USING EXISTING GROWTH MODELS TO PREDICT RCW HABITAT DEVELOPMENT FOLLOWING SITE PREPARATION: PITFALLS OF THE PROCESS AND POTENTIAL GROWTH RESPONSE

Benjamin O. Knapp and Joan L. Walker[1]

Abstract—Land managers throughout the Southeast are interested in restoring the longleaf pine (*Pinus palustris* Mill.) ecosystem, due in part to its value as habitat for the endangered red-cockaded woodpecker (*Picoides borealis*). In 2003, we established a study at Camp Lejeune, NC, to determine the effects of common site preparation treatments (mounding, bedding, herbicide, and chopping) on longleaf pine restoration on wet sites. We monitored mortality and measured root-collar diameter and height after three growing seasons. Although we found early increases in seedling growth in response to site preparation, it is unclear if these differences will persist throughout stand development. We extrapolated the results using existing growth-and-yield models to predict possible outcomes of site preparation on survival, dominant height, basal area, and quadratic mean diameter. Our projections suggest that stand structure for suitable foraging habitat could potentially be reached around 25 years earlier on the treatment with the most early growth (chopping/herbicide/bedding) when compared to the untreated check. However, liberal application of the models generates considerable uncertainty regarding interpretation of the results; we discuss the sources of error and suggest areas for needed research.

INTRODUCTION

Throughout the Southeastern United States, forest managers on lands supporting red-cockaded woodpeckers (*Picoides borealis*) (RCW) are increasingly interested in maintaining or creating RCW habitat. Favorable RCW habitat is commonly associated with a canopy dominated by longleaf pine (*Pinus palustris* Mill.), but historical land use and management practices have resulted in widespread conversion of longleaf pine forests to forests dominated by faster growing species such as loblolly pine (*Pinus taeda* L.) (Frost 1993). To increase RCW habitat quality, many land managers are now interested in rapidly reestablishing longleaf pine on sites dominated by other species.

Site preparation treatments are potentially useful management tools for increasing tree growth. Because site preparation is typically a single event that takes place just before seedlings are planted, seedling response is the strongest, and most often quantified, in the early years of stand establishment. A number of past studies have demonstrated the effectiveness of site preparation for increasing early growth rates and/or reducing early mortality of planted longleaf pine (e.g., Boyer 1988, Haywood 2007, Knapp and others 2006) and other southern pine seedlings (e.g., Knowe and others 1992, Pritchett 1979, Rahman and Messina 2006). In production forestry, rapid establishment and early growth shortens time to financial maturity and thereby increases the landowners' investment. However, land managers wishing to restore RCW habitat must consider the effects of site preparation on a temporal scale that depends on the ecological requirements of the RCW rather than economic returns.

To facilitate restoration of RCW habitat, site preparation must shorten the time required for a stand to develop from seedlings to trees of the size and structure utilized by RCWs. Although RCWs generally favor older trees in the forest for use as cavity trees (often 80 to 150 years old), stand criteria for good-quality foraging habitat may be reached substantially sooner. According to U.S. Fish and Wildlife recovery standard guidelines (U.S. Fish and Wildlife Service 2003), a group of RCWs will use from 49 to 120 ha of forest surrounding cavity trees as foraging habitat, depending on site productivity and habitat quality. Stand structure for good-quality foraging habitat includes, but is not limited to: (1) at least 45 pines/ha that are >35 cm in diameter at breast height (d.b.h.), 60 years old, and total at least 4.6 m^2/ha basal area; (2) basal area of all pines ≥25 cm d.b.h. is at least 9.2 m^2/ha; and (3) basal area of pines ≤25 cm d.b.h. is lower than 2.3 m^2/ha and below 50 stems/ha. In general, these guidelines describe stands that are dominated by large, old pines and include low densities of smaller pines or hardwoods. The quality of foraging habitat generally improves with tree size, as indicated by the requirement of a minimum number of large (>35 cm d.b.h.), old (≥60 years old) trees. However these guidelines suggest that 9.2 m^2/ha basal area of 25 cm d.b.h. trees is an important structural characteristic that may be a threshold for stands becoming RCW foraging habitat. It is not clear when artificially regenerated stands will reach the required structure for foraging habitat, or whether short-term effects of site preparation on longleaf pine seedlings will result in long-term differences in stand establishment.

The objectives of this study were to: (1) project theoretical growth and stand structure following site preparation using existing longleaf pine growth-and-yield models to predict development of RCW habitat and (2) discuss problems we encountered that introduced error and uncertainty into the results. This modeling approach was based on several assumptions: (1) the effects of site preparation persist throughout stand development, (2) survival and growth of current trees are solely determined by the size and number

[1] Research Technician and Research Plant Ecologist, U.S. Department of Agriculture Forest Service, Southern Research Station, Clemson, SC, respectively.

of trees in the previous time step, and (3) tree size variation within a stand is minimal so the quadratic mean diameter (QMD) and mean d.b.h. are approximately equal. Although a number of growth-and-yield models exist for longleaf pine, most are for stands ≥20 years old, and application is often restricted to specific site and stand conditions. Additionally, the biology of longleaf pine presents unique challenges for developing models of stand growth at young ages, due to the extended and often variable period of time in the grass stage (Goelz 2001). Consequently, we were liberal in application of existing models, resulting in greater error in our results. However, this exercise demonstrates theoretical scenarios for longleaf pine stand development after site preparation and clearly shows our need for a better understanding of the dynamics of stand development.

METHODS

Study Site

This study was conducted on Marine Corps Base Camp Lejeune, NC, located within the Atlantic Coastal Flatlands section of the Outer Coastal Plain Mixed Forest Province (Bailey 1995). All study sites were on Leon fine sand (sandy, siliceous, thermic, Aeric Alaquod), which is characterized by light-gray-to-white sand within the first 30 to 60 cm, underlain by a dark B horizon of organic accumulation. The B horizon was sufficiently cemented to form a hardpan of varying thickness (15 to 25 cm), and consequently this soil type is poorly drained, with internal drainage impeded by the hardpan layer (Barnhill 1992).

Experimental Design

The study design was a randomized complete block, with location as the block factor. Eight common site preparation treatments were randomly assigned to approximately 0.4-ha measurement plots in each block, with 15-m buffers between plots to reduce treatment overlap. Prior to site preparation, all blocks were harvested and sheared to remove standing vegetation. The eight experimental treatments were applied in August 2003: a check (no-site preparation), six treatments that combined two initial vegetation control treatments (chopping or herbicide) with three planting site conditions [flat (no additional treatment), mounding, or bedding], and a more intense treatment including chopping, herbicide, and bedding. In this paper, the treatments are often referred to by their initials as follows: flat or check (F), chopping and flat (CF), herbicide and flat (HF), chopping and mounding (CM), herbicide and mounding (HM), chopping and bedding (CB), herbicide and bedding (HB), and chopping, herbicide, and bedding (CHB).

Study plots were handplanted in December 2003 with container-grown seedlings from locally collected seed. Prior to planting, seedlings were culled to remove individuals of low vigor; average root-collar diameter of planted seedlings was 6.6 mm with a standard deviation of 1.2 mm.

Data Collection

Seedling survival was monitored in 2005, after 2 years of growth. In 2006, a subsample of 20 seedlings was randomly selected for third-year growth measurements. We used digital calipers to measure root-collar diameter (RCD) and a height pole to measure height to the terminal bud of all seedlings selected for measurement. Seedlings were determined to be in height growth when the terminal bud reached a height of 15 cm (Boyer 1988, Nelson and others 1985). Because most of the seedlings were in the grass stage, we calculated mean dominant height as the tallest half of surviving trees per plot. Boyer (1983) found that this fraction of grass stage seedlings represented a large number of vigorous seedlings that would likely become dominant and codominant canopy trees. Mean survival, RCD, and dominant height are summarized by treatment in table 1.

At four additional 10-year-old longleaf pine plantations, we randomly selected two 100-m^2 sampling plots to measure tree growth at age 10. Within each sampling plot, we marked each tree with a numbered aluminum tag and recorded RCD, d.b.h., and total height. The 10-year-old plantations were either bedded or not prepared prior to planting, and all plantations were on Leon soils.

Model Selection and Application

We searched the literature for the most appropriate models for our stand and site types. To our knowledge, Brooks and Jack (2006) developed the only model available to project stand growth and development for stands younger than 9 years old. Because models do not exist for the specific conditions of our study sites, we were liberal with model application and describe model assumptions that may be violated in table 2.

Table 1—Mean trees/ha, root-collar diameter, and dominant height used as starting points for projecting growth

Treatment	Trees/ha[a]	Root-collar diameter	Dominant height
		mm	*m*
CB	876	29.1	0.188
CF	819	18.9	0.031
CHB	782	35.8	0.645
CM	788	25.4	0.126
F	812	17.5	0.018
HB	776	34.0	0.400
HF	795	23.6	0.101
HM	777	30.6	0.299

CB = chopping and bedding; CF = chopping and flat; CHB = chopping, herbicide, and bedding; CM = chopping and mounding; F = flat; HB = herbicide and bedding; HF = herbicide and flat; HM = herbicide and mounding.

[a] Trees/ha were calculated from second-growing season survival (2005); root-collar diameter and dominant height were measurements taken 3 years after planting (2006).

Table 2—Description of models used to project stand growth for our study

Model	Variables[a]	Stand characteristics[b]	Site description[b]	Possible model violations[c]
Brooks and Jack (2006)	- Survival - Dominant height - Basal area	- Age 2 to 19 - Stand density 674 to 2,322 TPH - Basal area 1.2 to 31.2 m^2/ha	- Well-drained soils - Southwest Georgia	- Seedlings used in model development were ≥1.4 m tall, i.e., all were out of the grass stage. Our measurements were primarily seedlings in the grass stage; we calculated basal area from root-collar diameter. - Our study sites are poorly drained. Growth may differ based on drainage.
Lohrey and Bailey (1977)	- Survival	- Age 16 to 38 - Planting density from 618 to 6,178 TPH - Surviving density from 74 to 3,823 TPH - Unthinned plantations	- Site indices (25 years) from 9 to 22 m - Central LA and east TX	- We used this model to project survival to age 50, extrapolating past the maximum age used in model development - The model was developed in a different region than our study.
Farrar (1985)	- Basal area	- Age 11 to 90 - Basal area from 3.7 to 37.0 m^2/ha - Even-age natural stand - Period thinning	- Site indices (50 years) from 14 to 29 m - Regionwide study from east gulf region	- Model developed in naturally regenerated stands in the east Gulf Region. Site and stand conditions are different from our study. - Model developed from stands thinned on 5-year intervals; the author suggests restricting use of this model to short growth periods, not to exceed 30 years.

TPH = trees/ha.

[a] Represent the variables we used each model to project.

[b] Describe important information about the stands/sites used in model development.

[c] Describes some possible sources of error introduced into our projections.

Projections of QMD and basal area were used as a gauge of RCW habitat suitability, assuming that 9.2 m^2/ha basal area of 25 cm d.b.h. longleaf pine trees is an appropriate threshold for good-quality foraging stand structure.

Survival—To project survival to age 19, we used a model that projects future number of trees from stand age and current number of trees, developed by Brooks and Jack (2006) (equation 1):

$$N_2 = N_1 * Exp\left\{\alpha_1\left(\left(\frac{A_2}{10}\right)^{\alpha_2} - \left(\frac{A_1}{10}\right)^{\alpha_2}\right)\right\} \quad (1)$$

where

N_2 = projected survival in trees/ha at age A_2
N_1 = current trees/ha at age A_1
A_1 = stand age at the start of the growth period
A_2 = stand age at the end of the growth period
α_1 = –0.206745, and α_2 = 0.360652

To extend survival projections from age 19 to age 60, we used a model developed for unthinned longleaf pine plantations by Lohrey and Bailey (1977) (equation 2):

$$N_2 = N_1\left\{Sin^2\left[\frac{\pi}{2} + \left(1 - \frac{A_1}{A_2}\right)*\left(\beta_1 + \beta_2 * \sqrt{N_1} + \beta_3 * A_1 + \beta_4 * (A_1)^2\right)\right]\right\} \quad (2)$$

where

β_1 = –2.827365
β_2 = –0.032141
β_3 = 0.221332
β_4 = –0.004125

Dominant height—Brooks and Jack (2006) used a modified Chapman-Richards height/age projection function for other southern pines (Pienaar and Shiver 1980) to predict dominant height. Future dominant height is projected from stand age and current dominant height for plantations ages 2 to 19, as follows (equation 3):

$$DHT_2 = DHT_1\left[\frac{1 - Exp(\lambda_1 * A_2)}{1 - Exp(\lambda_1 * A_1)}\right]^{\lambda_2} \quad (3)$$

where

DHT_2 = projected dominant height at age A_2
DHT_1 = current dominant height at age A_1
λ_1 = –0.07576
λ_2 = 2.099041

Basal area—We used a model developed by Brooks and Jack (2006) to project basal area to age 19. This model predicts future basal area from current basal area, current and future dominant height, and current and future survival for plantations age 2 to 19 (equation 4):

$$BA_2 = Exp\{Ln(BA_1)+\delta_1(Ln(DHT_2)-Ln(DHT_1))+\delta_2(Ln(N_2)-Ln(N_1))\} \quad (4)$$

where

BA_2 = projected basal area at age A_2
BA_1 = projected basal area at age A_1
$\delta_1 = 1.817699$
$\delta_2 = 7.398342$

In applying this model, we calculated current basal area from measurements of RCD, with the assumption that basal area calculated from RCD could be used in place of basal area calculated from d.b.h. However, taper of the tree stem will cause diameter at the root collar to be larger than d.b.h., and consequently, basal area projected from RCD would be substantially larger than basal area calculated from d.b.h.

To rectify this, we followed a number of steps to convert basal area calculated from RCD to an estimated basal area from d.b.h. First, we converted the basal area projected to age 10 (from equation 4) to QMD, which would represent mean RCD at age 10. Then we used the data we collected from 10-year-old plantations and simple linear regression to develop the following relationship between RCD and d.b.h. at age 10 (equation 5):

$$DBH = -0.6526 + 0.7405(RCD) \quad (5)$$

$r^2 = 0.86$; $n = 143$; SSE = 312.12; $P < 0.0001$

Using this relationship, we predicted d.b.h. at age 10 from the projected RCD and converted this back to basal area. Under the assumption that the relationship between RCD and d.b.h. was independent of age, we projected basal area at age 10 backward to age 3 and forward to age 19 using equation 4.

The model we selected for projecting basal area past age 19 was developed for a variety of stand ages (11 to 90), site indices (13.7 to 29.0 m, base age 50) and densities (3.7 to 37.9 m^2/ha basal area) in the east gulf region (Farrar 1985) (equation 6):

$$BA_2 = \left\{\frac{\theta_1}{\theta_2} - \left[\frac{\theta_1}{\theta_2} - (BA_1)^{(1-\theta_3)}\right] * \left(\frac{A_2}{A_1}\right)^{(-\theta_2(1-\theta_3))}\right\}^{\left(\frac{1}{1-\theta_3}\right)} \quad (6)$$

where

$\theta_1 = -1.0007$
$\theta_2 = -5.6643$
$\theta_3 = 1.3213$

This model was designed to predict longleaf pine growth in natural stands with periodic thinning. In this model, basal area is predicted from stand age and current basal area using a modified form of the Chapman-Richards growth function (Pienaar and Turnbull 1973).

Quadratic mean diameter—Projected basal areas were converted to QMD and plotted for each treatment.

RESULTS AND DISCUSSION

Both models used to project longleaf pine survival followed a reverse "J" shaped curve, with mortality greatest early in the growth period and slowing down over time (fig. 1). Previous studies have reported the greatest longleaf pine mortality in

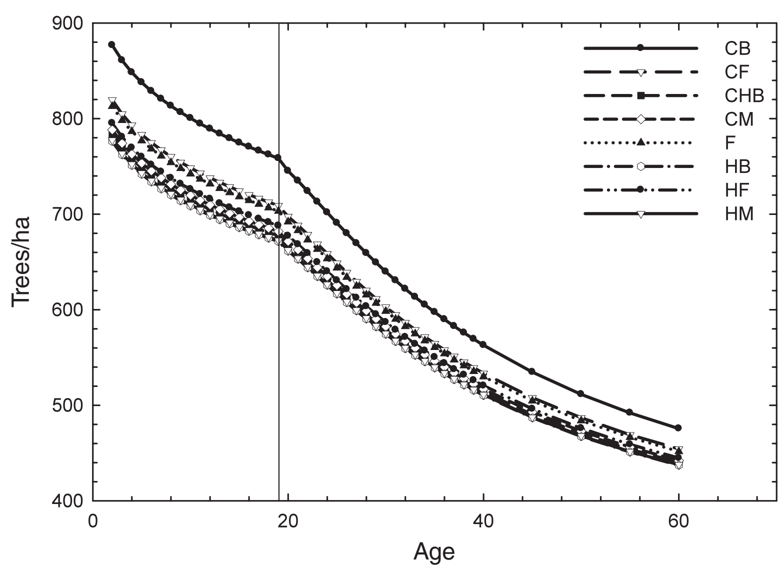

Figure 1—Trees per hectare projected from age 2 to age 60. Vertical line at age 19 represents a change in model from Brooks and Jack (2006) to Lohrey and Bailey (1977). (CB = chopping and bedding; CF = chopping and flat; CHB = chopping, herbicide, and bedding; CM = chopping and mounding; F = flat; HB = herbicide and bedding; HF = herbicide and flat; HM = herbicide and mounding)

the first year after planting (Boyer 1988, Knapp and others 2006), followed by a fairly low mortality rate through age 20 (Wilhite 1976). By age 60, projected survival ranged from 437 to 475 trees/ha, a level of stocking that would be unusually high for stands managed for RCWs. For example, a uniform stand with 25-cm d.b.h. trees requires only around 270 trees/ha to maintain 13.8 m^2/ha of basal area. It is likely that managers would periodically harvest to reduce stand density, allowing residual trees more resources for growth. Tree density would therefore be dictated by management activities rather than natural mortality and would not limit RCW habitat development.

Traditional growth models commonly use site index functions to predict dominant height (Farrar 1981, U.S. Forest Service 1976) but are unable to accurately account for changes in site quality caused by site preparation. Boyer (1980, 1983) compared height over age curves of young longleaf pine plantations established on old fields, mechanically prepared cutover forests, and unprepared cutover forests and found that site index curves were affected by site history/preparation as well as site quality. The Brooks and Jack (2006) model (equation 3) projected future dominant height from current dominant height rather than site index, thereby allowing us to account for differences in site quality resulting from site preparation.

Projected dominant height at age 19 was quite variable among the treatments, ranging from virtually no height growth on CF and F to over 10 m on CHB (fig. 2). Projections for some treatments were lower than expected. For example, it is unlikely that dominant height of a 19-year-old stand would remain below 2 m, as projected for CM, CF, HF, and F, unless seedlings never emerged from the grass stage. On sites with intense competition, it is possible that grass stage emergence would not occur without site improvement, i.e., site preparation. However, it is also likely that error was introduced into our projections by applying the Brooks and Jack (2006) model (equation 3) to data from grass stage seedlings. Treatments with age-3 mean dominant height >15 cm (CHB, HB, HM; table 1) were likely to have a greater proportion of seedlings out of the grass stage and result in more accurate projections of dominant height. On CHB, in which the majority of seedlings had emerged from the grass stage by age 3, our projection of dominant height at age 19 was similar to the dominant height of 19-year-old longleaf pine reported in a study conducted on Leon sand in northeastern Florida (Wilhite 1976), suggesting that model accuracy may be greatly improved as seedlings emerge from the grass stage.

Basal area and QMD growth projections were very different among the treatments, ranging from 5.3 to 23.7 m^2/ha basal area (fig. 3) and 9.8 to 21.1 cm QMD (fig. 4) at age 19. In the Wilhite (1976) study, 20-year-old longleaf pine plantations had a basal area of 14.5 m^2/ha and d.b.h. of approximately 12.7 cm. Prior to planting, those sites were prepared by scarifying the soil several times with an agricultural disk harrow and mechanically removing saw palmetto [*Serenoa repens* (Bartram) Small]. Such site preparations would fall within the range of site preparation intensity used in our study, and therefore it is not surprising that the values reported by Wilhite (1976) are within the range of projected values for basal area and QMD reported in our study.

When considering RCW habitat suitability, all treatments were projected to reach a basal area of 9.2 m^2/ha by around age 25 (fig. 3), suggesting that tree diameter will be a more

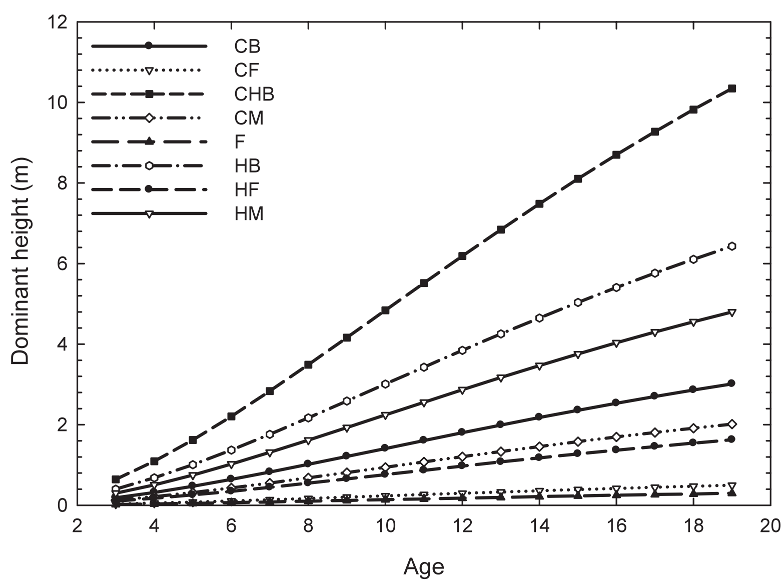

Figure 2—Dominant height (m) projected for ages 3 to age 19 using the model developed by Brooks and Jack (2006). (CB = chopping and bedding; CF = chopping and flat; CHB = chopping, herbicide, and bedding; CM = chopping and mounding; F = flat; HB = herbicide and bedding; HF = herbicide and flat; HM = herbicide and mounding)

important indicator of when these stands will become good-quality foraging habitat. For instance, CHB is projected to reach a basal area of 9.2 m^2/ha around age 11, at which point QMD is only 13.8 cm (fig. 4). Assuming that stands will first become usable as RCW habitat when QMD reaches 25 cm, our growth projections indicate drastic treatment differences in time to habitat suitability. Three treatments, CHB, HB, and HM may be expected to reach suitable size for foraging habitat by around age 30, with the fastest growing treatment (CHB) projected to reach 25 cm QMD at around age 25. On the other hand, the slowest growing treatments, F and CF, will not be suitable for RCW habitat until around age 50.

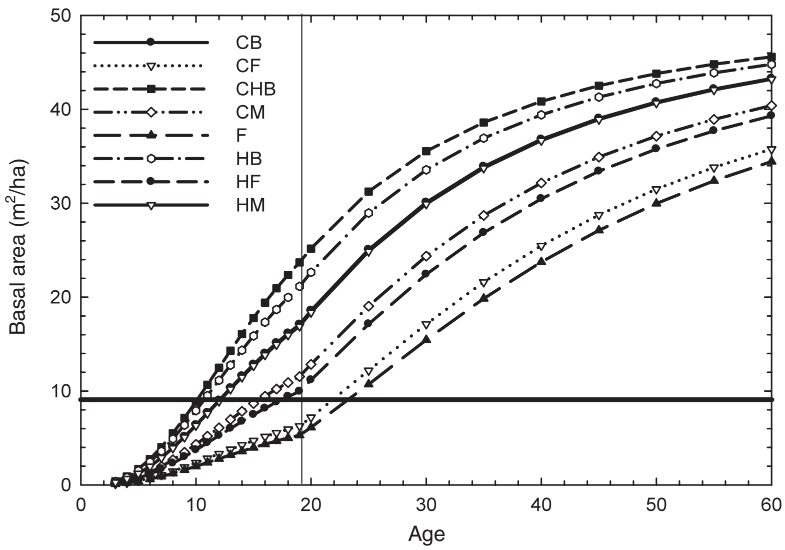

Figure 3—Basal area (m^2/ha) projected from age 3 to age 60. The vertical line at age 19 represents a change in model from Brooks and Jack (2006) to Farrar (1985). The horizontal line at 9.2 m^2/ha represents the lower basal area limit recommended for good-quality RCW habitat. (CB = chopping and bedding; CF = chopping and flat; CHB = chopping, herbicide, and bedding; CM = chopping and mounding; F = flat; HB = herbicide and bedding; HF = herbicide and flat; HM = herbicide and mounding)

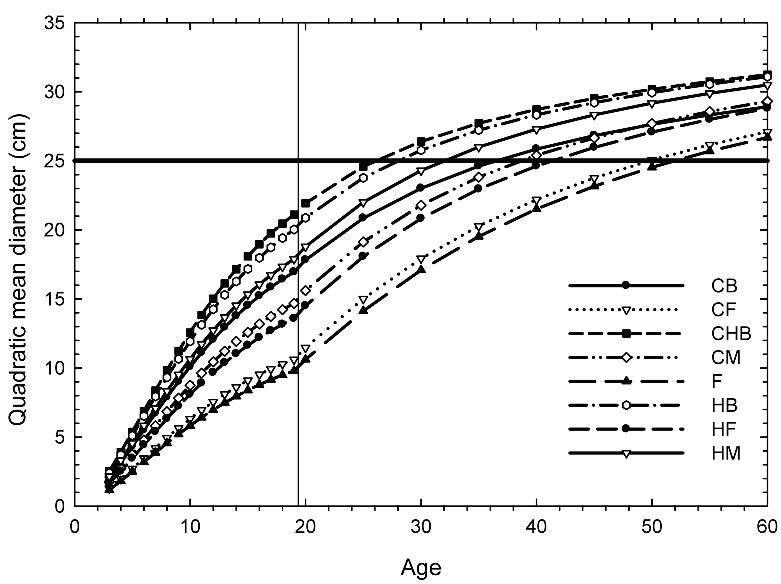

Figure 4—Quadratic mean diameter (cm) projected from age 3 to age 60. The vertical line at age 19 represents a change in model from Brooks and Jack (2006) to Farrar (1985). The horizontal line at 25 cm represents the lower basal area limit recommended for good-quality RCW habitat. (CB = chopping and bedding; CF = chopping and flat; CHB = chopping, herbicide, and bedding; CM = chopping and mounding; F = flat; HB = herbicide and bedding; HF = herbicide and flat; HM = herbicide and mounding)

Our results demonstrate theoretical differences in stand development following site preparation, but we acknowledge the uncertainty introduced by such liberal application of existing models (table 2). Error in our projections caused by exceeding model limitations was compounded by combining models for long-term extrapolation. Perhaps the most serious problem with modeling stand development of young longleaf pine is the unpredictable growth of grass stage seedlings. Currently, no models are available to translate grass stage measurements (primarily RCD) to projections of sapling/tree measurements (height/d.b.h.). Although it is accepted that grass stage emergence typically occurs when the root collar approaches 2.5 cm (Boyer 1990), emergence at the stand level and subsequent growth patterns are not fully understood and therefore difficult to model. The Brooks and Jack (2006) model (equation 4) was developed to project stand growth from a young age but assumes that seedlings have reached a height of at least 1.4 m (d.b.h. height). Many seedlings in our study were measured in the grass stage, violating that assumption and reducing the reliability of resulting model projections.

In this modeling exercise, we assume that effects of site preparation will last throughout stand development; however, there is evidence that early increases in longleaf pine growth following site preparation do not persist throughout stand development (Boyer 1996). For example, Boyer (1985) studied the effects that timing of release from competition had on short- and long-term longleaf pine growth response by comparing growth following complete hardwood competition control applied at ages 1, 2, 3, 4, and 8, and an unreleased check. At age 10, dominant tree height was greatest on treatment plots released at age 1 and decreased with each subsequent year of release. By age 31, however, dominant height was similar among all released treatments but remained significantly greater than the unreleased check. It is possible that as stands develop and canopies close, competition from understory species is reduced and growth is more strongly influenced by site productivity and intraspecific competition than by understory competition (Boyer 1983). However, it remains unclear how long the effects of mechanical treatments that change microtopography, i.e., bedding and mounding, would impact site productivity and tree growth.

An important benefit of increased early growth is a reduction in the length of time that seedlings remain in the grass stage. Longleaf pine seedlings have the ability to persist in the grass stage for over 10 years in unfavorable conditions (Pessin 1944) and in extreme cases may never enter height growth. Emergence from the grass stage is critical to stand establishment, and site preparation treatments may be one way to ensure successful height growth. On sites with extreme competition, improved chances for emergence may justify use of site preparation, regardless of subsequent growth benefits. It is logical that early grass stage emergence should correspond with shorter time to maturity. However, the ability of longleaf pine to make up for early growth deficits (Boyer 1983, 1985, 1996) suggests that this may not be the case and highlights our lack of knowledge about the early stages of stand development.

CONCLUSIONS

Our model projections demonstrate theoretical differences in stand development following site preparation but also make clear some problems associated with modeling growth of young longleaf pine. Assuming that stands become suitable foraging habitat when trees ≥25 cm d.b.h. reach a basal area of 9.2 m^2/ha, we projected that CHB would become habitat 25 years faster than the untreated check. Our results suggest that site preparation may be a useful tool for land managers wishing to shorten the time required to grow longleaf pine plantations into RCW habitat on this site type. However, we acknowledge the uncertainty of our results and intend for this study to raise questions for future research rather than provide concrete management guidelines for landowners.

ACKNOWLEDGMENTS

This study was funded by the Strategic Environmental Research and Development Program, sponsored by the U.S. Department of Defense, U.S. Department of Energy, and U.S. Environmental Protection Agency. We appreciate the field support provided by Bryan Mudder and Susan Cohen.

LITERATURE CITED

Bailey, R.G. 1995. Description of the ecoregions of the United States. 2d ed. Rev. Misc. Publ. 1391. Washington, DC: U.S. Department of Agriculture. 108 p.

Barnhill, W.L. 1992. Soil survey of Onslow County, North Carolina. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service. 139 p.

Boyer, W.D. 1980. Interim site-index curves for longleaf pine plantations. Res. No. SO-261. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 5 p.

Boyer, W.D. 1983. Variations in height-over-age curves for young longleaf pine plantations. Forest Science. 29: 15–27.

Boyer, W.D. 1985. Timing of longleaf pine seedlings release from overtopping hardwoods: a look 30 years later. Southern Journal of Applied Forestry. 9: 114–116.

Boyer, W.D. 1988. Effects of site preparation and release on the survival and growth of planted bare-root and container-grown longleaf pine. Georgia For. Res. Pap. 76. [Place of publication unknown]: Georgia Forestry Commision. Research Division. 8 p.

Boyer, W.D. 1990. *Pinus palustris* Mill. Longleaf pine. In: Burns, R.M.; Honkala, B.H., eds. Silvics of North America. Vol. 1. Conifers. Agric. Handb. 65. Washington, DC: U.S. Department of Agriculture: 405–412.

Boyer, W.D. 1996. Longleaf pine can catch up. In: Kush, J.S., comp. Proceedings of the first Longleaf Alliance conference—longleaf pine: a regional perspective of challenges and opportunities. Longleaf Alliance Report 1: 28–29.

Brooks, J.R.; Jack, S.B. 2006. A whole stand growth and yield system for young longleaf pine plantations in southwest Georgia. In: Connor, K.F., ed. Proceedings of the 13th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-92. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 317–318.

Farrar, R.M., Jr. 1981. A site-index function for naturally regenerated longleaf pine in the east gulf area. Southern Journal of Applied Forestry. 5: 150–153.

Farrar, R.M., Jr. 1985. Volume and growth predictions for thinned even-aged natural longleaf pine stands in the east gulf area. Res. Pap. SO-220. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 12 p.

Frost, C.C. 1993. Four centuries of changing landscape patterns in the longleaf pine ecosystem. In: Hermann, S.M., ed. Proceedings of the 18th Tall Timbers fire ecology conference. Tallahassee, FL: Tall Timbers Research Station: 17–43.

Goelz, J.C.G. 2001. Longleaf pine plantations: growth and yield modeling in an ecosystem restoration context. In: LeMay, V.; Marshall, P., eds. Proceedings of the forest modeling for ecosystem management, forest certification and sustainable management conference. Vancouver, BC, Canada: University of British Columbia, Forest Resources Management Department: 219–232.

Haywood, J.D. 2007. Influence of herbicides and felling, fertilization, and prescribed fire on longleaf pine establishment and growth through six growing seasons. New Forests. 33: 257–279.

Knapp, B.O.; Wang, G.G.; Walker, J.L.; Cohen, S. 2006. Effects of site preparation treatments on early growth and survival of planted longleaf pine (*Pinus palustris* Mill.) seedlings in North Carolina. Forest Ecology and Management. 226: 122–128.

Knowe, S.A.; Shiver, B.D.; Kline, W.N. 1992. Fourth-year response of loblolly pine following chemical and mechanical site preparation in the Georgia Piedmont. Southern Journal of Applied Forestry. 16: 99–105.

Lohrey, R.E.; Bailey, R.L. 1977. Yield tables and stand structure for unthinned longleaf pine plantations in Louisiana and Texas. Res. Pap. SO-133. New Orleans: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 53 p.

Nelson, R.L.; Knowe, S.A.; Gjerstad, D.H. 1985. Planted longleaf pine seedlings respond to herbaceous weed control using herbicides. Southern Journal of Applied Forestry. 9: 236–240.

Pessin, L.J. 1944. Stimulating early height growth of longleaf pine seedlings. Journal of Forestry. 42: 95–98.

Pienaar, L.V.; Shiver, B.D. 1980. Dominant height growth and site index curves for loblolly pine plantations in the Carolina flatwoods. Southern Journal of Applied Forestry. 4: 54–59.

Pienaar, L.V.; Turnbull, K.J. 1973. The Chapman-Richards generalization of von Bertalanffy's growth model for basal area growth and yield in even-aged stands. Forest Science. 19: 2–22.

Prichett, W.L. 1979. Site preparation and fertilization of slash pine on a wet savanna soil. Southern Journal of Applied Forestry. 3: 86–90.

Rahman, M.S.; Messina, M.G. 2006. Intensive forest management affects loblolly pine (*Pinus taeda* L.) growth and survival on poorly drained sites in southern Arkansas. Southern Journal of Applied Forestry. 30: 79–85.

U.S. Department of Agriculture Forest Service. 1976. Volume, yield, and stand tables for second-growth southern pines. Misc. Publ. 50. Washington, DC. 202 p.

U.S. Fish and Wildlife Service. 2003. Red-cockaded woodpecker (*Picoides borealis*) recovery plan. 2d rev. Atlanta. 296 p.

Wilhite, L.P. 1976. Slash, loblolly, longleaf, and sonderegger pines 20 years after planting on Leon sand in northeastern Florida. Res. Pap. SE-153. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Forest Experiment Station. 8 p.