

An Empirical Approach for Estimating Natural Regeneration for the Forest Vegetation Simulator

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Abstract—The “partial” establishment model that is available for most Forest Vegetation Simulator (FVS) geographic variants does not provide an estimate of natural regeneration. Users are responsible for supplying this key aspect of stand development. The process presented for estimating natural regeneration begins by summarizing small tree components based on observations from local Forest Inventory and Analysis (FIA) data sets. Average frequency and height for seedlings and small saplings by tree species are calculated from the data. Seedling recruitment is determined by relationships to the maximum stand density index. Small saplings regeneration is derived from a distribution pattern computed from current stand size and density conditions. Apportioning the small sapling frequencies according to the observed distribution pattern provides an expected natural regeneration estimate by stand size/density condition, or vegetation state. Associated small sapling shade tolerance factors can be applied to govern progressions in species composition across the stand size/density continuum. Repute, an FVS post-processing program, has been developed to automate the estimation process. An example from the Southwest U.S. is presented to demonstrate the methodology.

Introduction

Predicting the abundance of natural regeneration, that is seedling and sapling recruitment beneath an existing overstory, is a difficult task required of forest growth modeling. Regeneration response is a stochastic event and the phenomena that trigger adequate natural regeneration are not easily determined. Inventory data sets that could be used to develop algorithms rarely cite the statistical parameters needed to effectively predict regeneration establishment (Ferguson 1997). As a result, prediction estimates for regeneration are generally weak in a system that must account for all facets of stand development. The objective of this paper is to present a process based on seedling and sapling counts as summarized from existing inventory conditions that can be used to provide understory recruitment for the Forest Vegetation Simulator (FVS) (Dixon 2002).

Forest models can be designed based on either *growth* or *yield* processes. The distinction is that growth architecture integrates growth processes over time to estimate future states whereas yield architecture directly estimates the future state as a function of time. Regeneration models that use a growth-based approach tend to be complex and predict too many poorly understood processes (Stage 2002). Such models are rare. Instead, most use a yield-based approach to assemble a picture of stand regeneration (Ferguson and others 1986). The estimation process described here follows the yield-based method. Observed regeneration attributes are drawn from FIA samples to estimate the natural regeneration component of a given plot of the same ecological stratum. This approach implicitly presumes that

In: Jain, Theresa B.; Graham, Russell T.; and Sandquist, Jonathan, tech. eds. 2010. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate: Proceedings of the 2009 National Silviculture Workshop; 2009 June 15-18; Boise, ID. Proceedings RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 351 p.

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the inferences driving regeneration in the inventoried plots applies to regeneration of modeled plots (Ek and others 1997).

Relevant Questions

Simply assuming that regeneration will only occur following a disturbance is wholly inadequate for providing a fully functioning regeneration model. *Tree based mortality* resulting from morphological senescence creates canopy gaps enabling thrifty understory recruits to fill the void. *Stand based mortality* resulting from overstory crown closure provides a successional opportunity for shade tolerant understory tree species to take hold. Regeneration occupancy must be considered for each combination of stand size and density class. For every vegetation state, there are two basic questions to be addressed:

Quantity	→	How many seedlings/saplings should be established?
Quality ²	→	What is the species composition of those established?

For this estimation procedure, both seedlings and small saplings are taken into account for natural regeneration. Flushes of seedlings pulse into stand projections on a twenty-year period. Mortality algorithms within FVS take their toll on the seedling component. To ensure recruitment into larger diameter size classes, regulation of small saplings (trees between one and three inches diameter) is pursued. A distribution pattern for small sapling abundance is computed relative to the current vegetation state based on stand size/density criteria.

Stand structure, in terms of size and density, is defined using overstory quadratic mean diameter (qmd) and percent canopy cover, respectively. There are five recognized stand size classes: 0-5 inch, 5-10 inch, 10-15 inch, 15-20 inch, and greater than 20 inches overstory qmd. Overstory qmd is comprised of the largest 20 percent of the trees by diameter, with a minimum of 20 trees needed for the classification. Otherwise, overstory qmd is determined by the largest diameter trees that constituted 25 percent of the canopy cover. Three stand density classes are defined: 10-40 percent, 40-70 percent, and greater than 70 percent canopy cover (Crookston and Stage 1999). If the canopy cover is less than 10 percent, the density class is classified as nonstocked.

The size and density classification system was derived from forest plan revision work for the Colville, Okanogan, and Wenatchee National Forests located in Washington State (Jahns 2006). Vegetation states were developed from National Standards for Geospatial Data (USDA Forest Service 2003) and supplemented with Standards for Mapping of Vegetation in the Pacific Northwest Region (USDA Forest Service 2004). The national/regional standards proposed a resolution of vegetation classification that was far more detailed than necessary to address forest plan revision efforts. However, the standards allowed flexibility for aggregation into appropriate vegetation classes. Regional wildlife specialists were consulted for advice on appropriate size and density aggregations for species viability and proposed the aforementioned classification scheme.

²Quality in terms of species composition may be ambiguous but is used in the context of regeneration establishment to imply a tree species' ability to survive relative to a given site potential or relative to its tolerance of overstory shade.

Pattern Revelation

A supporting premise of the proposed natural regeneration procedure is that there is a regular periodicity of good seed years and subsequent seedling establishment that is normally followed by equally impressive seedling mortality. This “burst” and “bust” dynamic relative to actual survivorship is difficult to capture in forest growth modeling. Consequently, the tactic devised for predicting adequate natural regeneration targets the more stable population of small saplings. These trees generally have an acceptable girth and height to indicate having a root system firmly entrenched in mineral soil. Furthermore, they possess the capacity either to fill gaps due to overstory tree mortality or to follow successional recruitment trends as dictated by species shade tolerance.

Conditionally, seedlings are input into an FVS projection once per twenty-year period. During that time, seedlings are subject to the various FVS mortality mechanisms. A complimentary check is added to evaluate whether sufficient small saplings survived from the pool of seedlings to ensure a viable stream of ingrowth into larger diameter trees. Thus, a fully functioning regeneration system is in-place. The following text will detail the process.

Southwest Prototype

Many of the concepts behind the natural regeneration estimation process arose from work for landscape analysis. An example is presented based on recent forest planning efforts from the U.S. Forest Service Southwest Region. There are six National Forests in Arizona and five National Forests in New Mexico encompassing 20.6 million acres (fig. 1). Several terrestrial life zones exist within this diverse geographic area. Recent periodic and annual Forest Inventory and Analysis data sets were assembled to represent this landscape. Forest cover types, as comprised of plant associations, were used to stratify the data. FIA plot counts by cover type are shown in table 1. The Forest Vegetation Simulator can be used to model stand development of timberland and woodland communities. Methods developed for estimating natural regeneration will be described for the *Mixed Conifer—Dry* type.



Figure 1—Geographic location of National Forests within the USFS Southwestern Region.

Table 1—FIA plot count by forest cover type.

Forest cover	Type descriptor	Plot sample
Spruce-fir	Upper subalpine	69
	Lower subalpine	72
Mixed conifer	Wet—infrequent fire	48
	Dry—frequent fire	444
Ponderosa pine	Grass	495
	Gambel oak	295
	Evergreen oak	132
Pinyon-juniper	Woodland	1,354
Oak	Woodland	308
Total:		3,217

Inspection of the observed small sapling density within the Mixed Conifer-Dry strata (table 2) reveals the following pattern: Starting with any canopy cover class (row), then reading from the largest to smallest stand size class (columns, right to left), each smaller size class contains two to three times as many saplings as the next larger size class. Applying the average observed small sapling distribution factor (2.6330) among the size and density classes as shown in the bottom half of table 2 does a good job of smoothing inordinate jumps between adjacent classes. Derivation of the small sapling distribution factor will be described in the following paragraphs.

The natural regeneration estimation process begins by determining the vegetation state (i.e. size/density class) of each plot in the inventory. A reference template is displayed in table 3. A two-digit number indexes the size/density class combination. The first digit represents columns (qmd stand size classes), and the second digit represents rows (canopy cover density classes). For example, vegetation state 22 would indicate a size class of 5-10 inch qmd and a density class of 40-70 percent canopy cover.

Table 2—Mixed conifer—dry: small sapling distribution.

Canopy	Overstory QMD size class				
cover class	0-5	5-10	10-15	15-20	> 20
(%)	----- (inches)-----				
Observed small sapling frequency (trees/acre)					
10-40	739	233	59	62	15
40-70	1816	417	179	36	25
> 70		545	256	112	
Predicted small sapling frequency (trees/acre) ^a					
10-40	417	158	60	23	9
40-70	1098	417	158	60	23
> 70	2891	1098	417	158	60

^a Based on small sapling distribution pattern factor of 2.6330 derived from observed data.

Table 3—Mixed Conifer—Dry: Size/Density Template and FIA plot count.

Canopy cover class	Overstory QMD size class				
	0-5	5-10	10-15	15-20	> 20
(%)	----- (inches)-----				
Code reference guide ^a					
10-40	11	21	31	41	51
40-70	12	22	32	42	52
> 70	13	23	33	43	53
FIA plot sample ^b					
10-40	14	50	32	6	5
40-70	13	121	92	19	6
> 70		11	12	4	

^a Code reference guide provides a template for the size/density classes. A 22 code indicates a 5-10 inch qmd size class and a 40-70 percent canopy cover density class.

^b Of the 444 total FIA plots sampled within the Mixed Conifer-Dry strata, 59 were classified as nonstocked (canopy cover less than 10 percent) rendering 385 plots for small sapling analysis.

The six size/density classes used to compute the small sapling distribution factor are vegetation states: 21, 22, 31, 32, 41, and 42 (referred to as base cells). These cells contain the majority of FIA plots as displayed in the bottom half of table 3. Base cells are of primary interest in the natural regeneration estimation procedure. Note there is little need for additional natural regeneration in smaller size or closed density classes. These vegetation states are by definition either a “seedling/sapling” size class (i.e. 0-5 inches) or at “full site occupancy” in terms of stand density (> 70%). Accordingly, additional natural regeneration is not targeted for the 12, 13, 23, 33, 43, or 53 size/density classes.

The distribution factor is calculated as a weighted average of the base cells. Table 4 presents the calculation method. Vegetation states lying adjacent to base cells are used to determine a distribution factor for the base cell. The representative FIA plot samples serve as weights in the calculation. A composite distribution factor is determined by summing the base cells multiplied by their FIA plot sample and dividing by the total number of FIA plots residing in the base cells.

Table 5 displays composite small sapling distribution factors for each of the major forest cover types in the Southwestern Region. A trend can be noted related to the composition of timberland tree species compared to woodland. As timberland species diminish and woodland species increase in prevalence, the composite small sapling distribution factor increases. Given the relative proportional size and site occupancy of woodland tree species, this trend is reasonable.

Repute Program

Repute, an FVS post-processing program, has been written to implement the concepts of natural regeneration estimation process. The main Repute window is shown in figure 2. In brief, the Repute program processes output files from the Fvsstand Alone program (Vandendriesche 1997) to develop regeneration “addfiles” (i.e. auxiliary FVS keyword files). Within a FVS run, the Repute addfile determines the vegetation state (size/density class) as each projection cycle is processed; associates the composite distribution matrix that was based

Table 4—Mixed conifer—dry: calculation method for composite distribution factor.

Canopy cover class	Overstory QMD size class				
	0-5	5-10	10-15	15-20	> 20
(%)	----- (inches)-----				
	Size/density distribution factors^a				
10-40		2.3270	3.2815	1.1006	
40-70		2.2573 ^{b,c}	2.6764	4.5281	
> 70					
Composite distribution factor: 2.6330^{d,e,f,g}					

^a Refer to Table 2 (T2) – Observed Small Samplings Frequency for tree per acres values; Table 3 – Code Reference Guide for indicated size/density class; and, Table 3 (T3) – FIA plot sample for associated weights.

^b Size/Density 22 Distribution Factor = $((T2:12/T2:22)*T3:12+(T2:22/T2:21)*T3:21+(T2:22/T2:32)*T3:32+(T2:23/T2:22)*T3:23) / (T3:12+T3:21+T3:32+T3:23)$

^c 2.2573 = $((1816/417*13)+(417/233)*50+(417/179)*92+(545/417)*11) / (13+50+92+11)$

^d Refer to Table 3 – Code Reference Guide for indicated size/density class; Table 3 (T3) – FIA plot sample for associated weights; and, Table 4 (T4) – Size/Density Distribution Factors for class values.

^e Composite Distribution Factor = $(T4:21*T3:21+T4:22*T3:22+T4:31*T3:31+T4:32*T3:32+T4:41*T3:41+T4:42*T3:42) / (T3:21+T3:22+T3:31+T3:32+T3:41+T3:42)$

^f Base Cell sample size must contain 10 or more counts. Note that the plot sample for Base Cell 41 (T3:41) equaled six and therefore was reset to zero.

^g 2.6330 = $(2.3270*50+2.2573*121+3.2815*32+2.6764*92+1.1006*0+4.5281*19) / (50+121+32+92+0+19)$

Table 5—Composite small sapling distribution factors by forest cover type.

Forest cover	Type descriptor	Distribution factor
Spruce-fir	Upper subalpine	2.1199
	Lower subalpine	1.9529
Mixed conifer	Wet—Infrequent fire	1.9700
	Dry—Frequent fire	2.6330
Ponderosa pine	Grass	2.9019
	Gambel oak	3.0383
	Evergreen oak	2.8769
Pinyon-juniper	Woodland	2.7820
Oak	Woodland	2.8083

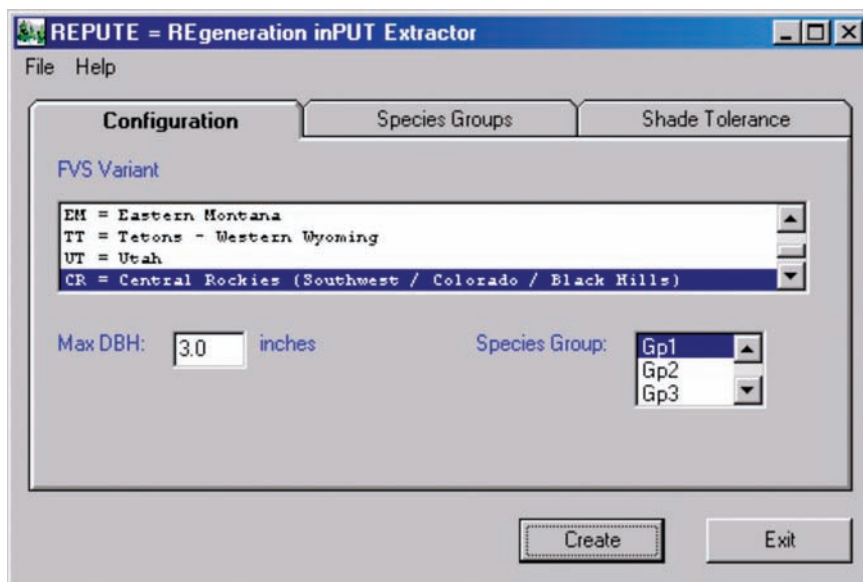


Figure 2—Repute user interface.

on observed small sapling frequencies; applies shade tolerance multipliers if applicable; inputs seedling reproduction; and, estimates small sapling ingrowth.

Implementation of the natural regeneration estimation procedure relies heavily on the Event Monitor (Crookston 1990) capabilities within the FVS model. There are limitations associated with using the Event Monitor that must be recognized such as the number of “compute variables” (199) and “conditional statements” (160). Conserving available resources of the Event Monitor is important. The natural regeneration estimation procedure was developed to be as efficient as possible. “Economies of Scale” principles were invoked. As developed, the vegetation classification system identifies fifteen combinations of size and density. Computing a composite distribution factor based on observed small sapling data allows rendering the fifteen size/density classes as a function of one multiplicative value.

Computed Size/Density Class

The natural regeneration estimation process begins by determining the vegetation state (i.e. size/density class) at each FVS projection cycle (fig. 3). The most important steps are outlined as follows. The Event Monitor DBHDist function is used to compute size class based on the largest 20 percent of the trees. Canopy cover, corrected for overlap, is used to calculate density class based on all trees. A qualifier variable (CCx) is computed to determine whether a plot is stocked (greater than or equal to 10 percent canopy cover) or nonstocked (less than 10 percent canopy cover) at the beginning of the projection cycle. If classified as nonstocked, the vegetation state is set to zero. A “regeneration state” variable is defined and set equal to the overstory vegetation state. However, there are times when a “bumper” regeneration pulse is allowed. Two additional statements are used to indicate the need. If a plot’s current stocking level is less than 25 percent of the specified Stand Density Index maximum (Long 1985) and if there is a minimum of at least 10 trees greater than nine inches in diameter (seed trees), then the regeneration state is set to equal one resulting in a significant flush of natural regeneration injected into the projection.

Line Number	Column Ruler							
	-----1-----	-----2-----	-----3-----	-----4-----	-----5-----	-----6-----	-----7-----	-----8-----
	Keyword	f1d1	f1d2	f1d3	f1d4	f1d5	f1d6	f1d7
1	*****							
2	*	Compute Vegetation State						*
3	*	- Composite: Size Class = QMD 5-inch class widths						*
4	*	Overstory Density = Canopy Cover S=10-40%/O=40-70%/C=70+%						*
5	*****							
6	Compute	0						
7	_TotTrCt	=Max(SpMcDBH(1,All,0,0.20,99.0,5.0,500.0,0),1)						
8	_LrgTrCt	=Max((SpMcDBH(1,All,0,0.20,99.0,5.0,500.0,0)*0.20),20)						
9	_DiaL	=DBHDist(3,_LrgTrCt/_TotTrCt*100)						
10	_DiaU	=DBHDist(3,6)						
11	_QMDc	=SpMcDBH(5,All,0,_DiaL,_DiaU,5.0,500.0,0)						
12	_CC00p	=SpMcDBH(7,All,0,00.00,99.0,0.0,500.0,0)						
13	_CCx	=LinInt(_CC00p,0,10,10,999,0,0,1,1)						
14	_SizCls	=LinInt(_QMDc,00,05,05,10,10,15,15,20,20,99,1,1,2,2,3,3,4,4,5,5)*_CCx						
15	_DenCls	=LinInt(_CC00p,0,40,40,70,70,999,1,1,2,2,3,3)*_CCx						
16	VegSt	=(_SizCls*10)+_DenCls						
17	_SDImIn	=LinInt(SpMcDBH(11,ALL,0,0.2,200,1,500,0), &						
18		0,BSDIMAX*0.25,BSDIMAX*0.25,9999,0,0,10,10)						
19	_SdTree	=LinInt(SpMcDBH(01,ALL,0,9.0,200,1,500,0), &						
20		0,10,10,99999,0,0,1,1)						
21	RgnSt	=LinInt(_SDImIn+_SdTree,0,1,1,2,2,9, &						
22		0,0,1,1,(_SizCls*10+_DenCls),(_SizCls*10+_DenCls))						
23	End							

Figure 3—FVS keyword addfile segment that computes size/density class (vegetation state) for each projection cycle.

Multiplicative Distribution Factor

A predominant vegetation state is determined from the observed FIA sample and is simply the size/density class that contains the most plots. This state is designated as the “index” cell. For the Mixed Conifer—Dry strata, size/density class 22 is the predominant vegetation state as a result of being comprised of 121 FIA plots from a total of 444 FIA plots (bottom of table 3). Across all FIA plots within this vegetation state, the average small sapling frequency is 417 trees per acre. The composite distribution factor is applied relative to the index cell. In this example, the 22 size/density class receives a multiplicative factor equal to 1.0000 (fig. 4). Successive smaller size classes and denser canopy cover classes

Line Number	Column Ruler								
	-----+-----1-----+-----2-----+-----3-----+-----4-----+-----5-----+-----6-----+-----7-----+-----8-----	Keyword	f1d1	f1d2	f1d3	f1d4	f1d5	f1d6	f1d7
1	*****								
2	*	Small Sapling	Composite Distribution Matrix					*	
3	*	- 2.6330 Factor	based on RegSt 22					*	
4	*****								
5	Compute	0							
6	_Sapp=LinInt(_RgnSt,	0,	1,	1,	11,	&			
7		11,	12,	12,	13,	13,	21,	&	
8		21,	22,	22,	23,	23,	31,	&	
9		31,	32,	32,	33,	33,	41,	&	
10		41,	42,	42,	43,	43,	51,	&	
11		51,	52,	52,	53,	53,	100,	&	
12		1.0000,	1.0000,	2.6330,	2.6330,	&			
13		1.0000,	1.0000,	2.6330,	2.6330,	6.9326,	6.9326,	&	
14		0.3798,	0.3798,	1.0000,	1.0000,	2.6330,	2.6330,	&	
15		0.1442,	0.1442,	0.3798,	0.3798,	1.0000,	1.0000,	&	
16		0.0548,	0.0548,	0.1442,	0.1442,	0.3798,	0.3798,	&	
17		0.0208,	0.0208,	0.0548,	0.0548,	0.1442,	0.1442)		
18	_Saps=	417							
19	End								

Figure 4—FVS keyword addfile segment that associates a multiple of the composite distribution factor based on dominant “22” size/density class.

are multiplied by the composite distribution factor. Successive larger size classes and less dense canopy cover classes are divided by the composite distribution factor. This allows apportioning the index cell's sapling frequency (417 trees per acre) across all size/density classes and renders the predicted values as displayed in the bottom portion of table 2. As such, the question of regeneration “quantity” is addressed.

Shade Tolerance Multipliers—Small Saplings

In the absence of disturbance events, either human or natural, tree species succession follows capacities for survival in light of overstory shading (Spurr and Barnes 1973). Transitions in species composition do not affect all forest cover types equally. For example, the species ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) is considered shade “intolerant” (USDA 1990). If found in a Ponderosa Pine forest cover type, it is very resilient and will regenerate as opportunities arise. However, if ponderosa pine is found in a Mixed Conifer forest cover type, it will struggle to survive without disturbance. Shade tolerance considerations governing ponderosa pine regeneration are important in the latter situation, but not in the former. The Repute program allows the user the option to include shade tolerance effects for small saplings. This feature addresses the “quality” aspect regarding species composition of natural regeneration.

Figure 5 displays small sapling shade tolerance multipliers used for intolerant species such as ponderosa pine. Shade tolerance multipliers were developed using inventory data sources from throughout the Interior West (Colville-Okanogan-Wenatchee National Forests, Clearwater-Nez Perce National Forests,

Line Number	Column Ruler						
	Keyword	f1d1	f1d2	f1d3	f1d4	f1d5	f1d6
1	*****						
2	* Determine Small Sapling Shade Tolerance Multiplier *						
3	*****						
4	Compute	0					
5	_Shd1=LinInt(_RgnSt,	. . .					
6	_Shd2=LinInt(_RgnSt,	0,	1,	1,	11, &		
7			11,	12,	12,	13,	13,
8			21,	22,	22,	23,	23,
9			31,	32,	32,	33,	33,
10			41,	42,	42,	43,	43,
11			51,	52,	52,	53,	53,
12		100,	999,	&			
13		1,	1,	2.50,	2.50,	&	
14			1.75,	1.75,	1.50,	1.50,	1.00,
15			1.25,	1.25,	1.00,	1.00,	0.75,
16			0.10,	0.10,	0.25,	0.25,	0.35,
17			0.05,	0.05,	0.01,	0.01,	0.00,
18			0.01,	0.01,	0.00,	0.00,	0.00,
19		0,	0)				
20	_Shd3=LinInt(_RgnSt,	. . .					
21	_Shd4=LinInt(_RgnSt,	. . .					
22	_Shd5=LinInt(_RgnSt,	. . .					
23	End						

* Shade Tolerance Rating:

_Shd1 = Very Intolerant

_Shd2 = Intolerant

_Shd3 = Intermediate

_Shd4 = Tolerant

_Shd5 = Very Tolerant

Figure 5—FVS keyword addfile segment that determines a multiplier relative to size/density class and associated overstory shade tolerance for small saplings.

and Southwestern Region National Forests). Tree species were sorted by five shade tolerance ratings: very intolerant, intolerant, intermediate, tolerant, and very tolerant. Within these groupings, small sapling frequencies were averaged in accordance with the size/density classification matrix. All cells were then divided by the index cell in order to scale the shade tolerance matrix relative to the composite distribution matrix. In this manner, the two matrices could be joined (i.e. multiplied) to account for regeneration quantity and quality.

Table 6 provides an example for ponderosa pine small saplings within the Mixed Conifer—Dry strata. On average, 26.34 trees per acre were observed on all FIA plots. This value is distributed by the shade tolerance multipliers displayed in the upper portion of table 6 to render the expected ponderosa pine small sapling frequency as presented in the bottom portion of table 6.

Table 6—Mixed conifer—dry: Ponderosa pine small saplings expected abundance.

Canopy cover class	Overstory QMD size class (inches)				
	0-5	5-10	10-15	15-20	> 20
(%)	Small sapling shade intolerant multipliers ^a				
10-40	1.75	1.25	0.10	0.05	0.01
40-70	1.50	1.00	0.25	0.01	0.00
> 70	1.00	0.75	0.35	0.00	0.00
(%)	Expected small sapling frequency (trees/acre) ^b				
10-40	46.09	32.92	2.63	1.32	0.26
40-70	39.51	26.34	6.59	0.26	0.00
> 70	26.34	19.75	9.22	0.00	0.00

^aComparative analysis using observed small sapling data from throughout the Interior West. Index cell was divided into all other size/density class cells to compute the multiplier.

^bObserved ponderosa pine small sapling frequency dispersed from Index Cell to all other size/density cells based on shade intolerant multiplier. Values indicate expected small sapling frequency abundance.

Shade Tolerance Effects—Seedlings

Five phases of stand development based on relative stand density index have been postulated by Long (1985). They are:

- **0-25% of SDI^{max}** —A stand or group of trees at this density level is open-grown. There is little competition for moisture, nutrients, and sunlight.
- **25-35% of SDI^{max}** —A stand begins to experience tree-to-tree competition for moisture and nutrients. Less sunlight reaches the ground but site productivity is still increasing.
- **35-60% of SDI^{max}** —This is the range in which full site occupancy has been reached. Tree-to-tree competition has resulted in individual trees sacrificing growth. Site productivity is still increasing but has begun to plateau.
- **60-100% of SDI^{max}** —At this stage, tree-to-tree competition is so great that individual trees can no longer receive enough moisture, nutrients, and sunlight to survive. Self-thinning occurs but openings created by trees dying are quickly filled by the growth of surviving trees.

- **100%+ of SDI^{max}** —Full site occupancy and growth are lost as overstory trees become weakened and die. As mature trees die, openings are created for more shade tolerant tree species if the site is capable of supporting those species.

By default within FVS, background mortality occurs when the current stand SDI is below 55 percent of maximum SDI. Density related mortality begins when the relative stand density is above 55 percent of maximum SDI. Stand density peaks at 85 percent of maximum SDI (Dixon 2002). These thresholds were incorporated into the survivability logic for seedling recruitment for three realms of shade tolerance in the following manner:

- Intolerant: 25-55% of SDI^{max}
- Mid-tolerant: 35-85% of SDI^{max}
- Tolerant: 55-100% of SDI^{max}

Within the specified range for a shade tolerance realm, input of natural regeneration for seedlings is tapered from 100 to 0 percent of the target value.

Natural Regeneration Estimates

Repute selects tree counts and average height by species for the seedling (< 1-inch) and small sapling (2-inch) diameter classes from the Fvsstand Alone 'stand tables' to create separate tree species regeneration keywords (figs. 6 and 7). On a twenty-year basis, the natural regeneration estimation process checks whether conditions warrant a pulse of seedling/sapling reproduction. Target

Line Number	Column Ruler							
	-----1-----	-----2-----	-----3-----	-----4-----	-----5-----	-----6-----	-----7-----	-----8-----
	Keyword	f1d1	f1d2	f1d3	f1d4	f1d5	f1d6	f1d7
1	*****							
2	*	Seedling Establishment Values						*
3	*****							
4	If	0						
5	SpMcDBH(1,ALL,0,0,1,0,999,0)	LE _SEED AND &						
6	SpMcDBH(11,ALL,0,1,0,200,1,0,500,0)	LE BSDIMAX*0.85 AND &						
7	(_RGN EQ 1 OR _RgnSt LE 1) AND _RgnSt NE 12 AND _CANOPY LT 3 AND EVPHASE EQ 2							
8	Then							
9	Estab							
10	Natural	0	Parms(WF, . . .					
11	Natural	0	Parms(PP, &					
12	Max(((40.690-SpMcDBH(1,PP,0,0,1,0,999,0)),0))* &							
13	LinInt(SpMcDBH(11,ALL,0,0.2,200,1,500,0),BSDIMAX*0.25,BSDIMAX*0.55,1,0)* &							
14	LININT(SpMcDBH(2,PP,0,3,0,99,0,999,0)/Max(SpMcDBH(2,All,0,3,0,99,0,999,0),1), &							
15	0.00,0.02,0.02,0.05,0.05,1.99,0.40,0.40,0.80,0.80,1.00,1.00), &							
16	100.00, 0.00, 1.0, 0)							
17	Natural	0	Parms(DF, . . .					
18	Natural	0	Parms(AS, . . .					
19	End							
20	Compute	0						
21	_Rgn=0							
22	End							
23	Compute	20						
24	_Rgn=1							
25	End							
26	EndIf							
27	Compute	1						
28	_SEED=858							
29	End							

Figure 6—FVS keyword addfile segment that establishes seedling reproduction on a 20-year basis. Values by species (PP: Ponderosa Pine) for tree count (40.690 trees/ac) and average height (1.0 ft) are extracted from Fvsstand Alone 'stand tables.'

Line Number	Column Ruler						
	-----1-----	-----2-----	-----3-----	-----4-----	-----5-----	-----6-----	-----7-----8
	Keyword	f1d1	f1d2	f1d3	f1d4	f1d5	f1d6 f1d7
1	*****Small Sapling Ingrowth Values*****						
2	*	Small Sapling Ingrowth	Values				*
3	*****						
4	If	0					
5	SpMcDBH(1,ALL,0,1,3,0,999,0)	LE	_SAPS*_SAPP	AND	&		
6	SpMcDBH(11,ALL,0,1.0,200,1.0,500,0)	LE	BSDIMAX*0.85	AND	&		
7	(_RGN EQ 1 OR _RgnSt LE 1) AND _RgnSt NE 12 AND _CANOPY LT 3 AND EVPHASE EQ 2						
8	Then						
9	Estab						
10	Natural	0	Parms(WF, . . .				
11	Natural	0	Parms(PP, &				
12	Max(((26.339*_SAPS/_SAP2*_SAPP*_SAPF*_SHD2)-SpMcDBH(1,PP,0,1,3,0,999,0)),0)* &						
13	LININT(SpMcDBH(2,PP,0,3.0,99,0,999,0)/Max(SpMcDBH(2,All,0,3.0,99,0,999,0),1), &						
14	0.00,0.02,0.02,0.05,0.05,1.99,0.40,0.40,0.80,0.80,1.00,1.00), &						
15	100.00, 0.00, 12.1, 0)						
16	Natural	0	Parms(DF, . . .				
17	Natural	0	Parms(AS, . . .				
18	End						
19	Compute	0					
20	_Rgn=0						
21	_SAPF=((_SAPS*_SAPP)/(&						
22	+27.521*_SAPS/_SAP2*_SAPP*_SHD4 &						
23	+26.339*_SAPS/_SAP2*_SAPP*_SHD2 &						
24	+40.353*_SAPS/_SAP2*_SAPP*_SHD3 &						
25	+22.287*_SAPS/_SAP2*_SAPP*_SHD1 & . . .						
26	End						
27	Compute	20					
28	_Rgn=1						
29	End						
30	EndIf						
31	Compute	1					
32	_SAP2=312						
33	End						

* Example: Ponderosa Pine Small Sapling Target for Size/Density Class 32
 Value = 26.339 (observed small saplings, ponderosa pine, all size/density classes)
 _Saps = 417 (observed small saplings, all species, size/density class 22)
 _Sap2 = 312 (observed small saplings, all species, all size/density classes)
 _Sapp = 0.3798 (composite distribution factor for size/density class 32)
 _Sapf = 2.3220 (shade tolerance factor, all shade tolerance classes)
 _Shd2 = 0.25 (shade intolerant multiplier)

Target = 26.339*_SAPS/_SAP2*_SAPP*_SAPF*_SHD2
 Target = 26.339*417/312*0.3798*2.3220*0.25 = 7.76 small saplings per acre

Figure 7—FVS keyword addfile segment that ensure small sapling regeneration on a 20-year basis.

thresholds are based on the classified vegetation state. If existing frequencies are less than specified thresholds, natural regeneration is invoked. Checks are included that account for existing seedlings and small saplings so as not to exceed expected targets. Also, a test is performed to inquire whether enough mature trees of a given species are present to produce an adequate seed source. For a more in-depth discussion of the Repute program, a detailed Users Guide is available (Vandendriesche 2005).

Recall that seedlings are input as pawns for small sapling recruitment. The crux of the natural regeneration estimation process is insuring that a stable small sapling ingrowth component is available that will transition into larger diameter classes in subsequent projection cycles. An example is provided in figure 7. Input values and the resultant small sapling target for size/density class 32 are displayed. If existing small ponderosa pine saplings exceed the target value of 7.54, then

the “Natural” keyword operation is not performed. Conversely, if existing small ponderosa pine saplings are lacking, the target frequency of 7.54 trees per acre will be regenerated so long as there is a sufficient number of mature ponderosa pine capable of providing an adequate seed source.

Conclusions

In the absence of having the “full” regeneration establishment model available to provide natural reproduction into an FVS projection, users need to account for this important aspect of forest growth modeling. External regeneration imputation models have been developed and should be explored where available (Robinson 2007). Lacking these resources, the natural regeneration estimation procedure presented in this paper may serve to fill the void. The procedure presented describes the process of inputting a stable supply of small saplings into projection runs to procure a vital source of recruitment into larger diameter trees. Flushes of seedlings are also input to account for the smallest form of forest reproduction. The regeneration estimation method is well suited for natural growth simulations. It may also be suited following certain silvicultural treatments but may need augmentation based on professional experience.

Special situations may require creative solutions when running the Repute program. For example, in areas with intense deer browsing, it may be necessary to input larger diameter trees, greater than the small sapling size class, to represent the stable recruitment component. Having a representative supply of natural regeneration to input into a simulation run is vital.

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