2008 growing seasons, the number of slash pine seedlings and grass-stage (height < 15 cm) and bolt-stage (height 15 cm to 2 m) longleaf pine seedlings were recorded on all subplots.

Data for trees and pine seedlings from each of the five 0.1 ha subplots were combined and summarized as estimates of the mean for each 9 ha plot and analyzed by treatment and change through time. Stand density and basal area were calculated from tree diameter data. Height–diameter relationships for longleaf pine and slash pine were computed by regression analysis, using height and diameter data (Hintze 2007). Stand volumes ($m^3 \cdot ha^{-1}$) were calculated for each species, by summing individual tree volumes to a 10 cm top outside bark on an area basis and using our height and diameter data in regional equations (Saucier et al. 1981). Means of the dependent variables for each 9 ha plot were used to estimate the means and variances for the treatments. A repeated measures ANOVA was used to evaluate time and treatment effects and interactions (Hintze 2007). Responses of treatments were compared using pairwise contrasts. The trend through time after treatment was analyzed using orthogonal polynomials. Significant differences were discerned at the 0.05 level.

Results

Stand structure

On the Goethe State Forest flatwoods, harvest reduced density from 311 to 183 trees ha^{-1} with single-tree selection and from 321 to 165 trees ha^{-1} with group selection (Table 1). Declines in tree density were 41% following single-tree selection and 49% after group selection, with harvested stands significantly less dense than uncut controls. Cutting also reduced stand basal area from 16.3 to 11.7 $m^2 \cdot ha^{-1}$ with single-tree selection and from 16.7 to 10.3 $m^2 \cdot ha^{-1}$ with group selection. Declines in basal area were 28% following single-tree selection and 38% after group selection, again with lower residual basal areas than control stands. The similarity between treatments for percentage declines in density and basal area resulted from cutting trees across a range of diameter classes, as evidenced by no significant change in the quadratic mean tree diameter in the stands.

On the Blackwater River State Forest uplands, harvest reduced density from 338 to 264 trees ha^{-1} with single-tree selection and from 494 to 383 trees ha^{-1} with group selection (Table 2). Declines in tree density were 22% following both single-tree selection and group selection, with only single-tree selection stands significantly less dense than controls. Prior to treatment, group selection stands were significantly denser than controls. Cutting also reduced stand basal area from 14 to 11 $m^2 \cdot ha^{-1}$ with single-tree selection and from 16.9 to 11.2 $m^2 \cdot ha^{-1}$ with group selection. Hurricane Ivan reduced basal areas from a pre-impact estimate of about 16 to the 11.1 $m^2 \cdot ha^{-1}$ levels recorded in 2005 for the control stands. Declines in basal area from cutting were 21% following single-tree selection and 34% after group selection. As trees across a range of diameter classes were cut, little change occurred in the quadratic mean tree diameter. Stand development following group selection is shown in Fig. 1. Rising seedling numbers in the 1.3 cm diameter class during 2008 translated into a surge of new saplings in the 5 cm diameter class by 2009.

Tree volume and growth

On the Goethe State Forest flatwoods, total pine volume in treated stands prior to harvest averaged 137.1 $m^3 \cdot ha^{-1}$, which was similar to the 135.3 $m^3 \cdot ha^{-1}$ in control stands (Table 3). Overall, volumes were divided between longleaf pine and slash pine on an 80% to 20% basis in treated stands and a 59% to 41% basis in controls. Prior to cutting, a significantly greater volume of longleaf pine was present only in stands scheduled for treatment with single-tree selection (121.5 $m^3 \cdot ha^{-1}$). Both selection methods reduced stand volume to levels significantly less than in uncut controls (142.5 $m^3 \cdot ha^{-1}$). Single-tree selection reduced stand volume by 26% to 100.7 $m^3 \cdot ha^{-1}$, while group selection reduced stand volume by 36% to 88 $m^3 \cdot ha^{-1}$. Although small volume losses occurred among longleaf pine dominants in single-tree selection stands during the first posttreatment growing season (2008) because of post-harvest mortality and weather conditions, by the following growing season (2009), annual volume growth was again positive at 2%–4%.

On the Blackwater River State Forest uplands, total pine volume in treated stands prior to harvest averaged 98.6 $m^3 \cdot ha^{-1}$, which was not significantly different from the 89.3 $m^3 \cdot ha^{-1}$ in controls (Table 4). These volumes were predominantly longleaf pine, with slash pine comprising only 4% in single-tree selection stands and less than 1% in controls. Both selection methods resulted in stand volume reductions to levels that were significantly less than the

Table 1. Mean stand density, basal area and diameter responses to reproduction methods at the Goethe State Forest for pretreatment (2005) and posttreatment (2007–2009) years.

	Control	Single-tree selection	Group selection
Density (trees·ha⁻¹)			
2005	321	311	321
2007	316	183^{a,b}	165^{a,b}
2008	319	183^{a,b}	170^{a,b}
2009	324	183^{a,b}	168^{a,b}
Basal area ($m^2 \cdot ha^{-1}$)			
2005	15.9	16.3	16.7
2007	16.6	11.7^{a,b}	10.3^{a,b}
2008	16.2	11.6^{a,b}	10.3^{a,b}
2009	16.7	12.0^{a,b}	10.5^{a,b}
Quadratic mean diameter (cm)			
2005	22.6	25.4	23.9
2007	23.4	27.9	26.2
2008	23.1	27.7	25.9
2009	22.9	27.9	26.4

[a]Significantly different from control, $p < 0.05$.
[b]Significant change through time from pretreatment condition, $p < 0.05$.

Table 2. Mean stand density, basal area and diameter responses to reproduction methods at the Blackwater River State Forest for pretreatment (2005) and posttreatment (2007–2009) years.

	Control	Single-tree selection	Group selection
Density (trees·ha⁻¹)			
2005	363	338	494^{a}
2007	346	264^{a,b}	383^{b}
2008	393	291^{a,b}	447^{b}
2009	398	301^{a,b}	462
Basal area ($m^2 \cdot ha^{-1}$)			
2005	11.1	14.0	16.9^{a}
2007	11.6	11.0^{b}	11.2^{b}
2008	11.7	11.4^{b}	11.7^{b}
2009	11.9	11.6^{b}	12.0^{b}
Quadratic mean diameter (cm)			
2005	15.7	18.5	15.1
2007	16.5	18.5	15.5
2008	15.0	17.8	13.7
2009	15.2	17.5	13.7

[a]Significantly different from control, $p < 0.05$.
[b]Significant change through time from pretreatment condition, $p < 0.05$.

Fig. 1. Stand development following application of group selection via Pro-B at the Blackwater River State Forest uplands. Harvest during late 2006 caused a decline in tree density by winter 2007, mostly in diameter classes <40 cm. Increased seedling density was noted in the 1.3 cm diameter class by winter 2008, which led to an increased sapling density in the 5 cm diameter class by winter 2009.

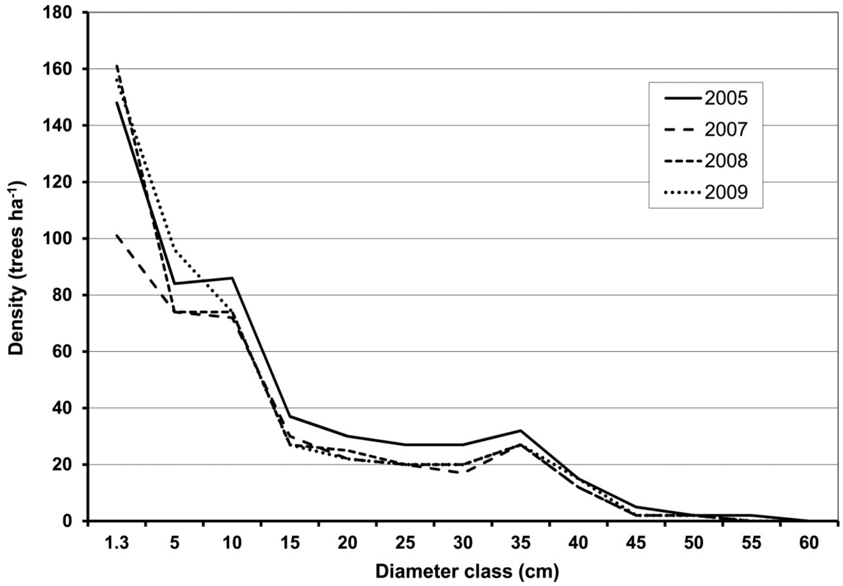

Table 3. Mean stand volume (m³·ha⁻¹) response to reproduction methods at the Goethe State Forest for pretreatment (2005) and posttreatment (2007–2009) years.

	Control	Single-tree selection	Group selection
Longleaf pine			
2005	79.4	121.5[a]	98.1
2007	82.5	90.0[b]	64.2[a,b]
2008	81.9	88.3[b]	64.7[a,b]
2009	79.7	92.1[b]	65.2[a,b]
Slash pine			
2005	55.9	14.4[a]	40.2
2007	60.0	10.7[a,b]	23.8[a,b]
2008	57.3	10.0[a,b]	23.7[a,b]
2009	63.7	10.2[a,b]	25.3[a,b]
Total pine			
2005	135.3	135.9	138.3
2007	142.5	100.7[a,b]	88.0[a,b]
2008	139.2	98.3[a,b]	88.4[a,b]
2009	143.4	102.3[a,b]	90.5[a,b]

[a]Significantly different from control, $p < 0.05$.
[b]Significant change through time from pretreatment condition, $p < 0.05$.

Table 4. Mean stand volume (m³·ha⁻¹) response to reproduction methods at the Blackwater River State Forest for pretreatment (2005) and posttreatment (2007–2009) years.

	Control	Single-tree selection	Group selection
Longleaf pine			
2005	88.6	96.7	97.1
2007	90.7	71.3[a,b]	72.8[a,b]
2008	90.8	74.8[a,b]	70.8[a,b]
2009	92.9	76.7[a,b]	73.0[a,b]
Slash pine			
2005	0.7	3.5[a]	0.0
2007	0.7	1.2[b]	0.0
2008	0.7	1.2[b]	0.0
2009	0.9	1.2[b]	0.0
Total pine			
2005	89.3	100.2	97.1
2007	91.4	72.5[a,b]	72.8[a,b]
2008	91.5	76.0[a,b]	70.8[a,b]
2009	93.8	77.9[a,b]	73.0[a,b]

[a]Significantly different from control, $p < 0.05$.
[b]Significant change through time from pretreatment condition, $p < 0.05$.

volumes remaining in the uncut controls (91.4 m³·ha⁻¹). Single-tree selection reduced stand volume by 28% to 72.5 m³·ha⁻¹, while group selection reduced stand volume by 25% to 72.8 m³·ha⁻¹. Although small volume losses occurred among longleaf pine dominants in group selection stands during the first posttreatment growing season (2008) because of post-harvest mortality and weather conditions, by the next growing season (2009), annual volume growth was positive at 3%.

Pine regeneration

On the Goethe State Forest flatwoods, grass-stage longleaf pine prior to treatment averaged 49 seedlings·ha⁻¹ overall, with only those in the group selection stands significantly lower at 22 seedlings·ha⁻¹ (Table 5). Two years after harvest (2008), longleaf pine in the grass stage significantly increased (143%) to 119 seedlings·ha⁻¹ overall. Bolt-stage longleaf pines were present in as yet very low densities (0–7 seedlings·ha⁻¹). Conditions favoring a rising density in grass-stage longleaf pines have not yet facilitated bolting of the seedlings. Slash pine densities, initially 25–35 seedlings·ha⁻¹, while rising in all stands, significantly increased only in group selection stands to 173 seedlings·ha⁻¹.

On the Blackwater River State Forest uplands, grass-stage longleaf pine prior to treatment averaged 4566 seedlings·ha⁻¹, overall (Table 6). Two years after harvest (2008), longleaf pine in the grass stage significantly declined by 69% to an overall average of 1430 seedlings·ha⁻¹. Bolt-stage longleaf pines were initially present at about 88 seedlings·ha⁻¹, with significantly higher densities in group selection stands (180 seedlings·ha⁻¹). Two years after harvest, bolt densities improved to become comparable in all treatments (164 seedlings·ha⁻¹ overall). Slash pine regeneration densities initially ranged from 0–22 seedlings·ha⁻¹ and increased significantly only in single-tree selection stands to 128 seedlings·ha⁻¹.

Table 5. Pine regeneration response (seedlings·ha^{-1}) to reproduction methods at the Goethe State Forest for pretreatment (2005) and posttreatment (2008) years.

	Control	Single-tree selection	Group selection
Grass-stage longleaf pine			
2005	62	64	22[a]
2008	101[b]	128[b]	128[b]
Bolt-stage longleaf pine			
2005	5	2	0
2008	7	5	0
All longleaf pine			
2005	67	66	22[a]
2008	108[b]	133[b]	128[b]
Slash pine			
2005	27	25	35
2008	47	57	173[a,b]

[a]Significantly different from control, $p < 0.05$.
[b]Significant change through time from pretreatment condition, $p < 0.05$.

Table 6. Pine regeneration response (seedlings·ha^{-1}) to reproduction methods at the Blackwater River State Forest for pretreatment (2005) and posttreatment (2008) years.

	Control	Single-tree selection	Group selection
Grass-stage longleaf pine			
2005	3732	5622	4345
2008	1796[b]	1208[b]	1287[b]
Bolt-stage longleaf pine			
2005	91	84	180[a]
2008	161[b]	126[b]	205
All longleaf pine			
2005	3824	5706	4525
2008	1956[b]	1334[b]	1492[b]
Slash pine			
2005	0	22	0
2008	7	128[a,b]	2

[a]Significantly different from control, $p < 0.05$.
[b]Significant change through time from pretreatment condition, $p < 0.05$.

Discussion

Goethe State Forest flatwoods

Stand dynamics reflected ecosystem maintenance with prescribed fire and tree removal, causing reductions in density, basal area, and volume. Following treatment, the stands continued growing at normal rates (2%–4%). This finding fits the pattern of no growth loss for periodically burned longleaf pine larger than sapling size (Boyer and Miller 1994).

These stands were characteristic of seldom-burned forests, with low-density regeneration of less than 70 grass-stage seedlings·ha^{-1} and 10 bolt-stage seedlings·ha^{-1}. Such low levels resulted from competition with saw-palmetto that came to dominate the understory during an earlier period of fire exclusion and create a shrub-canopy with very few openings for seedling establishment. Burning and mechanical disturbance of tree harvest sufficiently diminished shrub cover, so that grass-stage longleaf pine regeneration density more than doubled. This is encouraging, since regeneration is a key requirement for sustaining longleaf pine forests (Brockway et al. 2006). However, without significant differences among stands, the increase in seedling density from an average of 42 to 119 seedlings·ha^{-1} could not be attributed to cutting, but was more likely the result of large-scale factors, such as seed dispersal and weather.

A strong relationship exists between disturbances like fire and the composition of understory vegetation in forests (Outcalt 2000), with frequently burned stands having fewer woody plants and a greater prominence of herbaceous plants (Glitzenstein et al. 2003). Although fire can reduce the cover of shrubs like gallberry (Brockway and Lewis 1997), many burning cycles are required to reduce robust shrubs like saw-palmetto, with its extensive system of rhizomes and capacity for rapid regrowth. Since longleaf pine ecosystems are prone to and highly resilient to disturbances such as surface fire and partial canopy reduction (Stanturf et al. 2007; Outcalt 2008), they are well suited to management using periodic prescribed burning and selection cutting cycles. Stand dynamics after cutting showed no ingrowth of seedlings into the sapling stage or recruitment among larger trees. In this highly competitive environment, additional time may be required for pine development to ensue.

Blackwater River State Forest uplands

Stand dynamics were dominated by tree removal during unplanned hurricane salvage and planned tree harvest, with reductions in density, basal area, and volume. But regardless of treatment, pine growth continued at normal rates (3%). These stands were typical of forests that are regularly tended and burned with prescribed fire, having a well developed longleaf pine overstory with a lesser component of hardwoods and a grass-dominated understory with abundant longleaf pine regeneration. Although the forest was impacted by hurricane winds in September 2004, the machine traffic of salvage operations had little adverse effect on longleaf pine regeneration, with densities of 3732–5622 grass-stage seedlings·ha^{-1} and 84–180 bolt-stage seedlings·ha^{-1} in 2005. With no significant differences among the treatments, the decline of grass-stage longleaf pine, from an average of about 4500 to 1400 seedlings·ha^{-1}, could not be attributed to cutting. Nor could this 69% decrease be explained as mortality from prescribed burning, since the most recent fire had been in 2004. When considering the occurrence of several dry years during this time interval, the decline in grass-stage seedlings was most likely a result of drought-induced mortality across the entire site. Although grass-stage longleaf pine seedlings may persist for many years beneath the forest canopy, the longer they remain unreleased, the greater the probability they will die from competition, drought and (or) fire (Boyer 1990; Brockway and Outcalt 1998; Brockway et al. 2006).

Conversely, the rise in bolt-stage longleaf pine was encouraging, with the overall density increasing up to an average of 164 seedlings·ha^{-1}. But occurring across all stands, this change could not be attributed to cutting. Conditions causing the decline in grass-stage seedlings did not impair development of the bolt-stage seedlings. However, one could speculate that under less stressful conditions, perhaps a greater number of grass-stage longleaf pine seedlings might have initiated height growth and moved into the bolt stage. Competition intensity can influence the proportion of seedlings that emerge from the grass stage (Haywood 2000). Continued cycles of prescribed fire and periodic selection cutting should maintain conditions favorable for regeneration (Glitzenstein et al. 1995; Outcalt and Brockway 2010) and ecosystem resiliency to a variety of disturbance agents (Stanturf et al. 2007). Stand dynamics after cutting showed a rise in seedling numbers in the 1.3 cm diameter class during 2008 that translated into a surge of new saplings in the 5 cm diameter class by 2009.

Implementing uneven-aged silviculture

Single-tree selection has the advantage of maintaining a high level of canopy cover while periodically allowing removal of some trees from the forest. However, since longleaf pine is known to be intolerant of competition for light and soil resources, it was unclear whether it can regenerate and fully develop in the small space resulting from the death of a single overstory tree (Brockway et al. 2005*a*). Most evidence indicated that several longleaf pine trees must fall from the canopy before sufficient space is available to allow longleaf pine juveniles to begin recruiting into the canopy (Brockway et al. 2006). Group selection can simulate the natural gap-phase regeneration process of longleaf pine by simultaneously tending the forest matrix and creating small canopy gaps (Brockway and Outcalt 1998). Although natural regeneration often occurs widely in the forest, young longleaf pine are usually more concentrated and better developed in canopy gaps ranging from 0.1–0.8 ha in size. Gaps may resemble very small clearings or contain scattered mature trees (i.e., reserves) and typically regenerate as even-aged cohorts in an uneven-aged matrix. Thus, the resulting forest eventually becomes an uneven-aged mosaic of even-aged patches. Patches with similar age cohorts need to be sufficiently dispersed to achieve the desired result (Brockway et al. 2006). As long as herbaceous plants dominate the periodically burned gaps, longleaf pine seed should germinate, and seedlings will become established when good seed years are followed by favorable weather. Creating group openings at locations where regenerating seedlings already exist is an effective way to promote their release and eventual recruitment into the canopy.

Extensive research performed with BDq in North America has resulted in adaptations that improve its field application in a variety of forest types (Eyre and Zillgitt 1953; Arbogast 1957; Leak 1964; Leak and Filip 1975; Marquis 1978; Leak et al. 1987; Nyland 1987, 1998, 2007; Anderson et al. 1990; Farrar 1996; Guldin and Baker 1998; Guldin 2011). Pro-B is somewhat different, in that it was more recently developed to serve both timber production and biodiversity conservation purposes, while specifically retaining larger trees in the forest. The Pro-B stand structure is not rigidly defined by a *q*-value, recognizing that a diameter distribution may correspond to multiple *q*-values that can vary through time (Leak and Filip 1975). The usefulness of a *q*-value is that it helps a silviculturist maintain a greater number of trees in smaller diameter classes than in larger diameter classes, which is important for ensuring long-term sustainability in uneven-aged stands. However, tending an uneven-aged stand so that its diameter distribution exactly matches a *q*-defined curve is an exercise of imposing arbitrary human values on the ecosystem (O'Hara 1998). Doing so ignores the wider range of structures that can be sustainable (O'Hara 1996; Seymour and Kenefic 1998). A substantial problem with *q*-based approaches is that reliance on them can create a false sense of stability, where imbalances in age structure may not become evident until well after they can be easily addressed (Seymour and Kenefic 1998).

Alternatively, Pro-B stand structure is defined by the proportion of basal area distributed among diameter-class groups, typically in a ratio of 1:2:3 for small (<15 cm), medium (15–30 cm), and large (>30 cm) diameter classes, respectively, although other ratios may also be used. This ratio was developed for forests having trees no larger than 60 cm, with most less than 50 cm, at dbh. In BDq terms, this ratio would approximate a *q*-value of 1.3 for 5 cm diameter classes. When Pro-B is applied in forests containing trees of larger diameter, a different ratio among and different boundaries for diameter-class groups might be more appropriate. These can be established only after a stable target stand structure is defined. Alternative ratios and boundaries for diameter-class groups may also apply under circumstances where forest management seeks to maintain habitat conditions for at-risk wildlife species. For example, residual basal area ratios of 1:3:6 or 1:2:7 for small (<25 cm at dbh), medium (25–35 cm), and large (>35 cm) diameter classes are implied in the recovery plan for red-cockaded woodpeckers (*Picoides borealis* Vieillot) in the southeastern United States (U.S. Fish and Wildlife Service 2003). Developing new ratios and alternative diameter-class groupings suitable for differing forest conditions and management concerns will be areas of future research study.

Comparing selection systems

Single-tree selection differs from group selection by foregoing the deliberate creation of canopy gaps when tending the forest matrix. During each cutting cycle, the stand is reduced to an understocked condition with a target basal area low enough to initiate regeneration, by harvesting trees across a wide range of diameter classes to approximate an exponential depletion curve (e.g., reverse-J) for the diameter distribution. Long-term application results in a forest with an irregular canopy, many very small gaps <0.1 ha in size and a stable uneven-aged stand structure. While seedlings readily establish on the forest floor among the usually well-dispersed overstory trees, they normally do not recruit to the canopy until released by disturbances that sufficiently reduce the inhibitory influence of nearby competitors. Lightning and timber harvest are two common disturbances that can augment the size of such gaps, thus releasing suppressed longleaf pine seedlings (Moore 2001; Outcalt 2008). With repeated entries into a stand, removal of adjacent overstory trees can progressively enlarge very small gaps, so that they approach the dimensions of those created through group selection (Brockway et al. 2006). In actual practice, these two selection methods may converge together in the field through time. Ecological forestry provides a useful context for practicing selection silviculture (Franklin et al. 2007). By using natural disturbance regimes as a template for management actions that create and maintain suitably complex structures, viable natural processes, appropriate biological legacies, and sufficient recovery intervals, selection silviculture can be used to address concerns about conserving biodiversity, maintaining wildlife habitat, sustaining primary productivity, and providing ecosystem services (Palik et al. 2002).

Group selection mimics the natural gap-phase regeneration in longleaf pine ecosystems (Brockway and Outcalt 1998). This results in an uneven-aged mosaic of even-aged patches distributed across the landscape where a continuous overstory canopy is maintained, while seedlings regenerate in small gaps created by lightning and other local disturbance agents. Because competition from the overstory limits resource availability, seedling growth benefits most in 0.2 ha gaps at locations distal from overstory trees (Palik et al. 2003). Pre-settlement longleaf pine forests were complex and largely uneven-aged, where continuous tree recruitment occurred in areas of ≤1.2 ha (Pederson et al. 2008). Group selection typically creates gaps ranging from 0.1 to 0.8 ha distributed throughout the forest to simulate the desired uneven-aged structure (Brockway et al. 2006). Ideally, as the forest matrix is tended, gaps should be cut where advanced longleaf pine regeneration is already present, thereby decreasing the likelihood that they will become occupied by competing woody species. This method is compatible with prescribed fire on a 3 year cycle to control competing vegetation and maintain the forest floor in an appropriate condition for regeneration (Farrar 1996). Gap-based approaches, like group selection, can be used to sustain an uneven-aged forest structure that achieves a range of ecosystem stewardship objectives (Coates and Burton 1997).

The initial overall effect of applying single-tree selection and group selection with the Pro-B method was the expected reduction in tree density, basal area, and pine volume on both site types. On flatwoods, this was followed by an increase in longleaf pine regeneration that was unrelated to cutting. Here selection harvest had a low impact on the shrub-dominated understory, with only small reductions in saw-palmetto cover (<10%) that largely recovered by end of the second posttreatment growing season. Logging activity did not diminish shrub cover sufficiently to stimulate expansion of herbaceous plants. Achieving regeneration success with selection is challenging on sites with severe competition, such as flatwoods dominated by saw-palmetto (Farrar 1996). On uplands, tree density recovered in group selection stands within two years of treatment, and overall, grass-stage seedlings declined while bolt-stage longleaf pine increased in a manner unrelated to cutting. Single-tree selection stands were less changed than group selection stands, a result not unexpected, since deliberately cutting gaps in the forest canopy alters the spatial pattern of overstory retention and creates a somewhat different environment for understory plants and tree seedlings.

Selection silviculture with Pro-B

As Guldin (2006) aptly noted for southern forests, BDq can be more easily applied in the field if the number of diameter classes is reduced by basing them on five broad product classes (e.g., small pulpwood, large pulpwood, small sawlogs, medium sawlogs, and large sawlogs), and the tree tally is performed as a percentage reduction within each product class rather than as a numeric count of individual trees for each 5 cm diameter class. Similar steps for improving efficiency, when applying BDq in northern forests, were suggested decades ago (Leak et al. 1987; Nyland 1987). For example, one long-used target structure in northern hardwoods, with a 20 year cutting cycle, consists of 2.3 $m^2 \cdot ha^{-1}$ for the 5–13 cm diameter classes, 4.5 $m^2 \cdot ha^{-1}$ for 14–28 cm diameter classes, 6.8 $m^2 \cdot ha^{-1}$ for 29–40 cm diameter classes, and 2.3 $m^2 \cdot ha^{-1}$ for ≥ 41 cm diameter classes, resulting in a basal area ratio of 1:2:3:1 among residuals (Nyland 2007). However, traditional application of BDq, with its focus on timber products, tends to reduce important ecological structures, such as live trees for cavity-nesting species and snags, unless marking rules include retaining older trees and those with cavities (Kenefic and Nyland 2007). Since high vertical structural diversity and a wide range of cavity heights and sizes may prove to be characteristic of uneven-aged forests, selection silviculture might be best applied in a manner that conserves these ecological assets (Kenefic and Nyland 2000).

Pro-B represents a different approach, intended to simultaneously meet biodiversity goals and timber production objectives. As a streamlined and easy-to-apply method, it was developed for upland hardwoods in southern Missouri (Loewenstein 2005) and has also been applied in riparian hardwoods, loblolly pine, and longleaf pine. Broader testing on several continents should help forest managers determine whether the Pro-B method can serve as a useful means for applying selection silviculture in a wider variety of forest-types.

Our application of selection silviculture with the Pro-B method was a successful field test for cutting longleaf pine stands to a target residual basal area, leaving a desirable diameter distribution. Pro-B was easily learned and adeptly applied in the field by practitioners from a range of professional disciplines. The single-pass feature of this method made it a time-efficient procedure for practicing selection. With Pro-B, managers achieved the target residual basal area with a high level of precision. Basal area stabilized early after treatment and then steadily increased through time. Although Pro-B appears to be an effective method for implementing selection silviculture, one or more cutting cycles will be needed before its regeneration success can be more fully evaluated.

Application of single-tree selection and group selection with the Pro-B method was performed with the objective of leaving residual overstory trees distributed in a dispersed pattern to optimize the future dissemination of longleaf pine seed and needle litter within each stand. Although beneficial for longleaf pine regeneration and periodic surface fire, this practice might tend to homogenize overstory conditions within each stand and may be less desirable for some stewardship objectives than retaining trees in a more variable pattern (Franklin et al. 2007). Field application of Pro-B is sufficiently flexible, through spatial adjustments while tree-marking, that forest managers can choose overstory retention patterns that are either dispersed or aggregated, among stands or within the same stand.

Conclusion

Our field application proved that Pro-B is an easy-to-learn, accurate, efficient, single-pass method for applying selection silviculture. It can obtain target residual basal areas with a high degree of precision and adjust stand structure to progressively improve the distribution of tree diameter classes through time. Pro-B should be useful for guiding stands along a developmental trajectory to achieve aims that can be realized only in mature forests with sufficient structural complexity and viable ecological processes.

Implementing selection silviculture through the Pro-B method was beneficial overall, by moderately reducing basal area and freeing growing space for the current and next generations of longleaf pine. The overstories in all treated stands are growing well at ~3% annually. In that longleaf pine seedlings are abundant and developing in size at the upland site and increasing in number at the flatwoods site, application of single-tree selection and group selection through Pro-B appears at this early stage to foster natural regeneration and stand development, while harvesting substantial volumes of timber.

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