Development of External Regeneration Models for FVS: Another Wrench in the Toolkit

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Abstract—Despite more than three decades of development, only one full-featured regeneration model has been developed for the Forest Vegetation Simulator (FVS). Regeneration remains a challenging problem because of its all-or-none nature: the need for field inventories that span the vast range of stand structure conditions; the need to accommodate environmental and climatic influences, and the need to integrate these within the FVS core model source code. We introduce and provide two examples of a recent FVS capability that removes one hurdle from this difficult problem: allowing the development of external models that can be executed from within the FVS system with minimal modification to the FVS source code. External models developed from any computer programming language can be incorporated into FVS by obeying a few simple rules.

Introduction

Since its first publication more than three decades ago (Stage 1973), the Forest Vegetation Simulator (FVS) has grown to include twenty geographic variants in the United States. Additionally, model extensions that simulate the impacts of various insects, diseases, and fires have been developed. Despite this singular achievement—what other software with a 1973 vintage is still in use and constantly being enhanced?—FVS has only one full featured regeneration submodel (Ferguson and others1986; Ferguson and Crookston 1984, 1991; Ferguson and Carlson 1993)[2].

There are numerous reasons that few regeneration models exist. Biologically, regeneration is a hard science problem because it is an "all-or-none" event, making it harder to observe than more continuous processes like diameter and height growth. Inventorying seedlings, therefore, requires a multitude of intensive ground samples, and advances in remote sensing may never be able to contribute much at this small spatial scale. In the development of Ferguson's model, for example, over 12,000 regeneration plots were established in 500 stands. Regeneration can be triggered by sudden disturbances like wildfire, but also by slower on-going disturbances like root disease or stand senescence and decline, both of which create openings gradually. In the case of slow disturbances, it can be difficult to define the time or threshold cues that lead to regeneration. Finally, regeneration is not solely dependent on available overstory seed stock but also upon micro-site conditions for success. When triggered, it can appear as a flush of new seedlings or may sputter unevenly over time. Together, these three factors conspire to make it a hard science problem.

Regeneration can also be a hard management problem. Forestry practices geared toward commodity production have historically implemented even-aged rotations that inherently employ manual planting if necessary. Under this management regime, natural regeneration is usually ignored and is of little relevance for funding or research. However, over the past two decades this situation has changed, and it is now common practice for planners to develop forest management plans that incorporate ecosystem components that include natural disturbances such as insects, diseases, and fire. Under an environmental paradigm, natural regeneration takes on a more important role. In the century before us, forest planners must contemplate forest ecosystems in which complex, largely unknown relationships between global climate, species composition, disturbance agents, and invasive species all combine to make forecasting even more precarious. In

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[2] Some might say there are five such models. I consider the Northern Idaho/Inland Empire Regeneration Establishment model and the neighboring geographic variants (Central Idaho, Kootenai/Kaniksu/Tally Lake, Eastern Montana) that have adopted it, as well as the closely related Southeast Alaska regeneration extension, as one model.

this uncertain future, regeneration predictions will be an important component of forest planning, and the juxtaposition of a hard science problem with a hard management problem could signal either a perfect storm or a perfect opportunity.

Current FVS Regeneration Options

FVS geographic variants without the full establishment model extension have a range of options—some simple, some complex—for introducing regeneration. Figure 1 shows a hypothetical simple example in which the local silviculturist knows what will regenerate after a given disturbance. The Event Monitor (Crookston 1990) is invoked to thin the stand and immediately thereafter add new stems. Figure 2 shows a more complex hypothetical example that follows a simple rule: a 20 percent decline in stand basal area triggers regeneration of two species, Douglas-fir and lodgepole pine. The composition and amount of regeneration is equal to these two species' densities observed when the 20 percent threshold is detected by the Event Monitor. Compared to figure 1, rules like the one shown in figure 2 imply a deeper understanding of the processes driving stand regeneration.

At an even more abstract level, a fragment of a third and more complex example is shown in figure 3. The full example contains nearly 1,000 lines of Event Monitor statements and represents a regeneration model developed by Wilson, Maguire, and Ager (2003), hereafter referred to as the Blue Mountains model. This model mimics the key components of the Ferguson regeneration model by recognizing habitat types, site effects,

```
Line Nmbr   Column ruler
----+----1----+----2----+----3----+----4----+----5----+----6----+
  Keyword      fld1      fld2      fld3      fld4      fld5
If
Year EQ 2005
Then
ThinBBA                    30
Estab
Plant                       3       350        90         2
Plant                       7       120        90         2
End
EndIf
```

Figure 1—An example of simple regeneration following a stand entry using elementary Event Monitor capabilities. Not all possible keyword fields are shown.

```
Line Nmbr   Column ruler
----+----1----+----2----+----3----+----4----+----5----+----6----+
  Keyword      fld1      fld2      fld3      fld4      fld5
Compute           0
TPH_DF = SpMcDbh(1,3,0)
TPH_LP = SpMcDbh(1,7,0)
End
If
EVphase EQ 2 AND DBA% LT -20
Then
Estab
Plant                       3    Parms(TPH_DF,100,2,0.5,0)
Plant                       7    Parms(TPH_LP,100,2,0.5,0)
End
EndIf
```

Figure 2—A more complex hypothetical example of regeneration in which simple rules for regeneration are written using the Event Monitor and the stem density of species 3 and 7 (Douglas-fir and lodgepole pine) when a 20 percent decline occurs in stand basal area. In this example the lost stems are simply replaced by the current density of each species.

```
                         Column ruler
----+----1----+----2----+----3----+----4----+----5----+----6----+
   Keyword      fld1      fld2      fld3      fld4      fld5
Compute            1
SQRT_SL = Sqrt(Slope/100)
SL_Cos = Cos(Aspect*((2*3.1415)/360))*SQRT_SL)
SL_Sin = Sin(Aspect*((2*3.1415)/360))*SQRT_SL
GS_Harv = 10
GS_Harv2 = 100
E = Elev
EL = Elev/100
EL2 = EL*EL
GS_Cos = 10*SL_Cos
GS_Sin = 10*SL_Sin
LN_EL = ALog(EL)
HCycle = 100
Minus1 = 100
End
Compute            0
Add = 3
H = Yes
Heavy = No
! 963 lines deleted.
Natural            1  Parms(WP,SPA_PIMO,80,10,3,0)
Natural            1  Parms(PP,SPA_PIPO,80,10,3,0)
Natural            1  Parms(DF,SPA_PSME,80,10,3,0)
MinPlots          20
End
EndIf
```

Figure 3—A fragment of a complex Event Monitor regeneration model. Because of the way Event Monitor instructions are stored and processed, this example is extremely difficult to debug.

levels of disturbance, presence or absence of stocking, probability of regeneration for six species, and if present, existing seedlings per acre of each species. Its complexity provides some realism. However, this comes at the expense of being very difficult to debug within the Event Monitor. Also, there is a performance penalty when run in conjunction with the fire and fuels (FFE; Reinhardt and Crookston 2003) and parallel processing (PPE; Crookston and Stage 1991) extensions of FVS. Landscape simulations of this magnitude require immense use of the computer's hard drive to store stand-state information during the projection.

External Regeneration Model Examples

1: The Blue Mountains Model

Based on advanced FFE-PPE research studies led by Alan Ager, a new keyword—AddTrees—was incorporated into the Regeneration Establishment model source code. Figure 4 shows an example of this new keyword coupled with an external version of the Blue Mountains model. The external model codes the same relationships presented in the Event Monitor version shown in figure 3 as a stand-alone executable ("BMEstab.exe") written in Fortran (Ager and others 2007; Robinson 2004). The model name is entered as a supplemental record following the AddTrees keyword and may be invoked directly or conditionally through the Event Monitor. Although the example in figure 4 runs an executable program, the external model could be a batch file, shell script, R-script, or web service (depending on the operating system and connectivity to the internet or other databases). As long as the external process given on the AddTrees supplemental record results in the creation of a file in a standard format (described below), FVS will process the contents of the returned file and schedule natural regeneration.

The relationship between FVS and the Blue Mountains model is shown schematically in figure 5. The left part of the figure shows the cyclical sequence of events for a single stand within the BM-FFE-PPE. During each projection cycle, any Establishment

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+					
	Keyword	fld1	fld2	fld3	fld4	fld5
1	If					
2	*Condition*					
3	Then					
4	Estab					
5	AddTrees	0	5	1		
6	BMEstab.exe					
7	End					
8	EndIf					

AddTrees Keyword		
Field	**Value**	**Notes**
1	0	Years after *Condition* is true that the AddTrees keyword is scheduled
2	5	Years after AddTrees is run to schedule a Natural planting; age to assign new trees
3	1	Method 1 signals FVS to (1) read a single supplemental record containing an executable filename; (2) submit and run the named executable using a System call, appending a command line argument containing the ES1 filename after any other command line arguments; (3) read the ES2 output file created by BMEstab; and (4) use the content of that file to schedule Natural keywords in FVS.

Figure 4—An example showing how the AddTrees keyword is used as part of a sequence of establishment model keywords with the Blue Mountains regeneration model. Assuming a 10 model year time step, this keyword set simulates natural regeneration 14 years after the *Condition* becomes true. Additional details are found in the text.

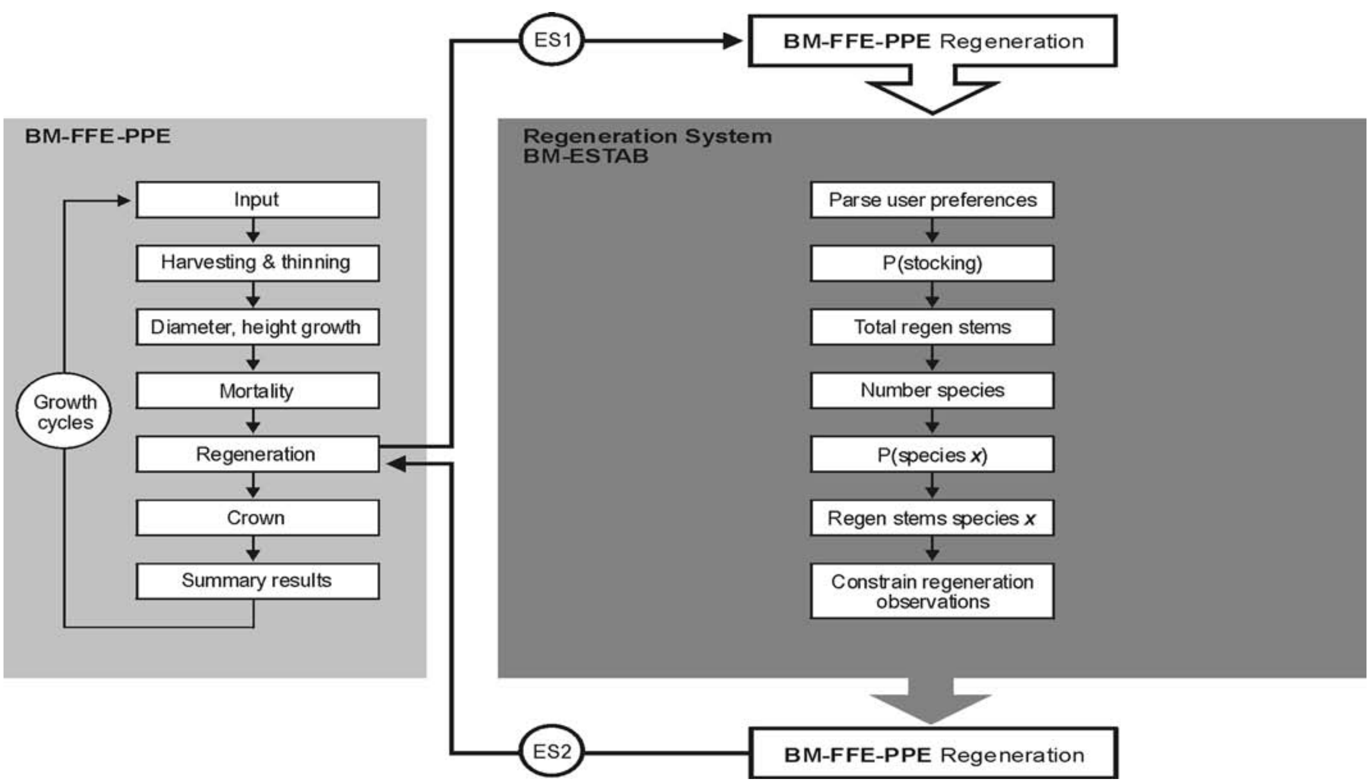

Figure 5—A simplified sequence of events is shown for predicting regeneration in a single stand within the BM-FFE-PPE. Additional details are found in the text.

model keywords are invoked at the end of the cycle, just prior to the creation of summary reports. When the AddTrees keyword is processed, a formatted text file (labeled ES1) is created by FVS. Then a call is sent by FVS to the operating system to run the Blue Mountains model (right side of fig. 5). The Blue Mountains model reads the ES1 file containing stand-state information for the projection cycle and predicts regeneration for the stand. Predicted regeneration is written to a second formatted text file (labeled ES2 in fig. 5). The Blue Mountains model exits and FVS resumes operation, reading the ES2 file and possibly scheduling natural regeneration keywords in a subsequent cycle.

The ES1 file is automatically created using instructions written in the FVS Fortran subroutine "esaddt.f." The prefix given to the ES1 file is a concatenation of the name of the FVS keyword file, the Stand Identifier, the FVS model year in which the file is created, and the 2-letter variant code. For example, given a keyword file "bmtest.key" containing a StdIdent keyword followed by "0404064" with the Blue Mountains model scheduled for 2010, the full name of the ES1 file would be:

bmtest_0404064_2010_BM.ES1

The actual content of the file is tailored to the needs of the Blue Mountains model as shown in figure 6.

When the Blue Mountains model starts, it searches for an initialization (INI) file of user preferences called "BMEstab.ini." In this model, the file contains three user-defined model parameters (fig. 7) that provide the model user with the flexibility to tune the model behavior if desired. As described more fully in Wilson and others (2003), the first of these parameters scales predicted regeneration up or down by a multiplier; and the second sets a probability threshold that can change the presence or absence of regeneration. The final parameter of the INI file allows the user to specify whether all intermediate files (ES1 and ES2) are to be kept after the run or whether they are to be automatically deleted.

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+	
1	bmtest	Stand ID
2	2011	calendar year to schedule
3	5	fld 2 of AddTrees keyword
4	49	FVS habitat code
5	40	slope (%)
6	90	aspect (degrees)
7	5000.0	elevation (ft)
8	259.1	before-thin Stand Density Index
9	259.1	after-thin Stand Density Index
10	121.0	basal Area (ft^2/ac)
11	121.0	after-thin basal area (ft^2/ac)
12	358.1	stem/ac (all species >1" dbh)
13	0.0	ABGR stem/ac (<1" dbh)*
14	0.0	ABLA stem/ac (<1" dbh)
15	0.0	LAOC stem/ac (<1" dbh)
16	0.0	PICO stem/ac (<1" dbh)
17	0.0	PIMO stem/ac (<1" dbh)
18	0.0	PIEN stem/ac (<1" dbh)
19	79.8	PIPO stem/ac (<1" dbh)
20	0.0	PSME stem/ac (<1" dbh)

* ABGR = *Abies grandis*; ABLA = *Abies lasiocarpa*; LAOC = *Larix occidentalis*; PICO = *Pinus contorta*; PIMO = *Pinus monticola*; PIEN = *Picea engelmannii*; PIPO = *Pinus ponderosa*; PSME = *Pseudotsuga menziesii*

Figure 6—The Blue Mountains model requires 20 lines of information written by FVS to an ES1 file. These include stand ID, calendar scheduling, site information, before- and after-thin stand information and information about small trees already present in the stand. This example has been annotated by adding comments after column 30; a working version is right-justified at column 30 without any comments.

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+
1	1.1 Multiply (default 1.0)
2	0.1 P_Add (default 0.5)
3	0 Keep: (default 1 = .TRUE.)

Figure 7—The Blue Mountains model searches for an INI file (described in the text) which can be used to adjust some aspects of the model's behavior. Users also have the choice of keeping or automatically deleting intermediate files for later inspection.

Line Nmbr	Column ruler 1 Keyword	 2 fld1	 3 fld2	 4 fld3	 5 fld4	 6 fld5	 7 fld6	 8 fld7	 9 fld8
1	1								
2	Bmtest								
3	431	2011	6	10	82	80	0	3	0
4	431	2011	6	3	243	80	0	3	0
5	431	2011	6	7	567	80	0	3	0
6	431	2011	6	4	367	80	0	3	0
7	End								

Line	Field	Value	Notes
1		1	This file has one set of stand instructions,
2		Bmtest	The stand name given by the StdIdent keyword
3 – 6	1	431	The internal FVS code for the Natural keyword
	2	2011	The year in which to schedule natural regeneration
	3	6	The number or fields of data for the keyword
	4	10,…	Fld 1 of the Natural keyword: species code number
	5	82,…	Fld 2 of the Natural keyword: stems acre^{-1} to plant
	6	80,…	Fld 3 of the Natural keyword: % survival
	7 – 9		*All other fields required by the Natural keyword*
7		End	End of the 'Bmtest' stand

Figure 8—The Blue Mountains model creates an output ES2 file that is subsequently processed by FVS to carry out natural planting. This example schedules planting of 4 species in 2011. To accommodate space restrictions in this printout, some blank spaces have been removed from the lines.

As the Blue Mountains model finishes, it creates an ES2 output file using the same naming rules used to create the ES1 input file. Since the purpose of the file is to send establishment information from the Blue Mountains model back to FVS, the content of the ES2 file is tailored to the production of the Natural regeneration keywords that are part of the existing FVS establishment model. The total number of records in the ES2 file depends on the number of species to be regenerated but every run produces at least three records (see fig. 8). The first record is right-justified to column 10. Apart from the first line, subsequent records are not strictly column formatted. FVS source code recognizes the ES2 file and natural regeneration is scheduled.

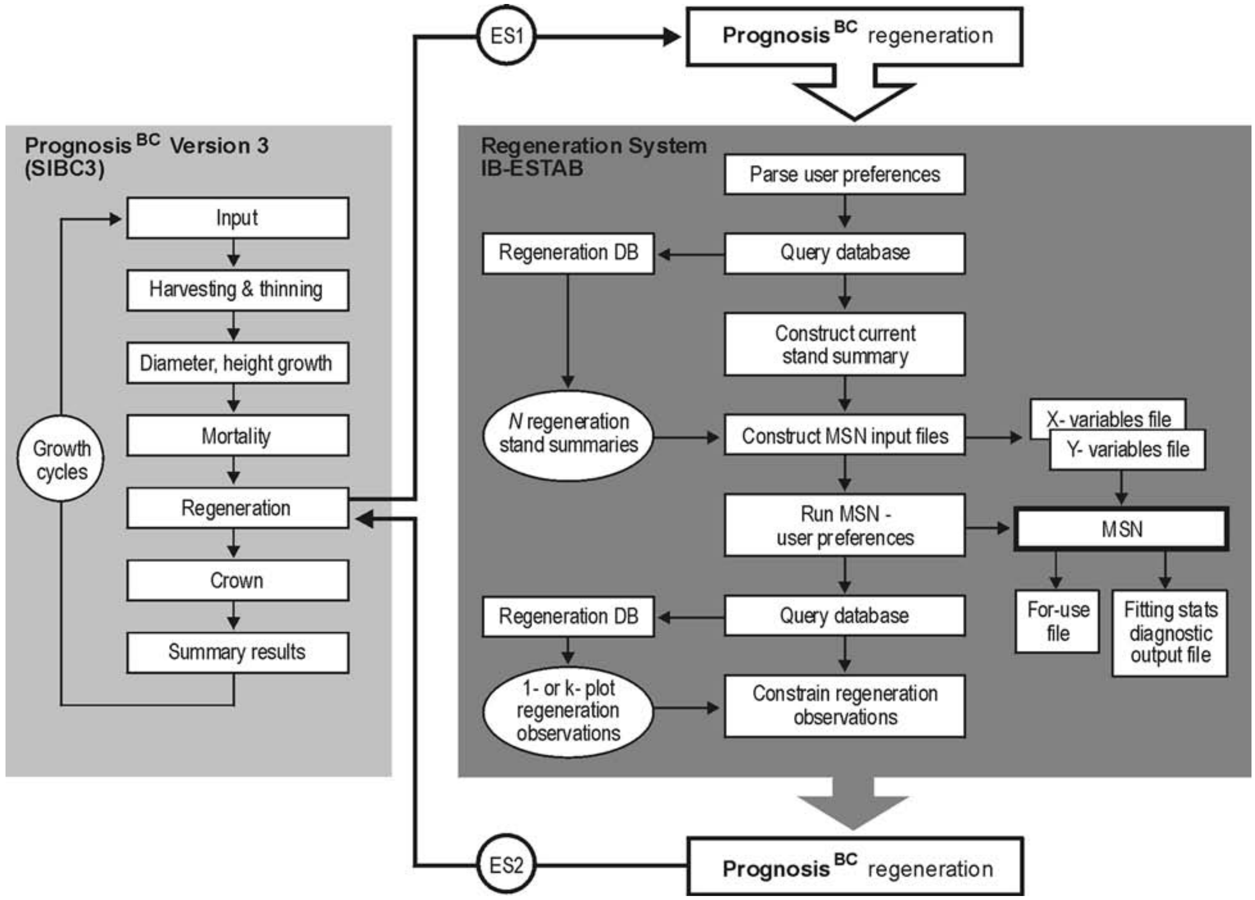

Figure 9—A simplified sequence of events is shown for predicting regeneration with Prognosis^{BC}. Additional details are found in the text.

2: The Prognosis^{BC} Model

For the past 5 years, the FVS community in British Columbia has been developing regeneration models based upon linking a growing database of regeneration observations[3] to FVS (Prognosis^{BC}) stand simulations using Moeur and Stage's (1995) Most Similar Neighbor (MSN) canonical procedure (Hassani and others 2004; LeMay and Temesgen 2005; Zumrawi and others 2005). The canonical procedure is implemented using MSN software (Crookston and others 2002), and as its prediction, selects the regeneration observed in the database stand that most closely matches the stand being simulated by Prognosis^{BC} (Robinson 2005). Like the Blue Mountains model, predictor variables include site and overstory variables. The Prognosis^{BC} model also includes variables for site disturbance, time since disturbance, and measures of overstory stand structure. A research application of the model has recently been developed for stands disturbed by mountain pine beetle. The site disturbance variables in this research application are replaced with stand snag variables. The framework that links Prognosis^{BC} with the MSN software and an Access database is shown in figure 9 with an example keyword set shown in figure 10.

A comparison of the Blue Mountains (fig. 5) and Prognosis^{BC} models (fig. 9) shows the ability of a common framework to handle a range of model complexity. The Blue Mountains model is a single executable while the Prognosis^{BC} system involves an intermediate program interacting with a database to dynamically set up the necessary MSN files. The MSN software is then called automatically, a match is found, and the database is again queried for the detailed regeneration information. From the user's perspective, the two

[3] As of April 2007, the database held 1,234 unique stands (most with multiple plots, some with remeasurement), with records for over 24,000 large trees, 16,000 small trees, and almost 45,000 regenerating stems.

```
Line                        Column ruler
Nmbr   ----+----1----+----2----+----3----+----4----+----5----+----6----+
          Keyword       fld1       fld2       fld3       fld4       fld5
   1   Estab
   2   PlotInfo
   3            1         5
   4   -999
   5   BurnPrep        1997       100
   6   MechPrep        1999       100
   7   AddTrees        1999         0          2
   8   ..\Regen\IBestab.exe ..\Regen\regen.mdb ..\Regen\MSN.exe 1
   9   End
```

Line	Field	Value	Notes
1			Begin an Establishment model keyword block
2			Begin entering plot information
3			Plot 1 is a ridge top (fld2 =5)
4		–999	End of plot information
5			Burning site preparation: 100% of site burned in 1997
6			Mechanical site preparation: 100% of site treated in 1997
7			AddTrees keyword
	1	1999	Year to simulate regeneration
	2	0	Years after AddTrees is run to schedule a Natural planting; age to assign new trees
	3	2	Method 2 signals FVS to: (1) read a supplemental record containing an executable filename and all its command-line arguments; (2) submit and run the record using a System call, appending an additional command line argument containing the ES1 filename; (3) read the ES2 output file created by IBEstab; and (4) use the content of that file to schedule Natural keywords in FVS.
8			Supplemental record: relative path and name of executable; relative path and name of database file; relative path and name of MSN program; canonical distance method for MSN
9			End the Establishment model keyword block

Figure 10—An example showing how the AddTrees keyword is used as part of a sequence of establishment model keywords with the Prognosis^{BC} regeneration model. Additional details are found in the text.

example models differ only in the number of command line arguments provided with the supplemental record: zero in the case of the Blue Mountains model and four arguments in the case of the Prognosis^{BC} model[4].

Linking Models to FVS: The Caveats

Even after developing a credible model, it is necessary to carefully consider the relationship between an existing simulated FVS stand and the regeneration predicted at a particular projection time step. For example, the simulated stand may already have some regeneration or small trees present, and adding predicted regeneration might incorrectly add too many small trees. The Blue Mountains model addresses this possibility by explicitly providing information about small stems to the model (see fig. 6), and then subtracts these existing small stems from the predicted regeneration. In the case of an MSN-based procedure there may be changes in stand structure between the time of the

[4] As figure 4 notes, the AddTrees keyword automatically adds the ES1 filename following any command line arguments provided in the keyword file.

disturbance (and in some cases, difficulty even assigning a single date to the disturbance) and the time at which regeneration is measured. In this case, further analyses of the sensitivity of model parameters, combined with good judgment and heuristics, may be required to create a useful database.

Conclusions

The system enhancement described here is based on a simple interface with the FVS model and is suitable for external models that interact with FVS through the automatic creation of keywords[5]. Fortunately, the Regeneration Establishment system of FVS is well-suited to this kind of linkage and the current interface code is both localized (in one subroutine) and simple to modify using FVS Fortran code that is in the public domain. The requirements of the external regeneration system are also modest, and consist of any process that creates a formatted text file (see fig. 8) with regeneration instructions for FVS to process. Development of the external regeneration model process is independent of FVS. As long as measures of stand structure (see fig. 6) are provided to the external model, the external process can predict the regeneration outcome, which can also be examined and tested outside of the FVS architecture. In short, iterative model development and testing can all take place before FVS is even considered as the engine to drive overall stand development.

Every model building exercise involves tradeoffs between simplicity and complexity. A simpler model may be easier to conceive, understand, and debug, but may gloss over details that are important in some circumstances. Moreover, conceptual model development is never a linear process. Models frequently—some might say always—go through cycles of conceptual development followed by experimental testing, refinement, further field work, and validation; only to be abandoned and re-emerge as newer models. Forest modelers and experimenters are equal and mutually dependent partners in this cycle, continually evaluating what to measure, when to measure, and how to measure the variables that drive regeneration.

Providing a means to invoke novel regeneration models is not a panacea for the shortage of existing models in FVS. Although one hurdle has been removed, the scientific work of creating such models still needs to be done, along with the substantial field work and validation required of every empirical or theoretical model.

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[5] Components of FVS, such as the growth and mortality sabmodels, are based on equations that act upon individual tree records and present a performance challenge for linkage with external models.

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