DEVELOPMENT OF META-MODELS FOR ASSESSING ECOLOGICAL EFFECTS OF ALTERNATIVE THINNING REGIMES

Steven L. Garman
Dept. of Forest Science
Oregon State University
3200 SW Jefferson Way
Corvallis, OR 97331
garmans@fsl.orst.edu
(541) 737-2777

Submitted To:

John H. Cissel
James H. Mayo
Central Cascades Adaptive Management Area/
Cascade Center for Ecosystem Management
Blue River Ranger District
Willamette National Forest
Blue River, OR 97413

1/01

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES CONT'D.

Pg.

LIST OF TABLES CONT'D.

INTRODUCTION

Simulation modeling offers a rapid means to evaluate potential implications of silvicultural prescriptions. However, even with well-designed experimental designs, simulation assessments can seldom evaluate every possible thinning combination. Interest in evaluating additional thinning regimes often arises after analyses of previous assessments, but these regimes can not always be evaluated from interpolation of existing simulation results. This is often due to the difficulty in determining trends in responses among input combinations. Newly designed thinning regimes thus must be evaluated by additional simulation experiments. Recursive evaluation of thinning regimes with simulation modeling can be costly and time consuming. These costs can easily preclude or severely limit exploration of thinning regimes.

Meta-model methods (i.e., making a model of a model) are commonly used to produce a proxy for complex simulation models. Essentially, these methods result in a statistical estimate of simulated responses given combinations of input conditions. Often, meta-models are little more than responses-surface models derived from polynomial regression methods. Although meta-models are typically used to evaluate model behaviors, they also provide a simple means to estimate simulated responses over a broad range of input conditions.

This goal of this study was to develop meta-models of key ecological attributes using results of a previous simulation assessment of thinning regimes (Garman et al. in press). Specific objectives were to generate statistical models to predict selected stand attributes and stand ages when live late-successional attributes satisfied specific threshold levels, for one and two rotations of the four rotation strategies being considered for the Central Cascades Adaptive Management Area. An additional objective was to create a computer program that used the meta-models to calculate selected responses for user-specified input thinning densities.

METHODS

Simulation Model

Details of the previous simulation study are given in Garman et al. (in press). In summary, the PNWGAP (formerly known as ZELIG.PNW ver.3.0) model was used to simulate thinning-treatment effects on stand dynamics. The initial condition used in all simulations was a site-class 3, 40-yr old Douglas-fir stand (Table 1) of the Young-stand Thinning and Diversity Study (Cascade Center for Ecosystem Management, 1993). Stems of the observed stand were evenly distributed over the initial 2.56-ha model stand (8 x 8 model plots). Environmental parameters (i.e., monthly mean temperature, precipitation, and solar radiation) used in all simulations corresponded to mid-elevation (ca. 800m) conditions of the Blue River Watershed, Willamette National Forest. Each simulation experiment was replicated eight times with different initial random-number seed values.

Table 1. Attributes of the initial stand used in all first-rotation simulation experiments.

Stand developmental stage	Total density (No./ha)	Total basal area (sq.m/ha)	Shade tol. basal area (sq.m/ha)	Mean dbh (cm) - standard deviation
Early stem-exclusion (40-yr old managed Douglas-fir)	648	42.3	1.85	27.5 - 8.6

Rotation strategies considered in the previous study included a 260-yr rotation with 15% canopy retention at the rotation harvest (i.e., stand age 260), a 180-yr rotation with 30% canopy retention, a 100-yr rotation with 50% canopy retention, and an 80-yr rotation with 15% canopy retention (standard matrix-allocation prescription) (Tables 2-5). The rotation harvest in all rotation strategies also included the artificial creation of 10 snags/ha >50-cm dbh from live stems (snags were created prior to the live-canopy retention) and a mixed-species underplanting.

Simulated thinning experiments for each rotation strategy consisted of variable entry times, thinning densities, and thinning methods prior to the rotation harvest. A total of 64 experimental thinning-density combinations were simulated over one rotation for each thinning strategy (Tables 2-5). A limited subset of first-rotation experiments was extended over a second rotation using a similar combination of 64 thinning treatments (Tables 2-5). For each simulation, values of late-successional attributes at rotation age prior to harvest and the stand age at which threshold values for these attributes were attained (q.v. Table 6) were recorded and analyzed. Also, total amount of extracted merchantable volume was calculated using the HARVEST model (Harmon et al. 1996).

A Late-successional Index (LSI) was derived to compare treatment effects when rotation intervals were too short for any of the threshold levels of live criteria to be satisfied:

$$LSI = ((BI + SQRT(STI + CHI))/2.0) * 100$$

where;

$$BI = 0.02 + (1 - EXP(-0.5 * \text{No. of large boles/ha}))$$

$$STI = (\text{No. of shade tolerant stems} > 40\text{-cm dbh/ha}) / 10.0$$

$$CHI = CHDI/8.0$$

The large bole (BI), shade-tolerant density (STI), and CHDI (CHI) components of the LSI index were constrained to a maximum of 1.0. Large boles had a greater influence on the LSI index than the other two attributes. LSI values range from 0 (least similar to late-successional conditions) to 100 (threshold values of all three criteria are met).

Table 2. Simulated silvicultural experiments for the early stem-exclusion developmental stage, 260-yr rotation strategy. Under Thinning method, 'below' refers to removal from below, 'proportional' refers to removal of stems while preserving species' size-class distributions. Target thinning density is the number of stems per hectare remaining in a thinning entry; retention level is the percent canopy cover retained in the rotation harvest.

Stand age (yrs since last rotation harvest)	Thinning method	Diameter limit (cm)	Target thinning density (No./ha) or retention level (% canopy cover)	Artificial creation of dead wood		Reforestation (No./ha)
				Snags (No./ha)	Logs (Mg/ha)	
First rotation experiment						
40	below	na	136, 272, 408, all	0	0	na*
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
260	below	na	15% (95% si, 5% st)**	10	0	988 (75% si, 25% st)
Second rotation experiment						
12	below	na	494	0	0	na
40	below	na	136, 272, 408, all	0	0	na
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
260	below	na	15% (95% si, 5% st)	10	0	988 (75% si, 25% st)

* na = not applicable

** 'si' = shade-intolerant species (mostly Douglas-fir), 'st' = shade-tolerant species (mostly western hemlock)

Table 3. Simulated silvicultural experiments for the early stem-exclusion developmental stage, 180-yr rotation strategy. Under Thinning method, 'below' refers to removal from below, 'proportional' refers to removal of stems while preserving species' size-class distributions. Target thinning density is the number of stems per hectare remaining in a thinning entry; retention level is the percent canopy cover retained in the rotation harvest.

Stand age (yrs since last rotation harvest)	Thinning method	Diameter limit (cm)	Target thinning density (No./ha) or retention level % canopy cover)	Artificial creation of dead wood: Snags (No./ha)	Artificial creation of dead wood: Logs (Mg/ha)	Reforestation (No./ha)
			First rotation experiments			
40	below	na	136, 272, 408, all	0	0	na*
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
180	below	na	30% (80% si, 20% st)**	10	0	741 (60% si, 40% st)
			Second rotation experiments			
12	below	na	494	0	0	na
40	below	na	136, 272, 408, all	0	0	na
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
180	below	na	30% (80% si, 20% st)	10	0	741 (60% si, 40% st)

* na = not applicable

** 'si' = shade-intolerant species (mostly Douglas-fir), 'st' = shade-tolerant species (mostly western hemlock)

Table 4. Simulated silvicultural experiments for the early stem-exclusion developmental stage, 100-yr rotation strategy. Under Thinning methods, 'below' refers to removal from below, 'proportional' refers to removal of stems while preserving species' size-class distributions. Target thinning density is the number of stems per hectare remaining in a thinning entry; retention level is the percent canopy cover retained in the rotation harvest.

Stand age (yrs since last rotation harvest)	Thinning method	Diameter limit (cm)	Target thinning density (No./ha) or retention level (% canopy cover)	Artificial creation of dead wood		Reforestation (No./ha)
				Snags (No./ha)	Logs (Mg/ha)	
			First rotation experiment			
40	below	na	136, 272, 408, all	0	0	na*
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
100	proportional	na	50% (40% si, 60% st)**	10	0	494 (65% si, 35% st)
			Second rotation experiment			
12	below	na	494	0	0	na
40	below	na	136, 272, 408, all	0	0	na
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
100	proportional	na	50% (40% si, 60% st)	10	0	494 (65% si., 35% st)

* na = not applicable

** 'si' = shade-intolerant species (mostly Douglas-fir), 'st' = shade-tolerant species (mostly western hemlock)

Table 5. Simulated silvicultural experiments for the early stem-exclusion developmental stage, 80-yr rotation strategy. Under Thinning method, 'below' refers to removal from below, 'proportional' refers to removal of stems while preserving species' size-class distributions. Target thinning density is the number of stems per hectare remaining in a thinning entry; retention level is the percent canopy cover retained in the rotation harvest.

Stand age (yrs since last rotation harvest)	Thinning method	Diameter limit (cm)	Target thinning density (No./ha) or retention level (% canopy cover)	Artificial creation of dead wood: Snags (No./ha)	Artificial creation of dead wood: Logs (Mg/ha)	Reforestation (No./ha)
			First rotation experiment			
40	below	na	136, 272, 408, all	0	0	na*
60	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
80	below	na	15% (95% si, 5% st)**	10	0	988 (75% si, 25% st)
			Second rotation experiment			
12	proportional	na	494	0	0	na
20	proportional	na	136, 272, 408, all	0	0	na
40	proportional	≥10-≤60	99, 198, 297, all	0, 2, 4	0, 5, 10	na
60	proportional	≥10-≤60	62, 124, 186, all	0, 2, 4	0, 5, 10	na
80	proportional	na	15% (95% si, 5% st)	10	0	988 (75% si, 25% st)

* na = not applicable

** 'si' = shade-intolerant species (mostly Douglas-fir), 'st' = shade-tolerant species (mostly western hemlock)

Table 6. Attributes and threshold values characteristic of late-successional forest conditions for the western hemlock series - modified from Franklin and Spies (1991) and USDA Forest Service Region 6 Interim Old-Growth Definitions (USDA Forest Service, 1993).

Attribute	Threshold Value
Density of large boles (>100 cm dbh)	10/ha
Canopy Height Diversity Index	8.0
Density of shade-tolerant species >40-cm dbh	10/ha
Density of snags >50-cm dbh, >5-m tall	10/ha
Log mass, ≥10 cm large-end diameter	30 Mg/ha

Experimental Design & Model Development

This study used response-surface regression methods to generate predictive models for stand attributes and developmental rates over a first and over a second rotation for the four rotation strategies evaluated in Garman et al. (in press) (Tables 2-5). Regression models predicting responses over the first rotation were based on data in Tables A1, A7, A13, and A22 in Garman et al. (in press). Separate regression models were developed to predict stand age when large bole, canopy-height diversity, and shade-tolerant stem density criterion was satisfied, and when all live criteria were satisfied. Also, models were developed to predict values of these criteria at the end of a rotation prior to the final rotation harvest, and to predict extracted merchantable volume. Because threshold levels of late-successional were generally not attained in the 80-100 yr rotation strategies, models were generated to predict the LSI index instead of age when all criteria were satisfied. Predictions of stand conditions consisted of number of stems >60-cm dbh and Stand Density Index (SDI) by thinning entry. Models were not generated for any dead-wood attribute. Independent variables of regression equations included the actual thinning densities in each of the three entries. Both second and third-order polynomial models were evaluated. Only significant variables (P <0.05) were included in a model; only models with the best fit are shown.

To develop predictive models of thinning performance after two rotations, 16 of the first rotation experiments were extended over a second rotation (see Tables 2-5). All 64 experiments were implemented in a second rotation assessment, for a grand total of 1024 thinning-density combinations (16 first-rotation strategies * 64 second-rotation strategies). The 16 first-rotation experiments were determined from a Latin-Hypercube experimental design (Table 7).

Table 7. First-rotation experimental thinning treatments used in generating data for the response-surface models of second-rotation performance. Stands at the end of the first-rotation thinning strategy were subjected to the full factorial experimental design for an additional rotation. Experiment number is from Table A1 in Garman et al. (in press). Thinning density refers to number of stems 10-60 cm dbh per hectare remaining after a thinning entry. 'All' refers to no entry.

	Thinning density by stand age		
Exp#	40	60	80
3	136	99	186
6	136	198	124
9	136	297	62
16	136	all	all
19	272	99	186
22	272	198	124
25	272	297	62
32	272	all	all
33	408	99	62
38	408	198	124
44	408	297	all
47	408	all	186
51	all	99	186
54	all	198	124
60	all	297	62
64	all	all	all

Response-surface models were similar to those evaluated for the first-rotation experiments except they included actual thinning densities of the first rotation. Also, because of the additional dimensions of the second rotation experiments, 3rd and 4th order terms were evaluated.

RESULTS & DISCUSSION

First-rotation Models

Regression results are shown in Tables 8-11. In general, third-order polynomial models provided the best fit. Across all rotation strategies, models of total merchantable volume explained 79-91% of the variation. Excluding the 100-yr rotation strategy, models for stand age when live-late-successional thresholds were attained or for Late-successional Index explained 77-96% of

Table 8. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 260-yr rotation strategy (First rotation experiment in Table 2). Independent variables are thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LSc - all live late-successional criteria; '(age)' refers to stand age (yrs) when threshold level of corresponding variable was satisfied; density (no./ha) and CHDI values are at age 260 prior to the rotation harvest. SDI is Stand Density Index.

	Independent variables									
Dependent variable	Intercept	TD40	$TD40^2$	$TD40^3$	TD60	$TD60^2$	$TD60^3$	TD80	$TD80^2$	$TD80^3$
Total merch. volume	1059.642	1.136065	-0.001021	0	0.067294	-0.000075214	0	-0.188808	0.000139	0
Live LSc (age)	-203.6501	2.193206	-0.005649	0.000004333	0.981709	-0.00163	0.000000788	0.175878	-0.000268	0.000000123
Large bole (age)	48.2217	0.415826	-0.000981	0.000000726	0.165367	-0.000239	9.93154E-08	0.08159	-0.000089225	2.34156E-08
No. large boles	-36.63964	0.420888	-0.001206	0.000000986	0.257525	-0.000412	0.00000019	0.131745	-0.00021	9.66021E-08
CHDI (age)	-251.9417	2.599894	-0.006785	0.000005236	1.094276	-0.001908	0.000000967	0.152904	-0.000333	0.000000199
CHDI value	19.98232	-0.051348	0.00013	-0.0000001	-0.014478	0.00002203	-9.2671E-09	-0.013613	0.000020393	-8.68616E-09
Shade tolerant stems (age)	-174.4745	1.933346	-0.00503	0.000003906	0.819514	-0.001391	0.000000682	0.192248	-0.000244	8.41028E-08
No. Shade tolerant stems	145.6446	-0.29207	0.00092	-0.000000782	-0.376377	0.000604	-0.000000275	-0.275374	0.000493	-0.000000245
Density of stems >60-cm										
Age 40	0	0	0	0	0	0	0	0	0	0
Age 60	44.66549	-0.257305	0.000541	-0.000000374	-0.002639	0.000002898	0	0	0	0
Age 80	64.18993	0.023384	-0.000685	0.000000787	0.229597	-0.0004	0.000000205	0	0	0
SDI										
Age 40	-28.042847	1.575321	-0.002057	0.000001167	0	0	0	0	0	0
Age 60	-51.178867	0.697732	-0.002171	0.000001788	1.662943	-0.001225	0	0	0	0
Age 80	0	0.675374	-0.002925	0.000002661	1.419096	-0.002111	0.000000895	0.973489	-0.000636	0

Table 8. Cont'd.

Model	n	MSE	Adj R^2	F	*P*
Total merch. volume	64	496.7	0.91	109.7	0.0001
Live LSc (age)	64	486.0	0.77	24.1	0.0001
Large boles (age)	64	21.7	0.86	44.9	0.0001
No. large boles	64	23.1	0.82	33.9	0.0001
CHDI (age)	64	772.6	0.68	15.7	0.0001
CHDI value	63	0.8	0.55	9.6	0.0001
Shade tolerant stems (age)	64	422.7	0.73	20.3	0.0001
No. Shade tolerant stems	64	77.5	0.72	18.8	0.0001
Density of stems >60-cm dbh					
Age 40	64	na	na	na	na
Age 60	64	0.1	0.99	4051.2	0.0001
Age 80	64	22.2	0.95	203.9	0.0001
SDI					
Age 40	64	0	1.0	-	>0.0001
Age 60	64	1309.1	0.93	185.6	0.0001
Age 80	64	2178.3	0.98	532.2	0.0001

Table 9. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 180-yr rotation strategy (First rotation experiment in Table 3). Independent variables are thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LSc - all live late-successional criteria; '(age)' refers to stand age (yrs) when threshold level of corresponding variable was satisfied; density (no./ha) and CHDI values are at age 180 prior to the rotation harvest.

Dependent variable	Independent variables									
	Intercept	TD40	$TD40^2$	$TD40^3$	TD60	$TD60^2$	$TD60^3$	TD80	$TD80^2$	$TD80^3$
Total merch. volume	450.0056	1.521453	-0.002667	0.000001481	1.128956	-0.001944	0.000000943	0.89234	-0.001631	0.000000826
Live LSc (age)	-203.6501	2.193206	-0.005649	0.000004333	0.981709	-0.00163	0.000000788	0.175878	-0.000268	0.000000123
Large boles (age)	48.2217	0.415826	-0.000981	0.000000726	0.165367	-0.000239	9.93154E-08	0.08159	-0.000089225	2.34156E-08
No. large boles	64.39079	-0.092705	0.000077311	0	0.026832	-0.000022765	0	-0.04544	0.000037364	0
CHDI (age)	-251.9417	2.599894	-0.006785	0.000005236	1.094276	-0.001908	0.000000967	0.152904	-0.000333	0.000000199
CHDI value	12.8931	-0.035476	0.000097889	-7.89697E-08	-0.012472	0.000021963	-1.13094E-08	0.007596	-0.000011224	4.26396E-09
Shade tolerant stems (age)	-174.4745	1.933346	-0.00503	0.000003906	0.819514	-0.001391	0.000000682	0.192248	-0.000244	8.41028E-08
No. Shade tolerant stems	148.7984	-0.571561	0.00164	-0.000001332	-0.480095	0.000775	-0.000000357	-0.082578	0.000138	-6.69664E-08

Model	n	MSE	Adj R^2	F	*P*
Total merch. volume	64	488.5	0.90	63.2	0.0001
Live Lsc (age)	64	486.0	0.77	24.1	0.0001
Large boles(age)	64	21.7	0.86	44.9	0.0001
No. large boles	64	30.2	0.59	16.0	0.0001
CHDI (age)	64	772.6	0.68	15.7	0.0001
CHDI value	64	0.2	0.52	8.7	0.0001
Shade tolerant stems (age)	64	422.7	0.73	20.3	0.0001
No. Shade tolerant stems	64	67.0	0.79	28.0	0.0001

Table 10. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 100-yr rotation strategy (First rotation experiment in Table 4). Independent variables are thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LS Index - late-successional index based on all live attributes; density (no./ha) and CHDI values are at age 100 prior to the rotation harvest.

Dependent variable	Independent variables									
	Intercept	TD40	$TD40^2$	$TD40^3$	TD60	$TD60^2$	$TD60^3$	TD80	$TD80^2$	$TD80^3$
Total merch. volume	120.1242	2.417718	-0.005525	0.000003922	1.099577	-0.002079	0.000001109	0.167639	-0.000359	0.000000193
Live LS Index	36.74457	-0.140238	0.000322	-0.000000219	-0.050308	0.000158	-0.000000123	0.1429	-0.000255	0.000000131
No. large boles	2.978045	-0.015887	0.000038785	-2.95867E-08	-0.007599	0.000015079	-8.7947E-09	0.000464	-0.000001197	6.60824E-10
CHDI value	9.905216	-0.020654	0.000037588	-2.16251E-08	-0.001933	0.000002257	-5.37747E-10	0.006354	-0.000015987	1.06186E-08
No. Shade tolerant stems	-5.869897	0.020623	-0.000044515	3.62442E-08	0.019235	-0.000020052	2.81208E-09	0.029368	-0.000040875	1.65639E-08

Model	n	MSE	Adj R^2	F	*P*
Total merch. volume	64	359.2	0.87	49.5	0.0001
Live LSc Index	64	96.3	0.18	2.5	0.0177
No. large boles	64	0.1	0.36	4.9	0.0001
CHDI value	64	0.4	0.49	7.8	0.0001
No. Shade tolerant stems	64	2.9	0.60	11.5	0.0001

Table 11. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 80-yr rotation strategy (First rotation experiment in Table 5). Independent variables are thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LS Index - late-successional index based on all live attributes; density (no./ha) and CHDI values are at age 80 prior to the rotation harvest.

Dependent variable	Independent variables									
	Intercept	TD40	$TD40^2$	$TD40^3$	TD60	$TD60^2$	$TD60^3$	TD80	$TD80^2$	$TD80^3$
Total merch. volume	354.6016	2.873419	-0.008273	0.000006685	0.530152	-0.001395	0.000000905	na	na	na
Live LS Index	-13.67135	0.119538	-0.000133	2.54709E-08	0.121067	-0.000147	4.47521E-08	na	na	na
No. boles (>80-cm dbh)	61.77906	-0.406603	0.000957	-0.000000708	-0.05868	0.00012	-7.33252E-08	na	na	na
CHDI value	11.90728	-0.073394	0.0002	-0.00000016	-0.000337	0.000006679	-6.13781E-09	na	na	na
No. Shade tolerant stems	-12.39582	0.0745	-0.000133	7.32516E-08	0.045356	-0.00005423	1.57481E-08	na	na	na

Model	n	MSE	Adj R^2	F	*P*
Total merch. volume	16	458.3	0.79	39.8	0.0001
Live LS Index	16	3.9	0.96	233.3	0.0001
No. boles (>80-cm dbh)	16	6.3	0.87	71.5	0.0001
CHDI value	16	0.1	0.84	54.8	0.0001
No. Shade tolerant stems	16	0.7	0.94	164.1	0.0001

the variation. Variation explained in other models ranged from 49-94%. Models of CHDI-related attributes explained the least amount of variation, ranging from 49-68%. Models for attributes other than extracted volume for the 100-yr rotation results are not reliable. The lack of consistent trends and/or variation among the thinning-density gradient for these treatments limited the ability of linear-regression models to adequate predict attributes. Other model forms, such as non-linear methods, may be attempted to improve predictive ability for the 100-yr rotation results.

Models for stem densities >60-cm dbh and SDI are shown in Table 8. Models are applicable to all four rotation strategies because of similar thinning methods among strategies. The obvious exception is that the age 80 predictions are not relevant in the 80-yr rotation strategy.

Second-rotation Models

Regression results are shown in Tables 12-15. Models for extracted volume, density of stems >60-cm dbh, and SDI explained 63-99% of the variance. Variance explained by models for other attributes ranged from 30-70%. Similar to results for the first-rotation models, models for CHDI attributes generally explained the least amount of variance.

The importance of thinning densities to long-term values of late-successional attributes varied among rotation strategies. Thinning densities in the first rotation had little influence on models for CHDI values at rotation harvest, and shade-tolerant attributes for the 80- and 260-yr rotation strategies. Thinning density at age 40 was not significant (*P* >0.05) in models for these attributes for the 180-yr rotation. Across all rotation strategies, thinning densities of the second rotation had little to no influence in predicting stand age when large-bole criterion was satisfied or large-bole density at the end of a rotation. For the 180-yr rotation, >10 large boles per hectare were retained in the first-rotation harvest in all treatments examined. Thus, there was no need to generate a second-rotation model for this attribute.

Table 12. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 260-yr rotation strategy (Second rotation experiment in Table 2). Independent variables are first rotation (FR) or second rotation (SR) thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LSc - all live late-successional criteria; '(age)' refers to stand age (yrs) when threshold level of corresponding variable was satisfied; density (no./ha) and CHDI values are at age 260 prior to the rotation harvest. SDI is Stand Density Index.

	Dependent variable							
Independent variables	Total merch. volume	Live LSc (age)	Large boles (age)	No. large boles	CHDI (age)	CHDI value	Shade tol. stems (age)	No. Shade tolerant stems
Intercept	-9463.149	-1254.494	-8620.553	-507.4449	-1465.749	10.74509	-20.30008	162.5358
FRTD40	161.8981	20.1044	133.5752	7.252044	24.48679	0	0	0
$FRTD40^2$	-0.810886	-0.100524	-0.668118	-0.036293	-0.122416	0	0	0
$FRTD40^3$	0.001625	0.000201	0.001337	0.000072666	0.000245	0	0	0
$FRTD40^4$	-0.000001109	-0.000000137	-0.000000912	-4.96E-08	-0.000000167	0	0	0
FRTD60	-5.183798	-0.233318	-1.853395	-0.112751	-0.122436	0	0	0
$FRTD60^2$	0.020904	0.00085	0.006942	0.000438	0.000424	0	0	0
$FRTD60^3$	-0.000029867	-0.000001158	-0.000009635	-0.000000614	-0.000000545	0	0	0
$FRTD60^4$	1.37E-08	5E-10	4.4E-09	3E-10	2E-10	0	0	0
FRTD80	0.049162	-0.003736	-0.2545	-0.000476	0	0	0	0
$FRTD80^2$	-0.002066	0	-0.000318	0	0	0	0	0
$FRTD80^3$	0.00000413	0	0.000001447	0	0	0	0	0
$FRTD80^4$	-2.1E-09	0	-9E-10	0	0	0	0	0
SRTD40	1.644631	0.522957	0.61466	0.204229	0.197119	-0.005865	0.822582	-0.192538
$SRTD40^2$	-0.003204	-0.001087	-0.001467	-0.000558	-0.000416	0.000013119	-0.00172	0.000453
$SRTD40^3$	0.000003248	0.000000997	0.000001652	0.000000583	0.00000044	-1.45E-08	0.000001423	-0.000000428
$SRTD40^4$	-1.3E-09	-4E-10	-7E-10	-2E-10	-2E-10	0	-4E-10	1E-10
SRTD60	0.037058	0.096484	0	0.275173	-0.239598	0	0.385913	-0.304958
$SRTD60^2$	0	-0.000071866	0	-0.000742	0.000711	0	-0.000891	0.000674
$SRTD60^3$	0	0	0	0.000000758	-0.000000821	0	0.000000747	-0.000000581
$SRTD60^4$	0	0	0	-3E-10	3E-10	0	-2E-10	2E-10
SRTD80	-0.026521	-0.090092	0	0.278949	-0.461587	0.012693	-0.06588	-0.39111
$SRTD80^2$	0	0.000879	0	-0.000807	0.001663	-0.000052752	0.000728	0.000786
$SRTD80^3$	0	-0.000001286	0	0.000000854	-0.000002037	6.91E-08	-0.000001089	-0.000000645
$SRTD80^4$	0	5E-10	0	-3E-10	8E-10	0	4E-10	2E-10

Table 12. Cont'd.

Independent variables	Dependent variable: Density of stems >60-cm dbh			SDI		
	Age 40	Age 60	Age 80	Age 40	Age 60	Age 80
Intercept	342.5555	330.941	65.04144	3460.083	-53.6308	6026.332
FRTD40	-5.162858	-4.982682	0	-49.9783	0.702566	-89.20762
$FRTD40^2$	0.025916	0.024987	0	0.249662	-0.001746	0.446012
$FRTD40^3$	-0.000051957	-0.000050063	0	-0.000499	0.000001302	-0.000893
$FRTD40^4$	3.55E-08	3.42E-08	0	0.00000034	0	0.000000609
FRTD60	0.086157	0.075807	-0.068071	0.930173	0.03129	0
$FRTD60^2$	-0.000314	-0.00027	0.000291	-0.003924	0	0
$FRTD60^3$	0.000000431	0.000000367	-0.00000043	0.000005801	0	0
$FRTD60^4$	-2E-10	-2E-10	2E-10	-2.7E-09	0	0
FRTD80	0.022847	0.024806	0	0.164071	0.237325	0
$FRTD80^2$	-0.000009172	-0.000029595	0	-0.000063465	-0.000441	0
$FRTD80^3$	-5.56E-08	-0.000000018	0	-0.000000353	0.000000226	0
$FRTD80^4$	0	0	0	3E-10	0	0
SRTD40	-0.005202	-0.008848	-0.32501	0.792614	0.839777	0
$SRTD40^2$	0.000025545	0.00003658	0.000845	0.000357	-0.001569	0
$SRTD40^3$	-4.65E-08	-5.85E-08	-0.000000888	-0.000001483	0.00000082	0
$SRTD40^4$	0	0	3E-10	8E-10	0	0
SRTD60	0	0.005158	-0.053162	0	1.442525	0.755775
$SRTD60^2$	0	-0.000022854	0.000165	0	-0.001321	-0.001863
$SRTD60^3$	0	3.29E-08	-0.000000198	0	0.000000396	0.000002025
$SRTD60^4$	0	0	1E-10	0	0	-8E-10
SRTD80	0	0	0	0	0	1.198729
$SRTD80^2$	0	0	0	0	0	-0.000708
$SRTD80^3$	0	0	0	0	0	0
$SRTD80^4$	0	0	0	0	0	0

Table 12. Cont'd.

Model	n	MSE	AdjR²	F	*P*
Total merch. volume	1024	1973.7	0.75	197.3	0.0001
Live LSc (age)	1024	260.0	0.64	107.2	0.0001
Large boles (age)	1024	146.7	0.50	74.2	0.0001
No. large boles	1024	18.9	0.77	184.5	0.0001
CHDI (age)	1024	138.2	0.55	71.5	0.0001
CHDI value	1024	0.2	0.30	62.2	0.0001
Shade tolerant stems (age)	1024	324.0	0.67	198.5	0.0001
No. Shade tolerant stems	1024	39.2	0.86	614.4	0.0001
Density of stems >60-cm dbh					
Age 40	1024	0.9	0.74	209.6	0.0001
Age 60	1024	0.8	0.73	155.0	0.0001
Age 80	1024	8.7	0.78	331.6	0.0001
SDI					
Age 40	1024	101.2	0.99	1365.5	0.0001
Age 60	1024	267.9	0.94	1452.6	0.0001
Age 80	1024	679.5	0.94	1748.9	0.0001

Table 13. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 180-yr rotation strategy (Second rotation experiment in Table 3). Independent variables are first rotation (FR) or second rotation (SR) thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LSc - all live late-successional criteria; '(age)' refers to stand age (yrs) when threshold level of corresponding variable was satisfied; density (no./ha) and CHDI values are at age 180 prior to the rotation harvest. SDI is Stand Density Index.

	Dependent variable							
Independent variables	Total merch. volume	Live LSc (age)	Large boles (age)	No. large boles	CHDI (age)	CHDI value	Shade tol. stems (age)	No. Shade tolerant stems
Intercept	231.2377	44.14681	0	30.84609	150.1011	5.272115	40.78671	129.3683
FRTD40	0.210721	0	0	0.027951	0	0	0	0
FRTD402	-0.000906	0	0	-0.000098609	0	0	0	0
FRTD403	0.000000864	0	0	9.18176E-08	0	0	0	0
FRTD404	0	0	0	0	0	0	0	0
FRTD60	3.83717	0.662164	0	0.013434	0.076946	0.00696	0.722994	-0.146903
FRTD602	-0.016951	-0.003094	0	0.000018977	-0.000468	-0.000022248	-0.00338	0.000695
FRTD603	0.000026326	0.000004895	0	-6.48338E-08	0.000000804	2.86742E-08	0.000005355	-0.000001104
FRTD604	-1.31904E-08	-2.46964E-09	0	3.53166E-11	-4.21588E-10	-1.26622E-11	-2.70655E-09	5.57917E-10
FRTD80	-1.892831	-0.358032	0	0	-0.076441	0	-0.405135	0.106081
FRTD802	0.012073	0.002312	0	0	0.000514	0	0.002605	-0.000608
FRTD803	-0.000020637	-0.000004064	0	0	-0.000000902	0	-0.00000457	0.000001052
FRTD804	1.05914E-08	2.13663E-09	0	0	4.7014E-10	0	2.40064E-09	-5.54947E-10
SRTD40	1.237142	0.715513	0	-0.042948	0	0.006161	0.74032	-0.369647
SRTD402	-0.003744	-0.002374	0	0.000096139	0	-0.000019747	-0.002504	0.000991
SRTD403	0.000004707	0.000002747	0	-7.63543E-08	0	2.52729E-08	0.000002939	-0.000001025
SRTD404	-2.03178E-09	-1.04807E-09	0	1.82623E-11	0	-1.10466E-11	-1.13456E-09	3.68717E-10
SRTD60	0.697494	0.253643	0	-0.080071	-0.235843	0.018864	0.24835	-0.467254
SRTD602	-0.001838	-0.001023	0	0.000256	0.000857	-0.000064099	-0.001021	0.001504
SRTD603	0.000002026	0.000001397	0	-0.000000341	-0.000001221	8.14341E-08	0.000001424	-0.000001884
SRTD604	-8.00962E-10	-6.05256E-10	0	1.58744E-10	5.97444E-10	-3.55599E-11	-6.32569E-10	8.19707E-10
SRTD80	-0.003435	-0.279908	0	-0.009922	-0.381603	0.035625	-0.280534	-0.178918
SRTD802	-0.000285	0.000466	0	-0.0000427	0.00074	-0.000105	0.000486	0.00055
SRTD803	0.000000601	-0.000000257	0	0.000000105	-0.000000519	0.000000112	-0.000000293	-0.000000623
SRTD804	-3.00505E-10	4.40142E-11	0	-5.46444E-11	1.0383E-10	-3.97044E-11	6.12423E-11	2.33564E-10

Table 13. Cont'd.

Independent variables	Density of stems >60-cm dbh			SDI		
	Age 40	Age 60	Age 80	Age 40	Age 60	Age 80
Intercept	22.92521	20.7744	22.51451	314.2305	134.297	152.4785
FRTD40	0.020477	0.025077	0.027793	-0.213722	0	0
FRTD402	-0.000045747	-0.000059366	-0.000076399	0.00048	0	0
FRTD403	3.49845E-08	4.53829E-08	6.37156E-08	-0.000000367	0	0
FRTD404	0	0	0	0	0	0
FRTD60	0.02018	0.014042	0.019048	-0.162491	0	-0.006444
FRTD602	-0.000023158	-0.000010642	-0.00002027	0.000317	0	0
FRTD603	8.07276E-09	2.28204E-10	5.00026E-09	-0.000000181	0	0
FRTD604	0	0	0	0	0	0
FRTD80	-0.013961	-0.012702	-0.008571	-0.045091	0	0
FRTD802	0.000032377	0.000029171	0.000024623	0.000057863	0	0
FRTD803	-2.07335E-08	-1.79962E-08	-1.71952E-08	-1.32913E-08	0	0
FRTD804	0	0	0	0	0	0
SRTD40	-0.002038	-0.002705	-0.022012	0.983526	0.494594	0.280227
SRTD402	0.000006013	0.000006973	0.000042029	-0.000729	-0.001508	-0.000699
SRTD403	-3.96503E-09	-4.3646E-09	-2.28182E-08	0.000000165	0.000001973	0.00000042
SRTD404	0	0	0	0	-8.99518E-10	0
SRTD60	0	0	-0.010576	0	2.240369	0.411648
SRTD602	0	0	0.000018872	0	-0.005588	-0.000641
SRTD603	0	0	-1.05034E-08	0	0.00000727	0.00000028
SRTD604	0	0	0	0	-3.51614E-09	0
SRTD80	0	0	0	0	0	1.658011
SRTD802	0	0	0	0	0	-0.002079
SRTD803	0	0	0	0	0	0.000000872
SRTD804	0	0	0	0	0	0

Table 13. Cont'd.

Model	n	MSE	$AdjR^2$	F	*P*
Total merch. volume	1024	420.6	0.81	185.2	0.0001
Live LSc (age)	1024	134.7	0.63	87.6	0.0001
Large boles (age)	1024	0	1.0	na	>0.0001
No. large boles	1024	2.7	0.73	146.0	0.0001
CHDI (age)	1024	23.9	0.90	546.9	0.0001
CHDI value	1024	0.1	0.84	338.5	0.0001
Shade tolerant stems (age)	1024	144.3	0.61	81.8	0.0001
No. Shade tolerant stems	1024	21.9	0.83	252.3	0.0001
Density of stems >60-cm dbh					
Age 40	1024	0.4	0.84	463.7	0.0001
Age 60	1024	0.5	0.81	362.8	0.0001
Age 80	1024	0.8	0.76	222.3	0.0001
SDI					
Age 40	1024	26.7	0.99	4614.8	0.0001
Age 60	1024	496.8	0.96	3327.9	0.0001
Age 80	1024	704.5	0.96	2517.2	0.0001

Table 14. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 100-yr rotation strategy (Second rotation experiment in Table 4). Independent variables are first rotation (FR) or second rotation (SR) thinning densities (TD - number of stems ≤60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LSc - all live late-successional criteria; '(age)' refers to stand age (yrs) when threshold level of corresponding variable was satisfied; density (no./ha) and CHDI values are at age 100 prior to the rotation harvest. SDI is Stand Density Index.

	Dependent variable							
Independent variables	Total merch. volume	Live LSc (age)	Large boles (age)	No. large boles	CHDI (age)	CHDI value	Shade tol. stems (age)	No. Shade tolerant stems
Intercept	43.51953	30.80205	-65.03959	17.49667	78.11961	6.72533	-62.63608	2.48309
FRTD40	1.534155	0.49871	0.467211	0.097739	0.372928	-0.005521	0.441156	0.03196
FRTD40^2	-0.003619	-0.001322	-0.001162	-0.000327	-0.001021	0.000012788	-0.001153	-0.000090808
FRTD40^3	0.000002808	0.000001029	0.000000919	0.000000287	0.000000823	-9.6E-09	0.000000892	7.31E-08
FRTD40^4	0	0	0	0	0	0	0	0
FRTD60	0.578622	1.450495	0.762798	0.088927	0.162639	-0.000829	1.155288	0.016345
FRTD60^2	-0.002429	-0.006354	-0.003148	-0.000257	-0.00028	0.000001235	-0.005188	-0.000032845
FRTD60^3	0.000004226	0.000009708	0.000004734	0.000000274	0.000000133	-6E-10	0.000008024	1.79E-08
FRTD60^4	-2.4E-09	-4.8E-09	-2.3E-09	-1E-10	0	0	-0.000000004	0
FRTD80	-1.640838	-0.548936	-0.399327	-0.001954	0.040893	0.000324	-0.574636	0.007419
FRTD80^2	0.00951	0.003636	0.00251	0	-0.000037539	-0.000000831	0.003701	-0.000013356
FRTD80^3	-0.000015671	-0.000006384	-0.000004279	0	0	6E-10	-0.000006437	6.6E-09
FRTD80^4	7.8E-09	3.3E-09	2.2E-09	0	0	0	3.4E-09	0
SRTD40	1.003196	-0.301971	0	-0.072756	-0.148919	-0.002959	0.068871	0.037078
SRTD40^2	-0.002283	0.001343	0	0.000254	0.000403	0.000005198	-0.000256	-0.000128
SRTD40^3	0.000002097	-0.000002157	0	-0.000000327	-0.000000302	-0.000000003	0.000000407	0.000000103
SRTD40^4	-6E-10	1.2E-09	0	1E-10	0	0	-2E-10	0
SRTD60	-0.000411	-0.02278	0	0.020535	-0.010514	-0.000626	-0.095578	-0.004063
SRTD60^2	0.000578	-0.000227	0	-0.000173	0	0.000002145	0.000406	0.000023422
SRTD60^3	-0.000002009	0.000000789	0	0.000000431	0	-2.9E-09	-0.000000767	-5.15E-08
SRTD60^4	1.7E-09	-6E-10	0	-3E-10	0	0	6E-10	0
SRTD80	0.851485	-0.969003	0	-0.021367	-0.664091	0.001495	0.019952	0.054469
SRTD80^2	-0.002591	0.003744	0	0.000029914	0.00186	-0.000006542	-0.000151	-0.000184
SRTD80^3	0.000002789	-0.000005486	0	0	-0.000001479	0.000000006	0.000000351	0.000000154
SRTD80^4	-9E-10	2.7E-09	0	0	0	0	-2E-10	0

Table 14. Cont'd.

Independent variables	Density of stems >60-cm dbh: Age 40	Density of stems >60-cm dbh: Age 60	Density of stems >60-cm dbh: Age 80	SDI: Age 40	SDI: Age 60	SDI: Age 80
Intercept	18.4232	52.69745	110.8063	241.9125	312.3278	390.8529
FRTD40	0.083151	-0.079407	-0.13128	0.085253	0	-0.288487
FRTD40^2	-0.000203	0.000291	0.000458	-0.000483	0	0.000751
FRTD40^3	0.000000154	-0.000000255	-0.000000384	0.000000478	0	-0.00000057
FRTD40^4	0	0	0	0	0	0
FRTD60	0.116073	0	-0.6865	0.109802	0.284856	-0.560708
FRTD60^2	-0.00018	0	0.00297	-0.000157	-0.001157	0.002382
FRTD60^3	7.83E-08	0	-0.000004493	5.54E-08	0.00000161	-0.000003629
FRTD60^4	0	0	2.2E-09	0	-7E-10	1.8E-09
FRTD80	0.050954	-0.004331	0.159065	0.064045	0	0.147185
FRTD80^2	-0.000071423	0.000043127	-0.001238	-0.000159	0	-0.001231
FRTD80^3	2.63E-08	-3.73E-08	0.00000229	0.000000105	0	0.000002293
FRTD80^4	0	0	-1.2E-09	0	0	-1.2E-09
SRTD40	0	0.009243	-0.07111	1.091563	0.248544	0.098709
SRTD40^2	0	-0.000042828	0.000186	-0.001562	-0.001123	-0.00084
SRTD40^3	0	3.96E-08	-0.000000233	0.000000888	0.00000178	0.00000152
SRTD40^4	0	0	1E-10	0	-9E-10	-8E-10
SRTD60	0	0	-0.01061	0	0.099992	-0.264926
SRTD60^2	0	0	0.000128	0	0.004746	0.001674
SRTD60^3	0	0	-0.000000311	0	-0.000012505	-0.00000332
SRTD60^4	0	0	2E-10	0	8.7E-09	1.8E-09
SRTD80	0	0	-0.00975	0	0	1.682711
SRTD80^2	0	0	0.000065804	0	0	-0.003057
SRTD80^3	0	0	-0.000000149	0	0	0.000000841
SRTD80^4	0	0	1E-10	0	0	1.4E-09

Table 14. Cont'd.

Model	n	MSE	AdjR^2	F	*P*
Total merch. volume	1024	268.1	0.94	706.3	0.0001
Live LSc (age)	1024	87.4	0.78	158.0	0.0001
Large boles (age)	1024	11.8	0.92	1024.9	0.0001
No. large boles	1024	2.3	0.79	209.6	0.0001
CHDI (age)	1024	113.2	0.72	178.6	0.0001
CHDI value	1024	0.01	0.86	355.3	0.0001
Shade tolerant stems (age)	1024	13.8	0.74	128.4	0.0001
No. Shade tolerant stems	1024	1.8	0.70	135.0	0.0001
Density of stems >60cm					
Age 40	1024	1.7	0.94	1709.8	0.0001
Age 60	1024	3.9	0.81	481.6	0.0001
Age 80	1024	3.3	0.90	411.0	0.0001
SDI					
Age 40	1024	36.2	0.99	7702.3	0.0001
Age 60	1024	349.8	0.94	1271.8	0.0001
Age 80	1024	228.0	0.96	972.5	0.0001

Table 15. Regression coefficients and model statistics for predicting extracted merchantable volume, stand attributes, and stand age when late-successional criteria were satisfied for the 80-yr rotation strategy (Second rotation experiment in Table 5). Independent variables are first rotation (FR) or second rotation (SR) thinning densities (TD - number of stems $\leq$60-cm dbh remaining after thinning) by stand age of entry (e.g., TD40 - thinning density at age 40). Polynomial terms are indicated by the superscript. Volume is m^3/ha; Live LS Index - late-successional index based on all live attributes, density (no./ha) and CHDI values are at age 80 prior to the rotation harvest. SDI is Stand Density Index. NOTE: threshold levels of live late-successional attributes were not achieved in these thinning experiments.

	Dependent variable							
Independent variables	Total merch. volume	Live LS Index	Large boles (age)	No. large boles	CHDI (age)	CHDI value	Shade tol. stems (age)	No. Shade tolerant stems
Intercept	346.323	44.20803		-2.966667		4.957523		-21.83035
FRTD40	-0.182832	0		0.035527		0		0
FRTD40^2	0.000536	0		-0.000075594		0		0
FRTD40^3	-0.000000428	0		5.23E-08		0		0
FRTD40^4	0	0		0		0		0
FRTD60	0	0		-0.019184		0		0
FRTD60^2	0	0		0.00008585		0		0
FRTD60^3	0	0		-0.000000127		0		0
FRTD60^4	0	0		1E-10		0		0
SRTD20	1.253236	0.23715		0.045513		-0.009705		0.185625
SRTD20^2	-0.003878	-0.000834		0.000119		0.000041006		-0.000702
SRTD20^3	0.000004689	0.000001088		-0.000000326		-5.96E-08		0.000000929
SRTD20^4	-0.000000002	-5E-10		2E-10		0		-4E-10
SRTD40	1.271935	0.120294		0		0.000112		0.125384
SRTD40^2	-0.003078	-0.000358		0		0		-0.000431
SRTD40^3	0.000002902	0.000000374		0		0		0.000000507
SRTD40^4	-9E-10	-1E-10		0		0		-2E-10
SRTD60	0.761364	0.254888		0		0.029874		0.139309
SRTD60^2	-0.001447	-0.000872		0		-0.000082714		-0.000454
SRTD60^3	0.000000967	0.000001071		0		9.32E-08		0.00000054
SRTD60^4	-2E-10	-4E-10		0		0		-2E-10

Table 15. Cont'd.

Independent variables	Density of stems >60-cm dbh Age 20	Age 40	Age 60	SDI Age 20	Age 40	Age 60
Intercept	-4.007279	-4.086966	46.10226	-33.33315	-157.6669	-64.55457
FRTD40	0.038779	0.036403	0	-0.137709	0	0
$FRTD40^2$	-0.000071552	-0.000069551	0	0.000241	0	0
$FRTD40^3$	4.49E-08	4.52E-08	0	-0.000000133	0	0
$FRTD40^4$	0	0	0	0	0	0
FRTD60	-0.016044	-0.011383	0	0.008209	0	0
$FRTD60^2$	0.000078647	0.000056698	0	-0.000021108	0	0
$FRTD60^3$	-0.00000012	-8.68E-08	0	1.44E-08	0	0
$FRTD60^4$	1E-10	0	0	0	0	0
SRTD20	0.046179	0.044735	-0.090828	1.420502	1.579728	0.935416
$SRTD20^2$	0.000204	0.000178	0.000107	-0.001515	-0.003258	-0.001688
$SRTD20^3$	-0.000000491	-0.000000435	-3.71E-08	0.000000503	0.000003148	0.000000915
$SRTD20^4$	3E-10	2E-10	0	0	-1.2E-09	0
SRTD40	0	0	0.058194	0	1.359528	0.556748
$SRTD40^2$	0	0	-0.000144	0	-0.002	-0.000944
$SRTD40^3$	0	0	8.95E-08	0	0.000001544	0.000000466
$SRTD40^4$	0	0	0	0	-5E-10	0
SRTD60	0	0	-0.032224	0	0	1.260011
$SRTD60^2$	0	0	0.00007536	0	0	-0.001266
$SRTD60^3$	0	0	-4.52E-08	0	0	0.000000355
$SRTD60^4$	0	0	0	0	0	0

Table 15. Cont'd.

Model	n	MSE	AdjR^2	F	*P*
Total merch. volume	1024	183.7	0.91	667.7	0.0001
Live LS Index	1024	16.4	0.67	174.2	0.0001
No. large boles	1024	0.5	0.98	5270.4	0.0001
CHDI value	1024	0.2	0.80	445.2	0.0001
No. Shade tolerant stems	1024	6.5	0.71	214.6	0.0001
Density of stems >60cm					
Age 20	1024	0.7	0.99	7096.0	0.0001
Age 40	1024	0.7	0.98	5907.3	0.0001
Age 60	1024	26.6	0.63	195.6	0.0001
SDI					
Age 20	1024	49.8	0.99	1329.6	0.0001
Age 40	1024	251.8	0.98	7009.4	0.0001
Age 60	1024	671.3	0.95	2227.5	0.0001

CAVEATS

Caution should be exercised when using the regression meta-models. Comparing meta-model predictions with actual simulation results revealed differential accuracy across the thinning-density design. Meta-model predictions tend to be less accurate at the end points of the design (i.e., for combinations involving the lowest or highest thinning densities of the experimental design), which is somewhat typical of response-surface models. In general, predictions of developmental rates of late-successional attributes are lower at the low end of the design (i.e., 136-99-62). Extracted merchantable volume tends to be over estimated at the upper end of the design (i.e., all-all-*).

Additionally, the user is responsible for determining the feasibility of a thinning combination. Strategies which retain more stems in a second or third entry than in a preceding entry are not always possible, although the number of feasible combinations increases with increasing removal of stems in preceding entries due to natural regeneration. Examples of feasible thinning combinations are presented in Appendix A of Garman et al. (in press). Related to this is the domain of realistic input conditions. Meta-models will not reliably predict results of thinning combinations outside the range of those used in the simulation experiments. Lastly, meta-models presented here are specific to the thinning methods of the simulation study (see Tables 2-5). They should not be used to estimate responses for any other thinning approaches.

In general, meta-model predictions should be used to compare relative merits of different thinning combinations. However, precision of estimates varies among attributes. Comparisons of meta-model predictions and simulated values are presented in Table 16. Percentiles of absolute percent difference shown in this table can be used as a guide to assess the general precision of model predictions, in addition to the model statistics presented in Tables 8-15. In general, extracted merchantable volume and stand age when all late-successional threshold levels were attained are the most reliable estimates, especially in the first-rotation models.

Table 16. Percentiles of absolute percent difference between meta-model predictions and simulated values. Value to the left of the '/' is 5th percentile; value to the right is 95th percentile.

Rotation strategy	Total merch. volume	Live LSc (age)	Large boles (age)	No. large boles	CHDI (age)	CHDI value	Shade tol. stems (age)	No. Shade tolerant stems
First Rotation								
260-yr	0.07/2.24	0.63/21.35	0.22/5.70	0.44/16.03	1.73/31.31	0.41/14.41	0.35/19.86	2.31/35.13
180-yr	0.15/3.79	0.63/21.35	0.22/5.70	0.47/22.23	1.73/31.31	0.28/8.85	0.35/19.86	1.49/51.45
100-yr	0.11/5.46	2.39/48.38[1]	na/na	0.00/81.29	na/na	0.72/15.31	na/na	0.57/67.99
80-yr	0.20/6.14	0.28/18.90[1]	na/na	0.00/33.37	na/na	0.29/12.77	na/na	0.00/33.26
Second Rotation								
260-yr	0.48/12.97	0.52/19.57	1.53/75.58	0.67/24.34	0.74/29.20	0.12/6.57	0.70/26.02	0.61/22.55
180-yr	0.22/6.18	0.62/19.60	0.00/0.00	0.56/14.99	0.33/12.84	0.22/7.47	0.68/20.46	1.01/33.10
100-yr	0.22/7.85	0.67/27.89	0.26/21.60	0.47/12.71	0.81/33.42	0.09/2.75	0.42/19.63	0.65/21.76
80-yr	0.09/3.82	2.60/8.46[1]	na/na	0.26/13.34	na/na	0.40/12.82	na/na	1.09/54.44

Rotation strategy	Density of stems >60-cm dbh			SDI		
	Age 40	Age 60	Age 80	Age 40	Age 60	Age 80
First Rotation						
260-yr	0/0	0.10/11.28	0.23/15.09	0/0	0.70/13.83	0.54/20.92
180-yr	0/0	0.10/11.28	0.23/15.09	0/0	0.70/13.83	0.54/20.92
100-yr	0/0	0.10/11.28	0.23/15.09	0/0	0.70/13.83	0.54/20.92
80-yr[2]	0/0	0.10/11.28	na/na	0/0	0.70/13.83	0.54/20.92
Second Rotation						
260-yr	0.27/14.31	0.66/14.65	1.23/32.32	0.10/5.37	0.53/12.88	0.98/57.87
180-yr	0.11/4.43	0.10/5.23	0.22/7.22	0.06/2.14	0.27/7.57	0.29/10.16
100-yr	0.15/5.67	0.28/8.07	0.25/7.04	0.06/2.84	0.21/6.93	0.17/5.82
80-yr[2]	0.29/14.67	0.28/16.99	na/na	0.26/6.83	0.25/10.39	0.59/13.67

[1] - Live LS Index   [2] - values are for thinning entries at ages 20,40,60

CALCULATIONS WITH THE META-MODELS

Standard methods of calculation can be employed to derive meta-model estimates (e.g., hand-held calculator or spread-sheet). Additionally, an interactive computer program, called RESP, is provided to facilitate rapid assessment of thinning regimes. RESP uses the meta-models reported in Tables 8-15 to estimate ecological and timber volume responses over one to two rotations for the four rotation strategies (see Tables 2-5). RESP queries the user for the number of rotations, the rotation strategy, and thinning densities for up to three entries per rotation. Estimates of responses are displayed only on the screen. Definitions and units of the output are documented below.

FIRST ROTATION RESULTS	- designates results for a first-rotation strategy
Total Merch. Volume	- cubm/ha of volume removed in all thinning entries and final rotation harvest
Live LSc (age)	- stand age when threshold levels of all live late-successional attributes are attained
Live LS Index	- LS Index based on all live late-successional attributes. Displayed when threshold values are generally not attained (i.e., 100- and 80-yr rotation strategies).
Large boles (age)	- stand age when large-bole (>100-cm dbh) criterion is attained
No. large boles	- density of large boles (>100-cm dbh) at the end of the rotation but prior to the final rotation harvest
No. boles >80-cm dbh	- density of boles >80-cm dbh. Used in the 80-yr, first rotation strategy.
CHDI (age)	- stand age when CHDI criterion is attained
CHDI value	- CHDI value at the end of the rotation but prior to the final rotation harvest
Shade tolerant stems (age)	- stand age when shade-tolerant stem criterion is attained
No. shade tolerant stems	- density of shade-tolerant stems (>40-cm dbh) at the end of the rotation but prior to the final rotation harvest
No. stems >60-cm 1st entry	- density of stems >60-cm dbh present in the first thinning entry
No. stems >60-cm 2nd entry	- density of stems >60-cm dbh present in the second thinning entry
No. stems >60-cm 3rd entry	- density of stems >60-cm dbh present in the third thinning entry
SDI after 1st entry	- Stand Density Index resulting from the first thinning entry
SDI after 2nd entry	- Stand Denstiy Index resulting from the second thinning entry
SDI after 3rd entry	- Stand Density Index resulting from the third thinning entry

SECOND ROTATION RESULTS- designates results for a second-rotation strategy		
Total Merch. Volume	- cubm/ha of volume removed in all thinning entries and final rotation harvest	
Live LSc (age)	- stand age when threshold levels of all live late-successional attributes are attained	
Live LS Index	- LS Index based on all live late-successional attributes. Displayed when threshold values are generally not attained (i.e., 100- and 80-yr rotation strategies).	
Large boles (age)	- stand age when large-bole (>100-cm dbh) criterion is attained	
No. large boles	- density of large boles (>100-cm dbh) at the end of the rotation but prior to the final rotation harvest	
CHDI (age)	- stand age when CHDI criterion is attained	
CHDI value	- CHDI value at the end of the rotation but prior to the final rotation harvest	
Shade tolerant stems (age)	- stand age when shade-tolerant stem criterion is attained	
No. shade tolerant stems	- density of shade-tolerant stems (>40-cm dbh) at the end of the rotation but prior to the final rotation harvest	
No. stems >60-cm 1st entry	- density of stems >60-cm dbh present in the first thinning entry	
No. stems >60-cm 2nd entry	- density of stems >60-cm dbh present in the second thinning entry	
No. stems >60-cm 3rd entry	- density of stems >60-cm dbh present in the third thinning entry	
SDI after 1st entry	- Stand Density Index resulting from the first thinning entry	
SDI after 2nd entry	- Stand DensityJanuary 20, 2001 Index resulting from the second thinning entry	
SDI after 3rd entry	- Stand Density Index resulting from the third thinning entry	

NOTE: all density values are No./ha; stand age is in years since the last rotation harvest. If threshold levels of late-successional attributes are not attained by the end of the rotation (e.g., 80-100 yr first rotation strategies, and 80-yr second rotation strategy), stand-age estimates are not displayed and the LS Index is displayed instead of the Live LSc estimate. Also, density of boles >80-cm dbh is displayed for the 80-yr first-rotation treatments due the lack of development of large boles (>100-cm dbh). When evaluating a second-rotation strategy, results for the first-rotation treatment are displayed first followed by results for the second-rotation strategy.

To use RESP, copy RESP.exe and RESP.dat (which is the list of equation coefficients read by RESP.exe) from the enclosed diskette to the same directory on your hard disk. RESP can be executed by typing RESP at the DOS prompt, or through the Run menu item in Windows (when using the Run command, enter the pathname of the directory containing RESP.exe plus the full name of the program - RESP.exe). NOTE: upon terminating the program within Windows, the temporary DOS window created at program initiation may not go away. If this happens, simply select the delete button at the upper right of the temporary window.

LITERATURE CITED

Franklin, J. F. and T. A. Spies. 1991. Ecological definitions of old-growth Douglas-fir forests. Pages 61-69 *in* L. F. Ruggiero, K. A. Aubrey, A. B. Carey, and M. H. Huff (Tech. Eds.). Wildlife and vegetation of unmanaged Douglas-fir forests. USDA Forest Service, Pacific Northwest Research Station General Tech. Report PNW-GTR-285, Portland OR.

Garman, S. L., J. H. Cissel, and J. H. Mayo. in press. Accelerating development of late-successional conditions in young managed Douglas-fir stands: a simulation study. USDA Forest Service, Pacific Northwest Research Stn. General Tech. Report.

Harmon, M. E., S. L. Garman, and W. K. Ferrell. 1996. Modeling historical patterns of tree utilization in the Pacific Northwest: carbon sequestration implications. Ecological Applications, 6:641-652.

USDA Forest Service. 1993. Region 6: Interim old growth definition. Pacific Northwest Research Station, Portland, OR.