MODELING FOREST TIMBER PRODUCTIVITY IN THE SOUTH: WHERE ARE WE TODAY?[1]

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Abstract--The current southern species growth and yield prediction capability, new techniques utilized, and modeling trends over the last 17 years, were examined. Changing forest management objectives that emphasize more non-timber resources may have contributed to the continuing general lack of emphasis in modeling the timber productivity of the South's largest forest types-mixed pines and mixed pine-hardwood stands. Less than 10 percent of the literature during the period of this review pertained to growth and yield predictions of that resource. On the other hand, 45 percent of the literature centered on predicting the productivity of loblolly pine, almost all in plantations. Clearly the modeling emphasis has been, and continues to be, on the results of intensive management of the South's commercially valuable species, although some notable work has been done for other species and other forest types. Several new procedures have been developed for projecting tree and stand growth using whole stand, diameter distribution, and individual tree modeling approaches. New distribution-free and stand table projection techniques have also been presented. Basic information on the available complete growth and yield prediction systems produced for southern species during this review period is presented and summarized.

INTRODUCTION

In any endeavor periodic evaluation of where we are and where we have been helps determine where we should go. Evaluation is especially important in growth and yield research because it is long term in nature. Because many years of data collection are required to develop the most useful prediction models, the results of changed objectives come slowly. The authors felt that determination of the current status of growth and yield modeling in the Southern U.S. and an examination of modeling trends over the last several years would be both timely and useful to researchers and practitioners.

The growth and yield capability for southern species currently available to the public was examined using the forestry literature from the last 17 years. The most recent general review of this subject was published in 1983 (Hotvedt and Jackson 1983) although other excellent, but more narrow, reviews have been published since then (e.g., Bolton and Meldahl 1989; Buford 1987; Burkhart 1988, 1987, 1990; Farrar and Murphy 1990; Farrar and others 1988; Feduccia 1982). The following focuses on forests in the Southern U.S.; however models developed for some species, especially hardwoods, may also include other areas. The literature reviewed is placed into species-forest type categories and the complete newly-developed or recently-revised models for these categories are listed and referenced.

The specific objectives of this investigation follow: (1) to catalog and present the complete Southern U.S. growth and yield prediction systems developed or updated during the selected period, (2) to note new modeling procedures, and (3) to present overall modeling trends. Therefore, the component models are not covered in this paper. A future publication will include a more complete and in-depth review of the Southern U.S. growth and yield literature.

OVERVIEW OF NEW OR REVISED PROCEDURES AND SYSTEMS

Several new techniques to project and/or predict tree or stand growth were introduced during this period. Many emphasize growth and yield compatibility at different levels of resolution. For example, in diameter distribution models Hyink and Moser (1983) showed that compatibility could be achieved by using a parameter recovery process. Tang and others (1997), noted that these techniques emphasize finding ways to project growth of individual trees or tree size classes so that the aggregation of their growth equals predicted stand level growth (e.g., Daniels and Burkhart 1988) or they desegregate stand growth into the growth of the individual trees or tree size classes (e.g., Harrison and Daniels 1988, Nepal and Somers 1992, Somers and Nepal 1994, Zhang and others 1993).

In all modeling arenas, tree size-class information was recognized as the most desirable output which led to development of many more diameter distribution models (e.g., Bailey and others 1985, Baldwin and Feduccia 1987, Burk and Burkhart 1984, Lenhart 1988, Matney and Sullivan 1982, Zamoch and others 1991). Most of the models use the Weibull distribution and various parameter recovery techniques. A bivariate distribution approach using Johnson's S_{BB} distribution (Hafley and Buford 1985, Hafley and others 1982) was also introduced. Some combine techniques such as diameter distribution and stand table projection (e.g., Pienaar and Rheney 1993). Significant progress has been made in developing distribution independent systems (Borders and others 1987, Tang and others 1997) and stand table projection models (e.g., Cao and Baldwin, in press; Nepal and Somers 1992; Pienaar and Harrison 1988) that individually update each size class in the previous stand table.

The (PTAEDA) model (Daniels and Burkhart 1975), apparently the only distance-dependent individual tree model developed for the South, was updated (PTAEDA2,

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Burkhart and others 1987). Distance-indeoendent individual tree models developed include (G-HAT)(Harrison and others 1986), (GATWIGS)(Bolton and Meldahl 1990), (SETWIGS[3]), (FVS)(Teck and others 1996), and (TRULOB)(Amateis and others 1995). Some existing models were reworked to expand their usefulness. Green and Strawderman (1996) created a Bayesian version of a slash pine yield model (Zamoch and others 1991) that provides users with a measure of the variability of the yield estimates. This information is not available from the original model.

Almost all of this work was devoted for single species in even-aged stands. However, some significant new work was accomplished for mixed species stands (softwoods, hardwoods, or both) and uneven-aged management of single or multiple species. The work of Mengal and Roise (1990) and Schulte and others (1998a, b) is notable. Both teams used matrix modeling (Harrison and Michie 1985, Leslie 1945), which predicts a future stand diameter distribution based on a matrix of transition probabilities and the current diameter distribution. Diameter distribution modeling was also used to predict growth and yield in these kinds of stands (e.g., Knoebel and others 1986, Murphy and Farrar 1982 a,b; 1988). The remaining prediction systems developed during this period were individual-tree or stand-level models.

Additional publications compare models, evaluate model performance, and describe procedures for testing models and their parameters and new parameter estimation techniques. Several papers compare loblolly pine models (Borders and Patterson 1990, Buford 1991, Cao 1998, Clutter and Gent 1993, Harrison and Michie 1985). Shortt and Burkhart (1996) specifically compare models useful for inventory updating. Other studies include a quality assessment of a Weibull-based growth projection system (Gertner and others 1995); a description of procedures for selecting models, testing their goodness-of-fit, and estimating error in model predictions (Reynolds 1984, 1988); and a report on the spatial autocorrelation properties of diameter and height increment prediction from two loblolly pine stand simulators (Liu and Burkhart 1994). Borders and Bailey (1986), and Borders (1989) showed how some econometric techniques could be used to estimate parameters in sequentially related or seemingly unrelated systems of equations used in growth and yield modeling. Grender and others (1990) published their theory regarding Weibull parameter probability-weighted moment estimators and showed the derivation of these estimators. They thus provided a way to place more emphasis on larger sized, and more valuable trees in a diameter distribution modeling context. Amateis and McDill(l989) showed how the physical concept of dimensional compatibility could be achieved in growth and yield modeling. Lloyd and Harms 1986 applied the rule of self thinning in an individual stand growth model for mean plant size, and Zeide (1993) analyzed growth equations and reduced them into three general equation forms.

Density management diagrams were developed to help users schedule thinnings and the final harvest in loblolly and slash pine plantations (Dean and Baldwin 1993, Dean and Jokela 1992). A spreadsheet was developed to simplify these procedures for loblolly pine plantations (Doruska and Nolen 1999). A stand density index was also published for natural stands of shortleaf pine (Wittwer and others 1998).

COMPLETE PREDICTION SYSTEMS AVAILABLE

In this paper, a complete growth and yield prediction system contains all the components required to initially describe a stand and project growth of that stand into the future. Complete models are available for loblolly, slash, longleaf, shortleaf, mixed pine, mixed pine-hardwood, and hardwood stands (table 1). Most of them have been developed for loblolly pine, followed by slash pine, and then various hardwood species. All types of modeling approaches are represented (Harrison and Michie 1985, Munro 1974, Nepal and Somers 1992).

Two of the prediction systems, the Forest Vegetation Simulator (FVS) and The Timber Yield Forecasting and Planning Tool for Windows (WINYIELD), are quite different from the others and from each other. Forest Vegetation Simulator, the primary system currently used by the National Forest System of the USDA Forest Service (Teck and others 1996), is a system of several distance-independent individual tree model-based equation modules called variants. The variants represent different species and forest types within 19 geographic regions across the United States. The Southeastern (SE) geographic variant within FVS is based on the (GATWIGS) (Bolton and Meldahl 1990) and later (SETWIGS[1)] models. USDA Forest Service Inventory and Analysis data for Georgia, Alabama, and South Carolina were used in the database. These models include prediction equations for many softwood and hardwood species. WINYIELD (FORS 1997), formerly the Timber Yield Forecasting and Planning Tool (YIELD) (Hepp 1982) and then YIELDPLUS, is a computer program that enables selection from among 13 growth and yield models according to species and geographic location. The actual growth and yield prediction systems were developed by other researchers. Therefore WINYIELD might be more appropriately called a growth and yield model management system.

SOME OBSERVATIONS AND TRENDS

1. The amount of research done for a species or forest type appears to be highly correlated with the commercial value, manageability, and availability of the species (e.g., loblolly and slash pine). Political priorities or perceived importance are probably the next most important motivators for research. Prevalence of a species or forest type or the absence of growth and yield information are the least important factors (e.g., mixed species forests).

2. As a corollary to the previous observation, the most progress has been made in predicting the growth and yield of plantation forests, which cover the least area, and the least emphasis has been placed on naturally regenerated and mixed species stands, which cover the most area in the Southern U.S. and are directly owned by the greatest number of people. This is not a new, but a continuing phenomenon. Farrar and others (1986) observed the same situation 13 years ago and table 1 shows little progress has been made.

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[3] Bolton, R.K.: Meldahl, R.S. User's guide to a forest growth projection system for southeastern forests: SE-TWIGS. Unpublished guide available from the Auburn University, School of Forestry, Auburn, AL.

Table 1-A summary of the complete Southern United States growth and yield models developed or revlsed since 1981 and available to the public

Spec.	Program reference	Organization	Model type	Original site type	Mgmt. type	Geographic location	Stand trtmt.	Predictable data range: Age	Site index[a]	Basal area	Number
								Years	Feet	Ft²/acre	Trees/acre
Lob	Murphy 1983 (Farrar 1992)[b]	FS	WS	Ns	Ea	AR, LA, MS	Ut,T	8-75	68-127[d]	7-137	
Lob	Baldwin and Feduccia 1907 COMPUTE P-LOB	FS	Dd	CP	Ea	LA, MS, TX	Ut, T	5-45	40-78	47-126	
Lob	Clutter and others 1984	UGA	Dd	SPP	Ea	Cp of NC, SC, GA, FL	Ut	10-30	40-80		300-900
Lob	Bailey and others 1985	UGA	Dd	SPP	Ea	P and Cp of AL, GA, SC	Ut	IO-70	40-70		300-1500
Lob	Martin and Bdster [in press] Shiver and Brister 1996	UGA	WS	NS	Ea	GAP	ut	24-63	68-109[d]		59-408[c]
Lob	Matney and Sullivan 1982 OFLOBLOLLY	MSU	Dd	Ofp	Ea	AR, MS, TN	Ut. T	Q-34	55-83	46-210	
Lob	Ledbetter and others 1986	MSU	WS	Spp	Ea	AR, AL, LA, MS	ut	4-28	42-80		185-907
Lob	Matney and Belli 1995 Matney and Farrar 1992 CLOBLOLLY	MSU	Dd	Spp	Ea	AR, MS. LA, AL	Ut, T	5-30	50-70		150-900
Lob	Hafley and Buford 1985 Hafley and others 1982	NCSU	Dd	P	Ea	NC, SC, IA, IL	Ut, T	5-44	48-93		100-2722
Lob	Cao and others 1982 Burk and others 1984 PCWTHIN	VPI	Dd	Ofp	Ea	VA P and CP	T	12.30	50-70		115-1305
Lob	Burkhart and Sprinz 1984 (Farrar 1992)[b]	VPI	WS	Ofp	Ea	VA P and CP	T	10-40	50-70	70-130	
Lob	Burk and Burkhart 1984 NATLOB	VPI	Dd	NS	Ea	VA P and Cp, NC CP	Ut	13-77	50-102[d]		go-1220
Lob	Burkhart and others 1987 PTAEDA2	VPI	Ddit	SPP	Ea	S	Ut. T	8-25	34-97		275-950
Lob	Amateis and others 1996 TAUYIELD	VPI	WS	Spp	Ea	S	Ut, T	8-37	40-85		194-528
Lob	Amateis and others 1995 TRULOB	VPI	Diit	SPP	Ea	S	Ut. T	a-37	40-85		194-528
Lob	Amateis and others 1984 COYIELD	VPI	Dd	SPP	Ea	S	Ut. T	8-25	34-97		275-950
Lob	Schulte and others 1998a Schulte and others 1998b SOUTHPRO	UW	gm	Ns	Ua	S	Ut, T		1-7[e]		

Table 1-A summary of the complete Southern United States growth and yield models developed or revised since 1981 and available to the public (continued)

Spec.	Program reference	Organi-zation	Model type	Original site type	Mgmt. type	Geographi location	Stand mmt.	Predictable data range: Age	Site index'	Basal area	Number
								Years	Feet	Ft²/acre	Trees/acre
Lob and Slash	Bailey and Zhou[f] Dangerfield and Moot-head 1998 GAPPS	UGA	Dd. Stp	SPP	Ea		Ut. T				
Lob and Slash	Lenhart 1988	SFA	Dd	CP	Ea	TX	ut	3.19	29-129		104-1002
Lob and Slash	Lenhart 1996	SFA	ws	CP	Ea	TX	Ut	5-24	22-99		87-1002
Slash	Nance and others 1983	FS	Dd	CP	Ea	TX, LA, MS	ut. RI	8-47	30-85		250-1500
Slash	Zarnoch and others 1991 COMPUTE P-SLASH (CSLASH - Matney)	FS MSU	Dd	CP	Ea	TX, LA, MS	Ut, Ri	8-47	30-85		50-1500
Slash	Bailey and others 1982	UGA	Dd	SPP	Ea	GA, FL, SC	Ut, T	10-30	45-75		250-650
Slash	Grider and Bailey 1984 THEECIS	UGA	Dd	Ofp, SPP	Ea	GA, FL, SC, AL. MS	Ut, Ri	Q-32	45-80	25-150	250-650
Slash	Borders and Bailey 1986	UGA	Ws	SPP	Ea	VA, NC. SC. GA, FL, AL, MS	ut	2-25			100-1800
Slash	Bailey and others 1989 Martin and others 1999	UGA	Dd, Stp	SPP	Ea	GA, FL	Ut	10-18	43-78		303-795
Slash	Pienaar and Rheney 1993 Pienaar and others 1990	UGA	Dd. Stp	SPP	Ea	GA, FL, SC	Ut. T	10-30	48-73		300-600
Long	Farrar and Matney 1994 NLONGLEAF	FS	Dd	CP. Ns	Ea	MS, AL, GA, FL	Ut, T	15-95	45-95[d]		50-1050
Long	Farrar 1985a (Farrar 1992)[b]	FS	ws	Cp, Ns	Ea	MS, AL, GA, FL	Ut, T	IO-20	70-80[d]		300-1500
Long	Farrar 1985b (Farrar 1992)[b]	FS	WS	Cp. Ns	Ea	MS. AL, GA, FL	Ut, T	15-95	45-95'		10-1050
Short	Murphy and Beltz 1981 (Farrar 1992)[b]	FS	WS	Ns	Ea	AR, LA, MO, OK, TX	ut	14-81	44-101[d]	11-127	
Short	Murphy and Farrar 1985 (Farrar 1992)[b]	FS	WS	Ns	Ua	AR					
Short	Murphy1982 (Farrar 1992)[b]	FS	WS	Ns	Ea	AR. LA, MO. OK, TX	Ut	14-81	44-101[d]	11-127	
Short	Huebschmann and others 1998 Lynch and others [in press] SLPSS	OSU	Diit	Ns	Ea	AR, OK	T	20-80	50-80[d]	30-170	

Table 1-A summary of the complete Southern United States growth and yield models developed or revised since 1981 and available to the public (continued)

Spec.	Program reference	Organi-zation	Model type	Original site type	Mgmt. type	Geographi location	Stand trtmt.	Predictable data range Age	Site index'	Basal area	Number
								Years	Feet	Ft²/acre	Trees/acre
Lob and Short[e]	Murphy and Farrar 1982b, 1983 Farrar and others 1984 (Farrar 1992)[b]	FS	Dd	Ns	Ua	AR			80-90'	20-100	
Lob and short[e]	Murphy and Farrar 1988 (Farrar 1992)[b]	FS	Dd	Ns	Ua	AR				8-128	5-390
Mix	Kelly 1989	FS	ws	Ns	Ua	LA, MB, AL			50-120[c]	10-100	
Pop	Knoebel and others 1988 YPOP	VPI	ws. Dd	Ns	Ea	Apm NC. VA, GA	T	17-76	74-138[d]	44-209	
Hard	Harrison and others 1988 G-HAT	VPI	Diit	Ns	Ea	Apm of NC, TN, VA, GA	T	19-83	62-96[d]		384-1517
Hard	Bowling and others 1909	VPI	ws. Dd	Ns	Ea	NC, GA	T	19-66	51-81[d]		40-1517
Oak	Graney and Murphy 1994	FS	ws	Ns	Ea	Bm, AR	Ut, T	11-75	46-82[d]		
Oak	Murphy and Graney IQQ8	FS	n	Ns	Ea	Bm, AR	Ut, T	11-75	46-82[d]		
Bhard	Perkins, 1994 Perkins and others 1995	MSU	Diit	Ns	Ea	Stream bottoms of MS	ut	IQ-93	75-124	44-240	102-741
Bhard	Mengel and Roise 1990 Mengel and Young 1993 BYPS	NCSU	dcm	Ns	Ea	SE					
Bhard	Kenney 1983	NCSU		Ns							
Hard	Gardner end others 1982 Roeder and Gardner 1984	NCSU		Ns		S		20-40	IO-80	70-250	
Oakgum	FrancolQ88	MSU	Ws	Ns		Stream bottoms of MS	In	19-82	75-124	44-240	102-741
Oakfs	Zahner and Myers 1984	CU	Ws	Ns	Ea	SC	Ut	5-39	46-89	38-113	450-2800
cot	Cao and Durand 1991	LSU	Ws	P	Ea	MS	Ut	3-15	40-90[h]		
Sosp	Bdton and Meldahl 1QQO GATWIGS Bolton and Meldahl[f] SETWIGS Teck and others 1998 FVS	AU	Diii	P		AL, GA, SC		Based on FIA data collections over several years			
Sosp	McClure and Knight 1984	FS	WS	Ns	Ea	S	In	5-85	20-85		51-800
Sosp	Hepp 1982 FORS 1997 WINYIELD (YIELD and YIELDPLUS)	TVA	Varies	Ns, P	Varies	S	Varies	Dependent on internal model chosen 13 choices available			

Table l- A summary of the complete Southern United States growth and yield models developed or revised since 1981 **and available to the public (continued)**

Abbreviations:
Species: Shard = bottomland hardwoods, Cot = cottonwood, Hard = mixed hardwoods, Lob = loblolly pine, Long = **longleaf** pine, Mix = mixed **species** (pine/hardwood), Oak = upland oaks, **Oakgum** = red oak-sweetgum, Oakfs = oak from sprouts, Pop = yellow-poplar, Short = **shortleaf** pine, Slash = slash pine, Sosp = southern species.
Organization: AU = Auburn University, CU = Clemson University, FS = USDA Forest Service. UGA = University of Georgia, LSU = Louisiana State University, MSU = Mississippi State University, NCSU = North Carolina State University, OSU = Oklahoma State University, SFA = Stephen F. Austin University, TVA = Tennessee Valley Authority, UW = University of Wisconsin, VPI = Virginia Polytechnic Institute and State University.
Model type: **dcm** = diameter class matrix, Dd = diameter distribution, Ddit = distance dependent individual tree, Diit = distance independent individual tree, Stp = stand table projection, Ws = whole stand.
Original site type: Spp = site prepared plantation, Ofp = old field plantations, P = plantations, Ns = natural stands, Cp = cutover plantations.
Management type: Ea = even-aged, Ua = uneven-aged.
Geographic region: Apm = Appalachian Mountains, Bm = Boston Mountains, Cp = Coastal Plain, P = Piedmont, **S** = southwide, SE = southeast, State postal abbreviations.
Stand treatment: Ri = rust infected, T = thinned, Ut = unthinned.

[a].bess **age** 25 unless otherwise **specified.**
[b]**.BASIC and/or SuperCalc/Lotus** 1-2-3 template growth and yield programs written for the models indited
[c]**.pine** component **only.**
[d]**.base age 50.**
[e]**.site** productivity **class.**
[f]**.GaPPS** is a computer program developed by Bailey, R.L. and **Zhou, B.** in **1997** and is currently available from: Forest Biometrics Consulting, **200 Robin Road,** Athens, GA **30605.**
[g]**.not** fully complete model.
[h]**.base age** 10.
[i]**.Bolton,** R.K.; **Meldahl,** R.S. User's guide to a **forest** growth projection system for southeastern forests: SE-TWIGS. **Unpublished guide available from** Auburn **University,** School of Forestry, Auburn, AL.

3. Most (about 65 percent) of the recent publications describe the development and application of new models or techniques for various prediction systems and components. The majority of these models or techniques apply to plantation loblolly and slash pine, and many techniques papers were not tied to any data. The emphasis is on improvement of prediction precision and accuracy, or on provision of more input-output options for users, not on developing or applying even simple models to species or forest types where prediction capability is lacking. And many of the completed models were not packaged within computer programs for convenient delivery to the user.

4. Most growth and yield research emphasizes even-aged rather than uneven-aged management of stands. Validation (test of the model against an independent **dataset)** of published growth and yield prediction systems has not been emphasized.

5. The development and sophistication of growth and yield models has closely followed the development and improvement of computers and software. Most of the models used were developed some years ago. Although models have been significantly modified, the most notable progress occurs when computing tools and clever algorithms to fit and use the models become available.

6. Many of the management practices built into some older growth and yield studies are not used today. Thus, these data, valuable because of long-term growth and yield measurements, may not be directly applicable to today's management practices. However, great strides have been made in loblolly and slash pine modeling thanks to industry-government-university cooperative ventures and their large regional databases.

7. Recent growth and yield emphases in loblolly and slash pine plantations, aside from new technique development, have been on modeling improved tree and stand **quantity** and quality prediction by including the effects of intensive management practices such as site preparation, vegetation control, genetics, and fertilization (about 17 percent of the publications for those species). Modeling emphasis for extensively managed stands and forests appears to be less rigorous for tree quantity or quality, focusing more on species interaction, diversity, and stand dynamics.

6. The interest is increasing in biological process models to predict forest productivity and to better understand growth processes. Although thorough review of this literature was not possible, the authors believe widespread use of process models is still in the future. Increased development and operational application will be closely tied to advances in computer technology as well as to funding needed to collect enough data to develop statistically reliable models. However, linking biological process models and growth and yield models (e.g., Baldwin and others **1993, 1998)** and augmenting empirical models with edaphic and climatic variables (e.g., **Snowdon** and others 1996, **Woollons** and others 1997) are perhaps two intermediate steps in the transition.

9. A progressive step in the effective utilization of growth and yield models is their incorporation into more generalized management planning models or decision support or expert systems. Timber production planning

models such as the Forest Planning Tool (FORPlAN)(Hoekstra 1987) and the ecosystem management strategic planning system (SPECTRUM) (USDA 1996) have been evolving for several years. Development of the latter more general decision support models for forest ecosystems is in process (e.g., Rauscher 1999).

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