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The Western Spruce Budworm Dynamics Model: Version 3.1 Update and Notes on Behavior

Nicholas L. Crookston

$$P(AdultMort) = f_A [foliage]$$

$$Shoot\ Length = \frac{A_1}{1.0 + exp[A_2 + A_3 DDays]}$$

$$Def_{tree} \sim Beta\left(f_B [Def_{class}], f_C [Def_{class}]\right)$$

$$P(Topkill) = \frac{1.0}{\quad exp[-(b_1 Def_{tree} + b_2 HT_{tree})]}$$

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RESEARCH SUMMARY

The Budworm Dynamics Model, a component of the Budworm Modeling System, is herein revised. The resulting model is called version 3.1. Illustrations display the behavior of version 3.1 as compared to 3.0 and when run using various options and initial conditions. The model exhibits interesting and rich behavior. This paper offers an opportunity to begin exploring the model as a potential research, teaching, and management tool.

ACKNOWLEDGMENTS

CONTENTS

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INTRODUCTION

Crookston and others (1990) have published a user's guide to the Western Spruce Budworm Modeling System. The system is composed of four computer programs, one of which is the Budworm Dynamics Model. Although the scientific basis for this model has been described (Sheehan and others 1989) and its applications have been outlined (Stage and others 1985; Stage and others 1987), this paper is the first to demonstrate the model's behavior.

The Budworm Dynamics Model predicts budworm (*Choristoneura occidentalis* Freeman) population changes, foliage growth, budworm growth, feeding, and subsequent defoliation dependent on several site, stand, foliage, and weather conditions. Five host species are modeled: Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), grand fir (*Abies grandis* [Dougl.] Lindl.), white fir (*Abies concolor* [Gord. and Glend.] Lindl.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), and Engelmann spruce (*Picea engelmannii* Parry). A stochastic weather model is used to estimate weather (Bruhn 1980; Kemp and others 1989). Measurements of budworm populations, current defoliation, and routine stand examination data make up the input data. The Budworm Dynamics Model simulates budworm population dynamics on up to 30 spatially related stands at a time. Adult dispersal is simulated between stands. Because the model does not estimate tree growth, its use is limited to making short-term (up to 15 years) projections.

The scope of this paper is to demonstrate and describe some of the behavior of the Budworm Dynamics Model. Please read Sheehan and others (1989) and Crookston and others (1990) for necessary background information. In the process of preparing this report, some poor model behavior was discovered. This discovery prompted certain model changes to be made, leading to model version 3.1. The nature of the poor behavior and the details of the changes are presented before the model behavior is explored in more detail.

Appendices are included that contain input data and keyword files used to generate the examples. In addition, corrections to errors in the user's guide (Crookston and others 1990) and a description of a new keyword are appended.

VERSION 3.1 UPDATE

The Errant Behavior

Budworm-defoliated trees often look as if they have dead tops; more and more green needles are visible as your eye moves down the crown. Version 3.0 predicts a spatial distribution of defoliation within and between tree crowns that is not consistent with this classical budworm-caused defoliation pattern. Figure 1 illustrates a typical example and compares model
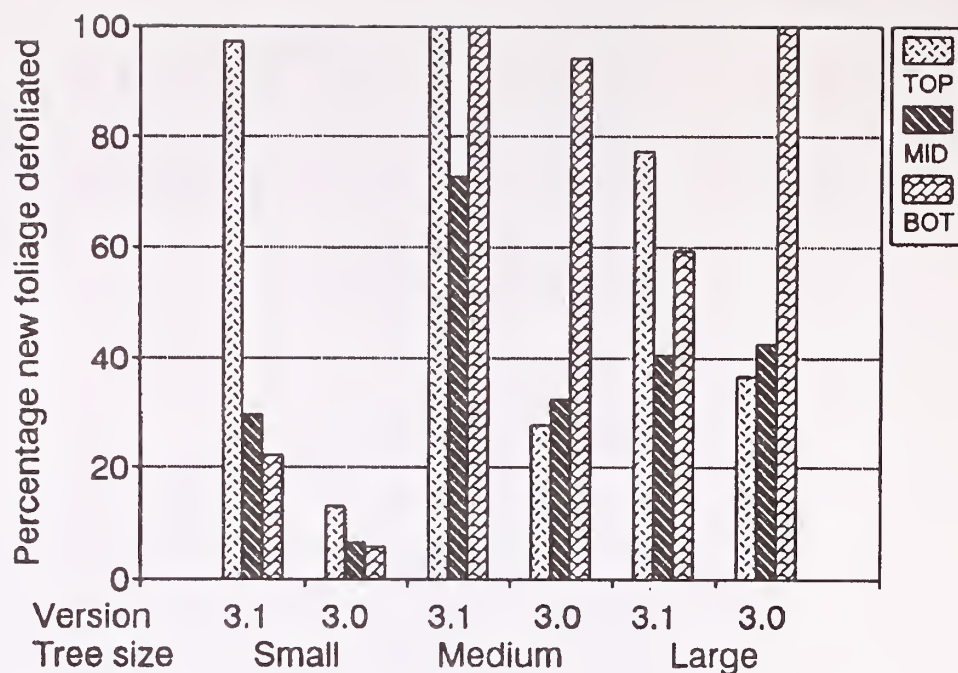
Figure 1—Percentage new foliage defoliated
from three crown levels of small, medium, and
large trees, grouped by model version and tree
size. The model conditions are the base case,
stand Bear02, year 1987.

versions. (Data used in this illustration came from Bear02; see "Contrast
Version 3.1 and 3.0", page 7.) Note that for model version 3.0, the bottoms
of medium and large trees are much more defoliated than the tops. Fur-
ther, the large and medium trees are much more defoliated than the small
trees.

Model version 3.1 exhibits better behavior. The small trees are defoli-
ated according to observers' expectations. The medium and large trees are
closer to expectations. The middle crowns of medium and large trees are
defoliated less than the bottom and tops. Figure 2 reveals a partial expla-
nation for this behavior. In figure 1, the defoliation is plotted as a percent-
age of the new foliage biomass within each crown level. For example, a
value of 30 percent defoliated from the bottom crown third of a large tree
indicates that 30 percent of the new foliage in the bottom crown level was
destroyed (eaten or cut off the tree by budworms). In figure 2, a value of 30
percent indicates that 30 percent of a tree's total new foliage was destroyed
in the bottom crown level. According to figure 1, the percentage defoliation
in the middle crown is lower than in other crowns; according to figure 2, a
large portion of the destroyed foliage on each tree came from the middle
crown levels.

Percentage defoliation can be misleading. It is the ratio of two model-
based predictions: the amount of foliage on a tree or in a crown level, di-
vided by the amount of foliage that would have been on the tree or in a
crown level had no budworm feeding taken place. The distribution of new
foliage over the crown levels is computed by the foliage dynamics portion of
the Budworm Modeling System (Crookston 1991). In this example, a large
proportion of the new foliage in medium and large trees is predicted to be
in the middle crown levels. In short, the budworm had to eat a lot of new
foliage in the middle crowns compared to eating foliage in the lower crown
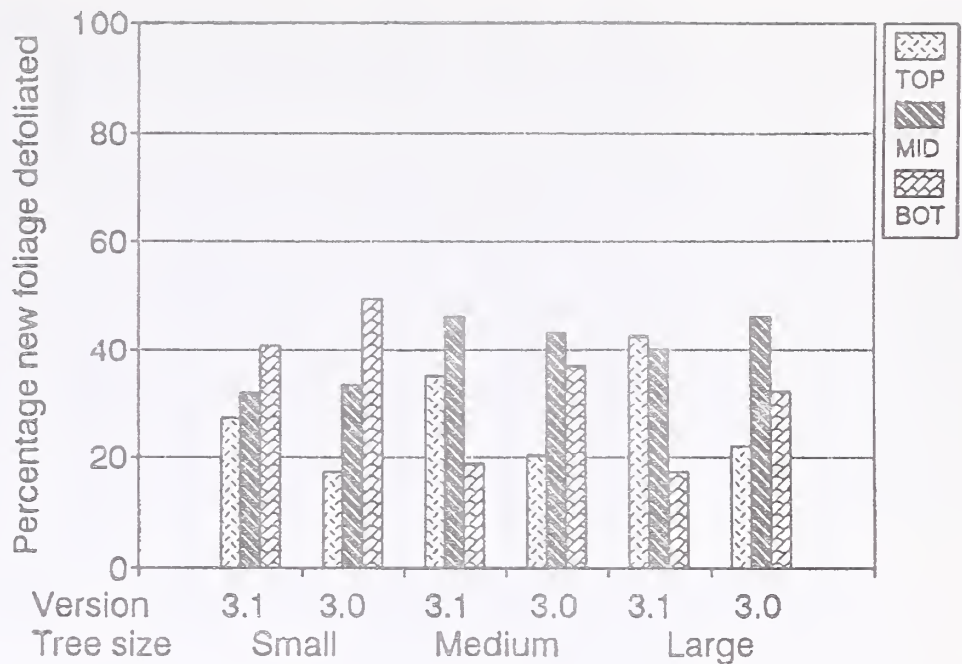thirds to achieve the same percentage defoliation.

Figure 2—Percentage of the total new foliage on small, medium, and large trees defoliated from within three crown levels, grouped by model version and tree size.

The conclusion is that version 3.1 is an improvement over 3.0 in respect to the spatial distribution of defoliation within and between trees and crown levels. However, the spatial pattern of defoliation predicted by version 3.1 may not be accurate enough to meet some potential needs.

Description of Changes

In correcting the behavior, an effort was made to maintain the larval dispersal (emerging second instar to pupation) concepts described by Sheehan and others (1989). Some other approach for modeling larval dispersal may provide even better results than achieved in version 3.1. Note that the Budworm Dynamics Model contains many subcomponents; some of the most interesting represent host and budworm phenology and feeding. These were not changed.

In version 3.0, budworm that find feeding sites do not migrate unless they consume the available foliage in the crown level (see page 42 in Sheehan and others). In version 3.1, 20 percent of the larvae disperse at every 20-degree-day step in addition to larvae that cannot find food within the foliage cells. The change resulted in an increase in dispersal-related budworm mortality over that predicted in version 3.0 and improved the spatial distribution of budworms and defoliation.

The other changes involved replacing equations 28 through 30 in Sheehan and others (1989) and the accompanying discussion with what is described below. The variable names used in Sheehan and others and other attributes of their notation are used here in describing the new model.

The goal of the dispersal model is to redistribute larvae stored in array $DISPBW_{c'h'r}$ (the number of dispersing budworm from crown level c', of host h', and larval cohort r) into $SAVEBW_{chr}$ (the number of dispersing budworm entering into crown level c, of host h, of cohort r). Those in $SAVEBW_{chr}$ are divided between $BUGSF_{chr}$ (the number of females in

3

crown level c, of host h, and cohort r), and $BUGSM_{chr}$ (the number of males) according to an assumed sex ratio of half males and half females. An additional goal of the dispersal model is to estimate dispersal-related budworm mortality, stored in array $DISPKL_{chs}$, the number of budworm killed that originate in crown level c, of host h, in 20-degree-day step s.

The mortality portion of the dispersal model is the same between versions 3.0 and 3.1; that is, equation 27 in Sheehan and others is still used. However, since 20 percent of the larvae disperse at every step in version 3.1, more larvae are subject to the mortality, and higher overall mortality results. Also, the assumptions regarding redispersal (described in step 5, below) of larvae landing on nonhost foliage differs between versions 3.1 and 3.0. This affects overall mortality as well.

Version 3.1 uses the following steps and formulas:

1. Compute the number of larvae that land on nonhost and reduce the dispersal pool accordingly. Those that land on nonhost may redistribute, as described below.

$$DISPNH_{cr} = DISPBW'_{c'h'r} PROBNH_c \tag{1}$$

$$DISPBW_{c'h'r} = DISPBW'_{c'h'r}(1 - PROBNH_c) \tag{2}$$

where

$DISPNH_{cr}$ = number of budworm dispersing onto nonhost, in crown level c and cohort r

$DISPBW'_{c'h'r}$ = number of budworm dispersing from crown level c', of host h', in cohort r

$PROBNH_c$ = the proportion of all foliage that is nonhost in crown level c

2. Compute relative crown preferences ($CPREF_{fc'h'ch}$) for budworms moving from crown c' on host h' to crown c on host h given the budworm are in lifestage f. This is a replacement for equation 28, page 43, in Sheehan and others. Tabulated values for $CPREF'$ are in table 8, page 36, of Crookston and others (1990). $CPREF$ represents directional preference of budworms of different ages.

$$CPREF_{fc'h'ch} = CPREF'_{fD(c'h'ch)}/\Sigma_c\Sigma_h \, CPREF'_{fD(c'h'ch)} \tag{3}$$

where

$D(c'h'ch)$ = an indexing function that returns the direction crown c on host h (the origination of dispersing larvae) in respect to crown c' on host h' (the destination of dispersing larvae)

3. Compute relative foliage preference values, $SPECPR_{ch}$ for each crown c and host h. This array of values takes the place of variable $TCLPR_c$ in equation 30 of Sheehan and others.

$$FOL_{ch} = (1{,}000 \; BUDS_{ch}) + FOLIAGE_{ch} \tag{4}$$

$$SPECPR_{ch} = FOL_{ch}/\Sigma_c\Sigma_h \, FOL_{ch} \tag{5}$$

where

$BUDS_{ch}$ = number of buds/ha in crown c on host h

$FOLIAGE_{ch}$ = amount of foliage/ha on crown c on host h

In the version 3.1 formulation, the value of $SPECPR$ is a relative measure of food quantity. It is computed differently from that used in version

3.0, but it serves the same purpose. The multiplier of *BUDS* (1,000) is used to give *BUDS* more weight than given other foliage in computing relative food supplies. In fact, the term labeled *FOLIAGE* perhaps should not be part of the calculations because *BUDS* represents the most preferred food source. However, in this formulation, *FOLIAGE* acts as a lower limit of food supply. If there are *BUDS*, *FOLIAGE* is nearly meaningless in the calculations of *SPECPR*. However, as *BUDS* approach zero, which happens after heavy feeding, the less-than-preferred food sources become important in computing *SPECPR*. Finally, the inclusion of *FOLIAGE* in equation 4 usually ensures that the denominator in equation 5 is greater than zero. This is a desirable condition from a computational point of view.

4. Compute the number of budworm arriving on crown c and host h of cohort r.

$$SAVEBW_{chr} = \sum_{c'}\sum_{h'}((DISPBW_{c'h'r}\ CPREF_{c'h'ch}\ CRWNWT) + (DISPBW_{c'h'r}\ SPECPR_{ch}\ (1 - CRWNWT))) \tag{6}$$

where

$CRWNWT$ = the weight given direction of movement over foliage, set to 0.5 by default

5. Then, if there are larvae in nonhost foliage, add them back into *DISPBW* and pass through the dispersal logic a second time. Even though budworms are known to feed on nonhost foliage, the Budworm Model does not allow larvae to feed on nonhost foliage. The second pass includes taking more dispersal mortality. If the second pass has already ended, add all of the remaining budworm that are on nonhost to those that have died (*DISPKL*). This logic differs from version 3.0 in that larvae of all ages are allowed to redisperse in version 3.1 and only those of specific ages are allowed to redisperse in version 3.0. Neither version allows dispersal of pupae.

MODEL BEHAVIOR

The Example Site   The stand data used in the examples of model behavior were collected from Bear Gulch, about 20 km south of John Day, OR. The site is a long and steep north-facing slope visible to travelers of U.S. Highway 395. The south-facing slope to the north of the study site contains little timber; the same is true for the south-facing slope south of the study site. Therefore, the site is bounded on the north and south by a significant area of essentially nontimber lands. The area is a Douglas-fir site that contained a large component of large ponderosa pine trees until they were logged in the mid-1980's. The remaining stand of mostly Douglas-fir with some scattered ponderosa pine was heavily defoliated by western spruce budworm soon after the site was logged. Table 1 lists several mensurational characteristics of the complete stand (BearAll) as recorded in 1986.

The actual defoliation of Bear Gulch is an extreme example of budworm-caused damage. In this paper, the tree inventory data taken prior to major budworm-caused tree mortality are used to illustrate the budworm model's behavior. The actual defoliation history is not presented. It is beyond the scope of this paper to present the results of a model validation study.

The original survey data from BearAll were divided into three subsets: data from the west end forms Bear01, data from the middle forms Bear02, and data from the east end forms Bear03. Table 1 characterizes each of

5

Table 1—Mensurational characteristics of the Bear Gulch study site

| Attribute[1] | Stand subset | | | |
	BearAll	Bear01	Bear02	Bear03
Stand size				
hectares	68	18	32	18
acres	168	44	79	44
Number of trees				
per hectare	1,003	1,212	791	1,409
per acre	406	491	322	571
percent Douglas-fir	100	100	99	100
percent ponderosa pine	0	0	1	0
Merchantable volume				
m³/ha	157.9	153.2	163.2	139.7
ft³/acre	2,256	2,189	2,332	1,995
percent Douglas-fir	89	76	93	88
percent ponderosa pine	11	24	7	12
Top height				
meters	23.2	19.8	23.9	22.5
feet	76.3	65.0	78.4	73.9
Basal area				
m²/ha	25.0	26.9	23.2	23.4
ft²/acre	109	117	101	102
Quadratic mean d.b.h.				
centimeters	17.8	16.8	20.1	14.5
inch	7.0	6.6	7.9	5.7
Total foliage biomass				
g/tree	5,956	6,463	6,168	4,302
kg/ha	5,974	7,833	4,879	6,062
New foliage biomass				
g/tree	1,509	1,640	1,566	1,085
kg/ha	1,514	1,988	1,239	1,529

[1]Converstion factors: 1 ft = 0.3048 m, 1 inch = 2.54 cm, 1 acre = 0.4047 ha, 1 ft²/acre basal area = 0.2296 m²/ha, 1 ft³/acre merchantable volume = 0.0700 m³/ha.

these subsets as well as the entire stand. The site was subdivided so that simulated budworm dispersal between portions of BearAll could be presented.

Indicator Variables

There are many ways to exhibit model behavior. Crookston and others (1990) have described the various outputs available from the Budworm Dynamics Model. In this paper, four stand-level variables are used to illustrate model performance:

Defol   The percentage of new foliage biomass destroyed (eaten and cut) averaged over all crown levels and tree-size classes.

Eggs   The number of budworm eggs laid per tree in each stand in the fall of the previous year. Eggs per hectare is the product of *Eggs* and the appropriate number of trees per hectare found in table 1. The *Eggs* hatch, larvae overwinter, feed during the next spring, and the survivors become adults; some of the adults are *Females* (described below).

F_tot   The total foliage biomass (grams per tree) on an average tree. This is the *adjusted potential foliage* value described on pages 14-15 of Crookston and others.

Females   The number of females produced per tree in the stand at the end of a feeding period. The *Females* disperse, within and between stands, and lay *Eggs*.

Generally, defoliation in one year reduces the available food supply the following year. The Budworm Dynamics Model does not include a tree growth model nor a tree mortality model. Tree sizes and numbers remain fixed for the entire projection period in the Budworm Dynamics Model. However, the model does include a foliage dynamics submodel that represents trees' response to defoliation and foliage recovery following a period of defoliation.

Listing 1, appendix A, is an SAS (SAS Institute 1985) program that summarizes data generated using the STATDATA keyword of the budworm model (see page 56, Crookston and others). The indicator variables were directly derived from those data.

It is desirable to display all four indicator variables on the same graph, as in figure 3 (this figure will be more fully described below). However, the scale of the variables differs from each other by several orders of magnitude. To meaningfully display the variables, each datum was divided by the maximum value for the run of values, and the *proportion* of the maximum value was plotted. At the bottom of the graph, a legend lists the indicator variables, displays the corresponding line types used to display the variables values, and lists the maximum values reached for each variable. To convert the values displayed on the graph from proportions to absolute values, multiply the proportion by the corresponding maximum.

Contrast Version 3.1 and 3.0

Figure 3 displays the indicator variables for stand Bear02 run using version 3.0 (top) and version 3.1 (bottom) for the base model conditions. The base model conditions are those listed as defaults in Crookston and others (1990), except that adult dispersal was simulated rather than using the net dispersal assumption. The base run includes all three subsets of Bear Gulch, Bear01, Bear02, and Bear03. Listing 2, appendix A, is the keyword file for the base run, and listings 3 through 5 are the foliage description files (described on pages 54-58 of Crookston and others).

The two versions exhibit similar behavior, particularly for the first 2 years of the projections. Although the maximum eggs and females in version 3.1 are higher than those in version 3.0, these increases did not necessarily lead to differences in defoliation. The differences can be traced to the changes made to the dispersal model. Other than the improvements described above (figs. 1 and 2), the two versions do not behave in significantly different ways when tested using this example site.

Although Bear02 is the only stand displayed in figure 3, graphs for the base case representing Bear01 and Bear03 are presented in later examples (see the tops of figs. 5 and 6).

VERSION 3.1 BEHAVIOR

In the following examples, only the behavior of version 3.1 is illustrated.

Effect of Spraying

The Budworm Dynamics Model is capable of simulating the effect of spraying (see pages 28-30, Crookston and others 1990). Figure 4 contrasts two spraying scenarios as they affected Bear02. Other than spraying, the statistics illustrated in figure 4 were generated using the base run conditions
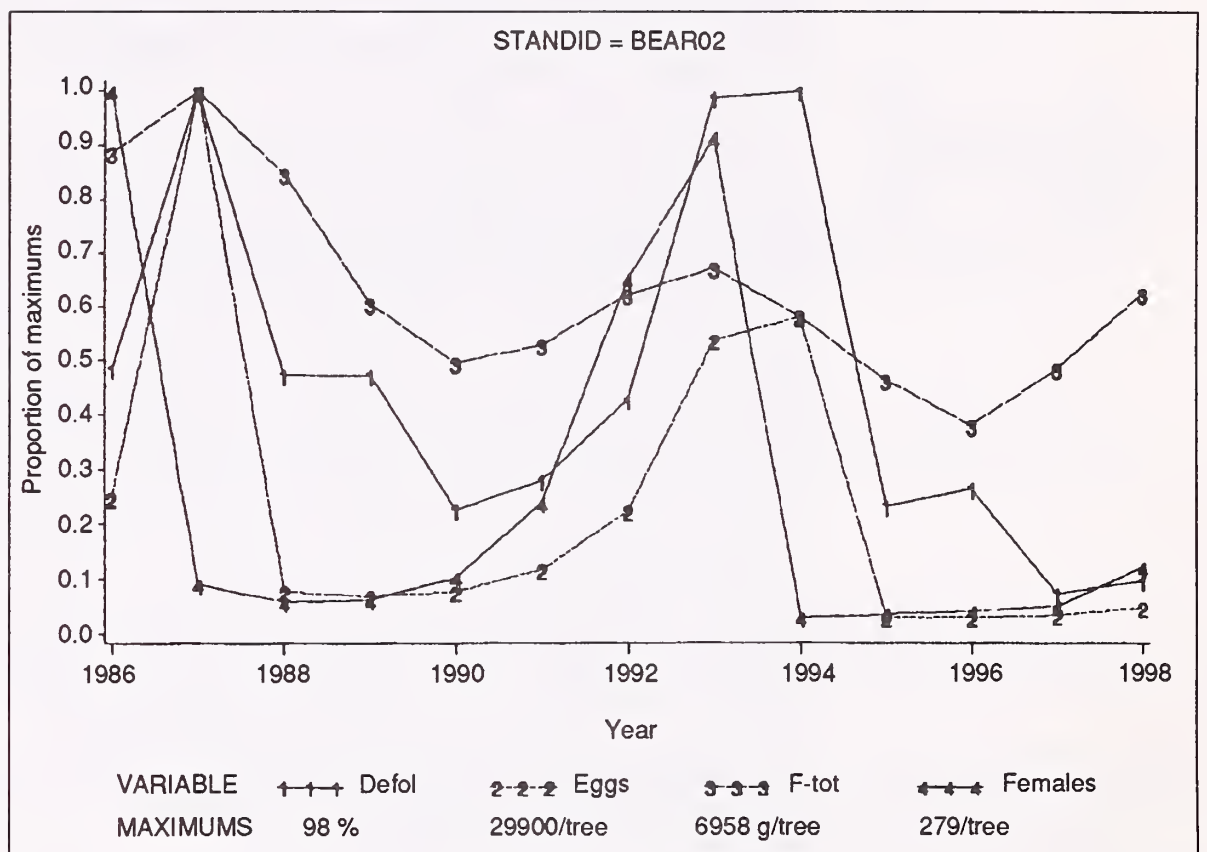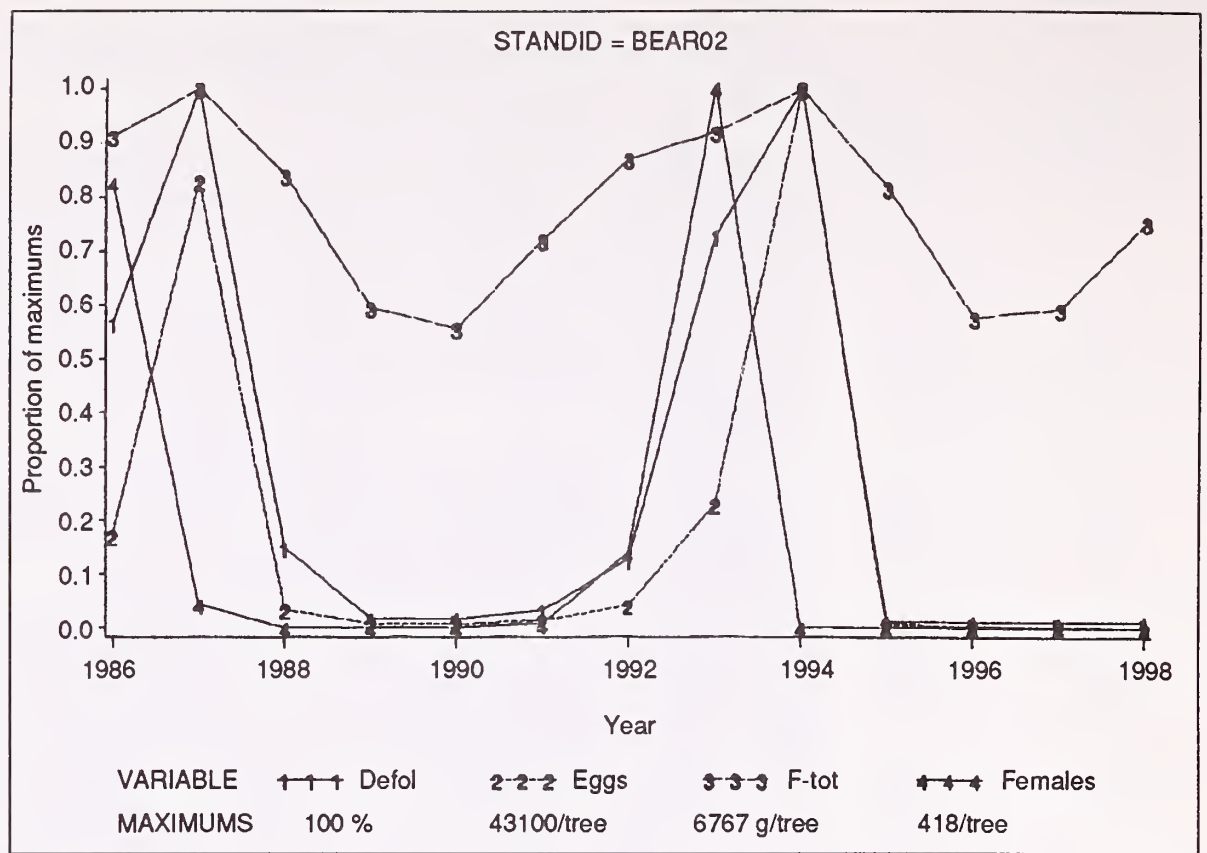
Figure 3—The indicator variables plotted for stand Bear02 using
model version 3.1 (top) and version 3.0 (bottom) for the base
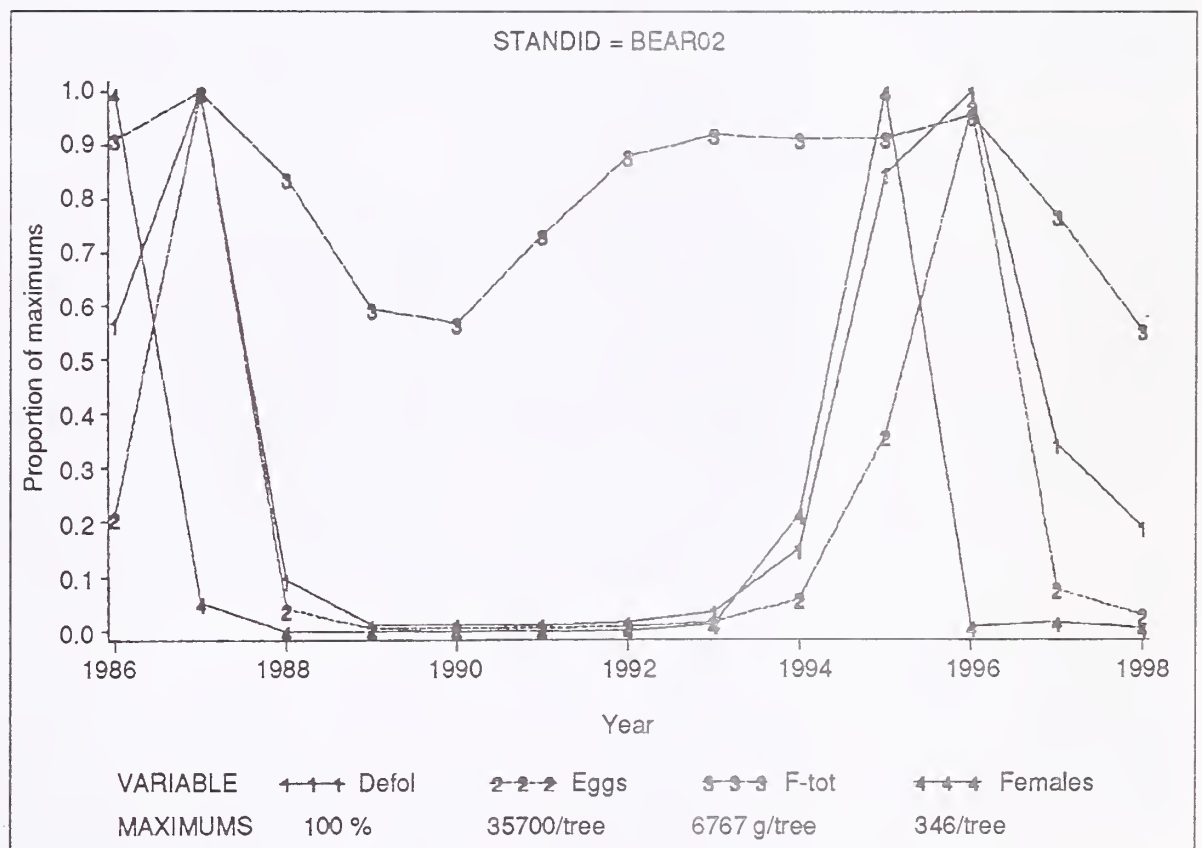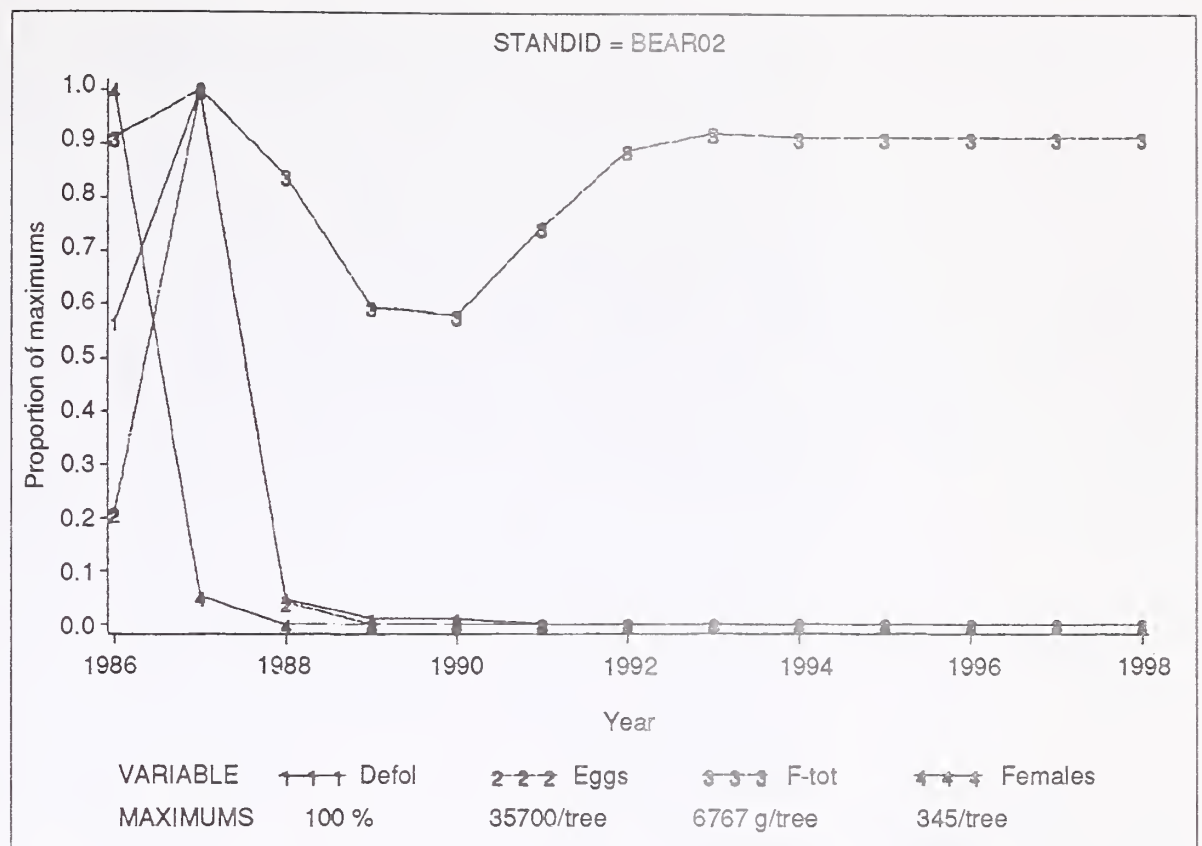case. See the description of the *indicator variables* in the body
of the text.

Figure 4—The indicator variables plotted for stand Bear02, for the base case with SPRAY (top) and SPRAY with efficacy reduced from 91 to 40 percent kill (bottom).

and version 3.1 as described above. Unless the user specifies a different spray efficacy, 91 percent of the budworm are killed on the day the spray is applied. This efficacy profile was designed to represent an application of chemical insecticide and must be modified by model users to represent the efficacy of currently used biocides. The spray is applied when the following conditions are reached (unless otherwise specified): when the previous year's new-foliage defoliation exceeds 50 percent, when there are over 10 spring second-instar larvae per 100 shoots, when shoot elongation exceeds 10 percent, and when the average budworm is in the fourth instar.

The top of figure 4 demonstrates that the simulated spray "did the job." The population dropped nearly to zero, then died out completely, and the foliage biomass (F_tot) returned to preoutbreak levels. To see the contrast between spraying and not spraying, compare this figure to the top of figure 3. The spray was triggered in 1988. However, the difference between the top of figure 3 and the top of figure 4 seems insignificant in 1988. In the spray case, no resurgence of the budworm population occurred.

The bottom of figure 4 represents model output with spray efficacy dropped to 40 percent kill from the default of 91 percent. As you can see, the modeled population recovered from the spray by 1995 and was sprayed again. This compares to a 1993 recovery for the unsprayed case (top of fig. 3).

Changing Foliage Quality Assumptions

Foliage quality *may* influence budworm population dynamics (Cates and others 1983). Sheehan and others (1989) included the ability to represent differential foliage quality as it may influence larval mortality and weight gain in the budworm model. Crookston and others (1990, page 40) altered the default values used by the model to represent the efficacy of the foliage quality assumptions.

The top of figure 5 illustrates the simulated population dynamics in Bear01 when not representing foliage quality. This is the base run, and Bear01 can be compared to Bear02 by comparing the tops of figures 3 and 5. The bottom of the figure 5 illustrates Bear01 run with a representation of foliage quality. The effect of reducing weight gain and increasing mortality lengthened the outbreak and resulted in more tree biomass being destroyed in the first 5 years of the simulated outbreak compared to not representing foliage quality. However, once the outbreak subsided, it did not return when foliage quality effects were represented, and it did return when foliage quality effects were ignored. Further research is needed to establish the validity of the foliage assumptions used in the model.

Changing Dispersal Assumptions

The Budworm Model simulates dispersal of adults between forest stands. The base case uses the simulated dispersal component of the model. The tops of figures 3, 4, and 5 illustrate that dispersal from one or two stands can be important to defoliation levels in an adjacent stand. Notice that the egg levels (*Eggs*, top of fig. 6) for Bear03 are apparently sustained by populations in Bear01 and Bear02. Subsequent new-foliage defoliation is quite high in Bear03 even though egg levels were lower.

The bottom of figure 6 indicates what happened to the population in Bear03 when the net dispersal loss assumptions were used in place of simulated dispersal. Under the net dispersal option, the model is "blind" to the characteristics of a stand's surroundings. A portion of the adults are assumed to die, and no immigration is modeled.

With no influx of budworms, Bear03's population collapsed in 1988 and did not recover. When simulated dispersal was used in the base case,
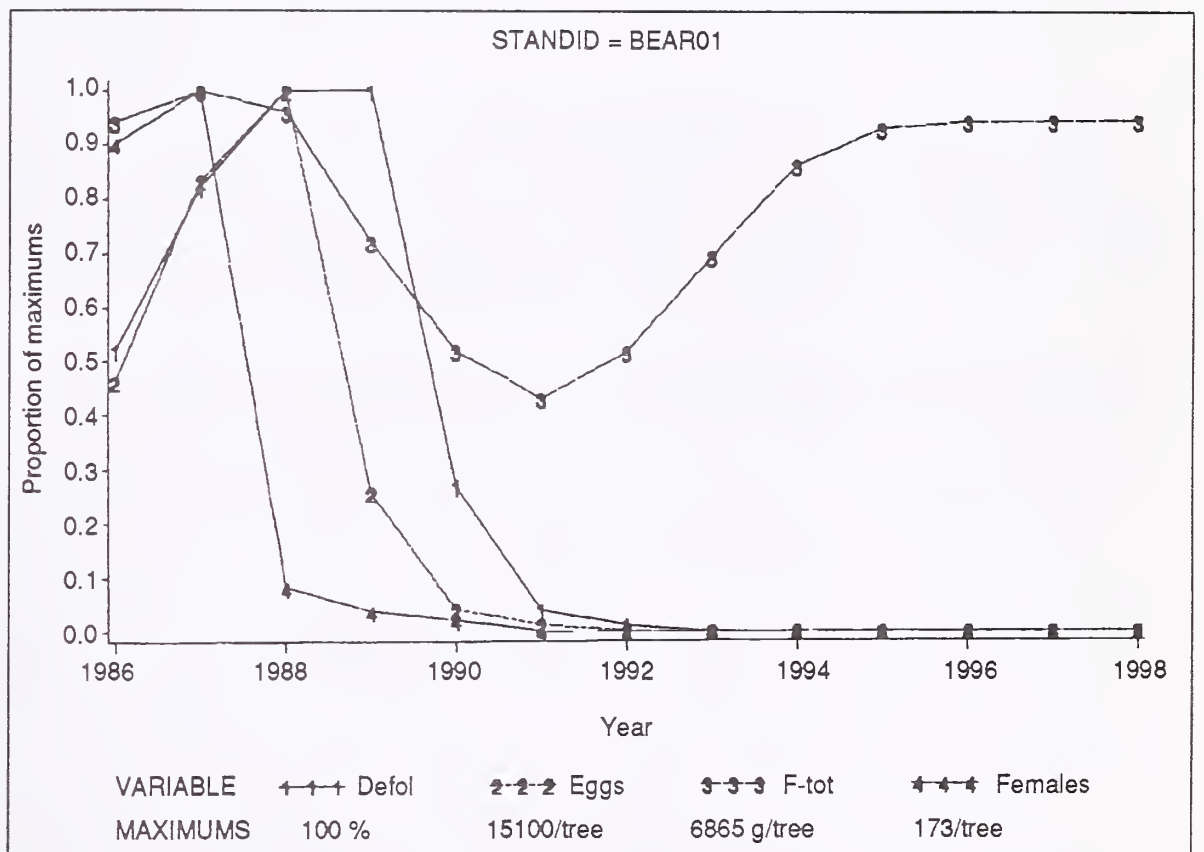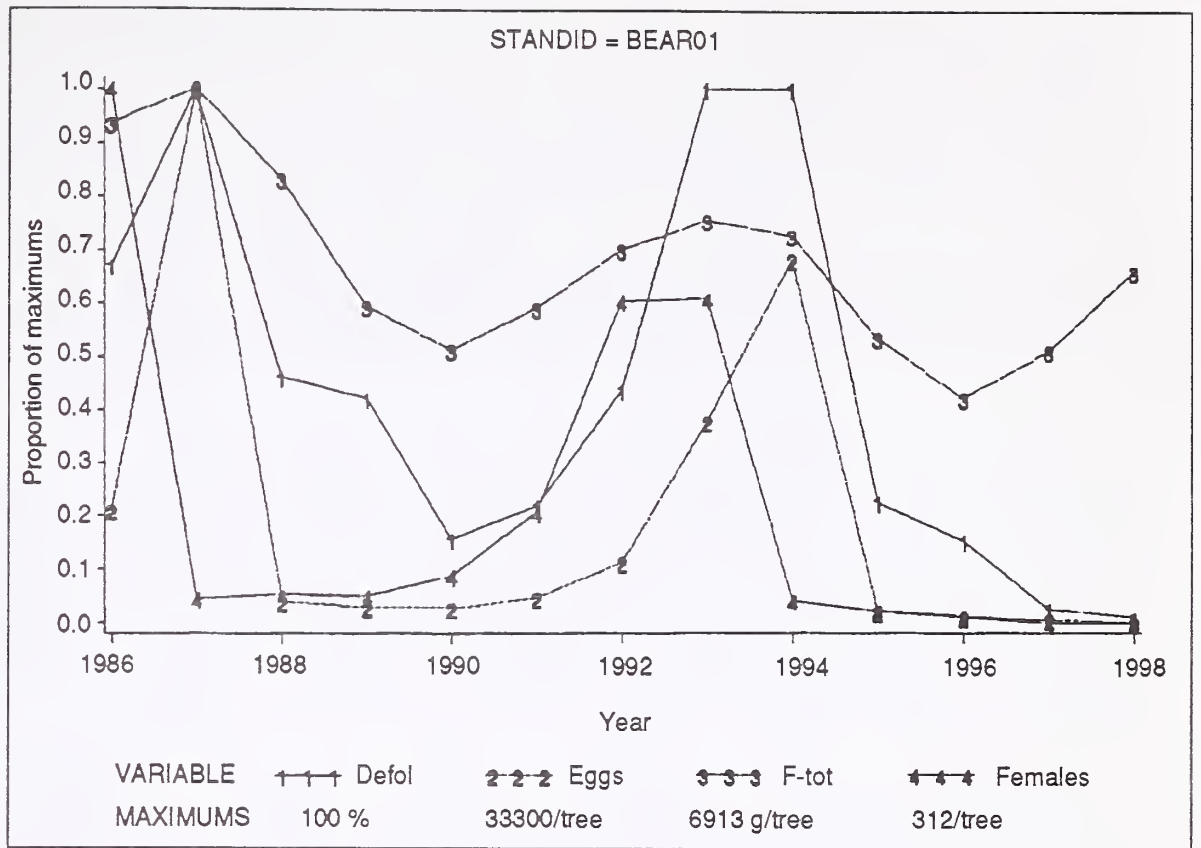
Figure 5—The indicator variables plotted for stand Bear01 using the base case (top) and with the influence of foliage quality assumptions (bottom).
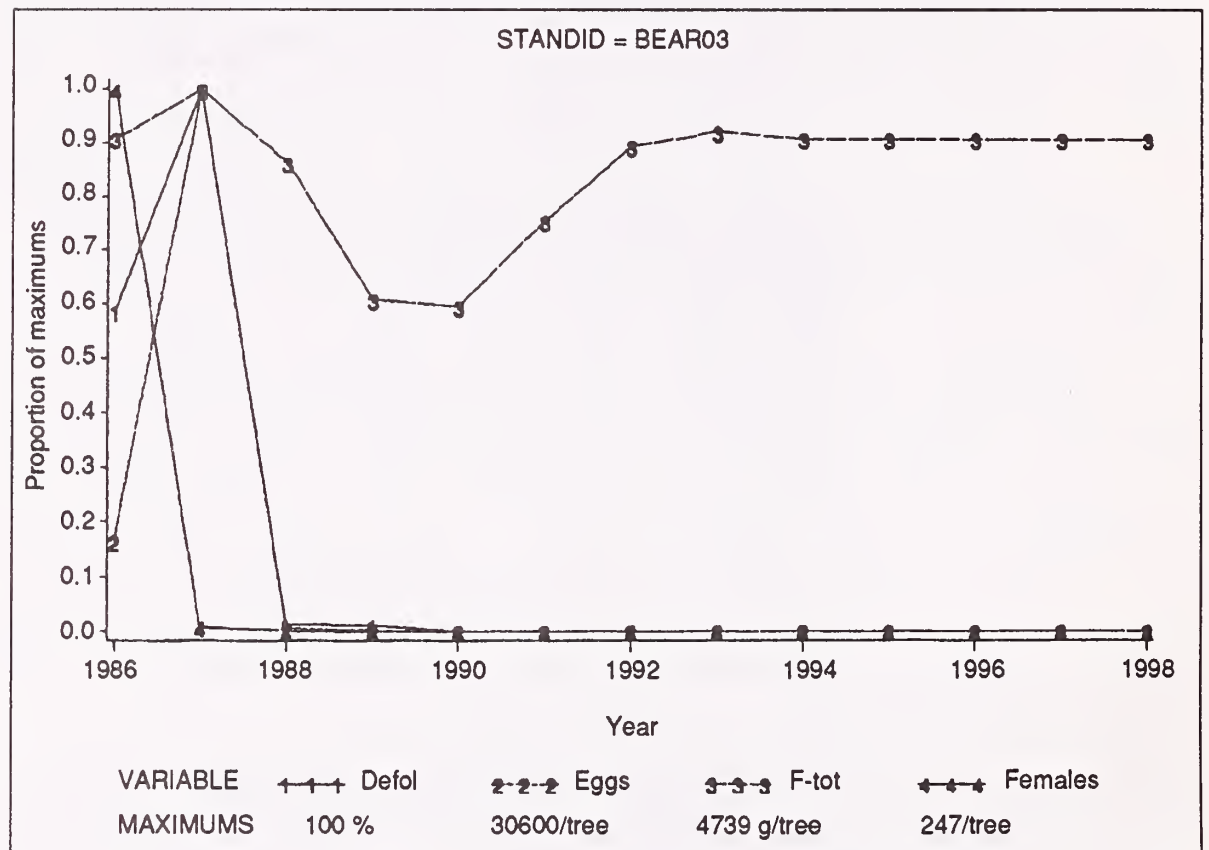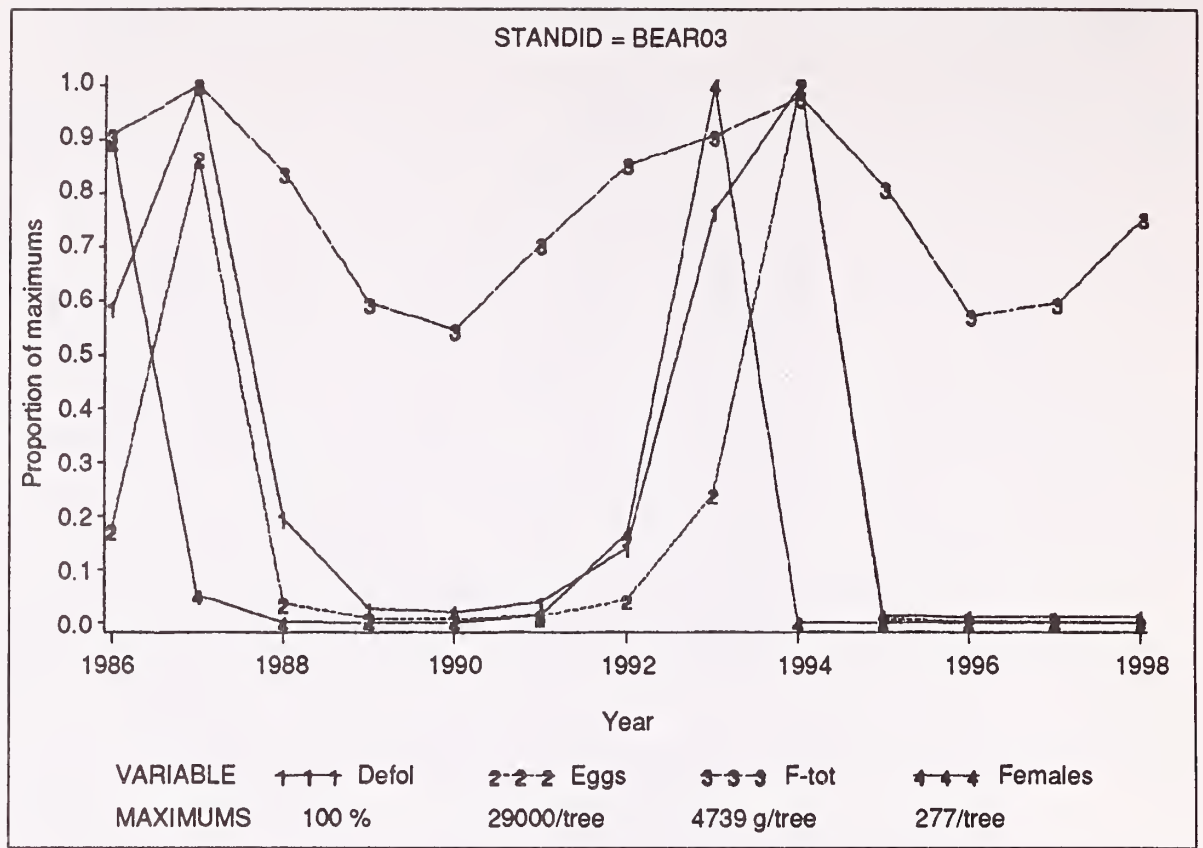
Figure 6—The indicator variables plotted for stand Bear03 using the base case (top) and with net dispersal (bottom).

Bear01 and Bear02 appeared to be the "stable" supply of budworm to stand Bear03. But they must also have been supplying each other with a supply of budworms because when the net dispersal options was used, all three stands experienced the same population crash illustrated for Bear03 in the bottom of figure 6. An alternative explanation is that the default net dispersal mortality rates are too high.

These results indicate that the dispersal assumptions taken when using this model can profoundly influence the results. There is little doubt that dispersal plays an important role in the dynamics of natural budworm populations.

Changing Initial Egg Numbers

One of the most important initial conditions of the Budworm Dynamics Model is the number of initial eggs. The top of figure 7 illustrates the performance on the indicator variables from Bear01 when the default egg distribution was replaced with 400,000 eggs/ha. For these runs, this number of eggs is considerably less than the default of 5 egg masses/m^2 of foliage used by the model. In fact, the default egg populations imply there are 8.5 million eggs/ha in stand Bear01, 5.9 million/ha in Bear02, and 7.1 million/ha in Bear03.

Compare the tops of figures 5 and 7. The outbreak takes a few years to grow when egg levels start out at 400,000/ha. Once the population rises to high levels, in 1989, it crashes to near zero levels in 1 year. The sudden crash is evident in both figures, but they differ in the dynamics that follow the initial crash.

Part of the difference in dynamics that follow the initial crash is due to the model component that represents host food supply. The model component that represents foliage dynamics reduces the ability of trees to grow new foliage after prolonged periods of defoliation (Crookston 1991). Foliage levels recover a little faster following a short, yet massive, outbreak (fig. 5, top) compared to a longer and equally massive outbreak.

Changing Weather Stations

Perhaps the most interesting feature of the Budworm Dynamics Model is its use of a daily weather model (Kemp and others 1989) to drive the phenology of the host shoot development and budworm feeding, growth, and development. The predicted daily weather for a given stand depends on the certain parameters representing weather patterns of an individual weather station. A lapse rate, based on the difference in elevation between the station and the stand, is used to adjust the simulated temperature for a weather station to better represent conditions in a stand. The default station is McCall, ID. Parameters for four weather stations are stored in the model; parameters for other stations have been published by Kemp and others (1989). The fourth station is Baker City, OR, which is much closer to the example study site near John Day.

Figure 7, bottom, illustrates the behavior of the indicator variables for Bear01 when Baker City's weather is simulated, 400,000 eggs/ha are assumed, and the other base case settings are used. Therefore, the difference between the top and bottom of figure 7 is caused by the change of weather. Baker City's weather caused the outbreak to take an additional year to explode. Otherwise, similar outbreak profiles are evident.

Stochastic Milieus

Two examples are used to illustrate variable model behavior given (1) variable egg parameters and (2) variable weather conditions. It has been
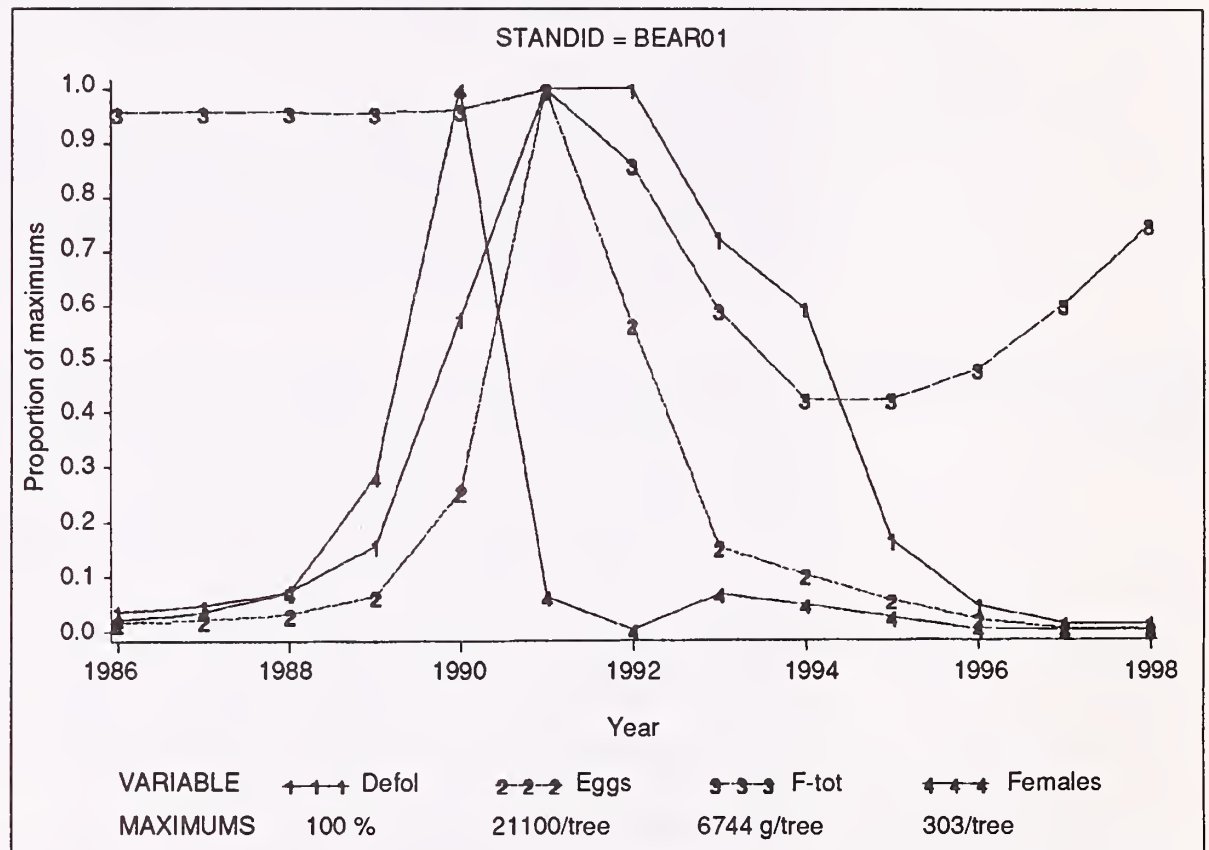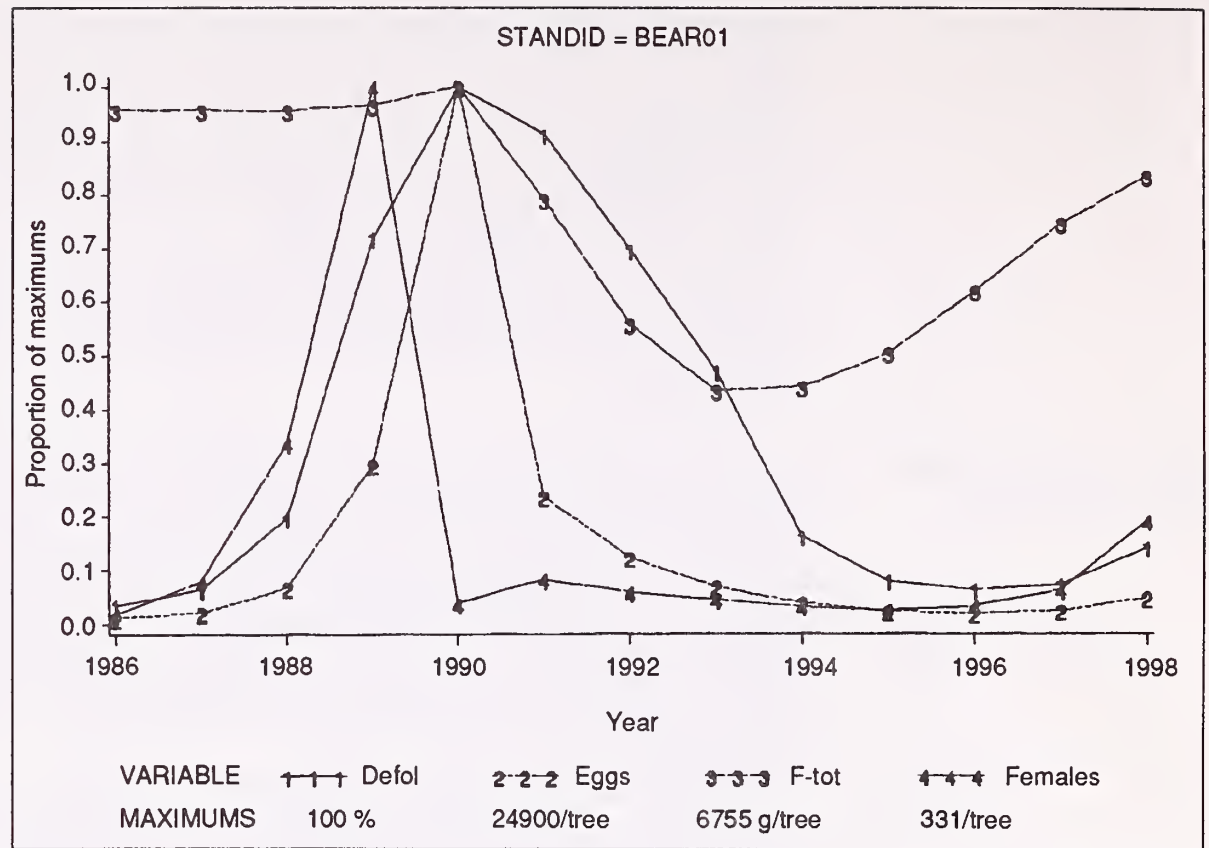
Figure 7—The indicator variables plotted for stand Bear01 using the base case with total eggs set at 400,000/ha (top). The run displayed in the top graph is repeated in the bottom graph with the additional modification of running with weather station 4, Baker City, OR.

14

pointed out that changing the initial egg levels results in different model behavior. Egg levels can be measured in the field, with different amounts of error, depending on the sampling system employed. Other initial conditions also have associated measurement error. Stand characteristics are an easy example: timber surveys can have large sampling errors. In this paper, however, sampling error of tree conditions is not explored.

Another source of variation is in model parameters. For example, the effects of foliage quality on budworm weight gain and mortality are modeled as being constant. That is, when a rate is applied, its value is assumed known without error. In fact, several parameters in the model's relationships have corresponding measurement errors that are ignored by the model. In some cases, model constants should be variables that have stochastic characteristics. This is a weakness of many models besides the Budworm Dynamics Model. This source of variability is ignored in this paper.

Weather varies through time. The high temperature on May 1 of one year is rarely duplicated the next year. A stochastic weather model has been included in the Budworm Modeling System to represent the influence of variable weather on budworm dynamics. This weather model will simulate a different run of daily temperatures when its pseudorandom number generator is seeded with some new value. Reseeding the weather model's random number generator offers a convenient way to explore the potential effects variable weather patterns have on budworm dynamics. Each of the various patterns have the same characteristic means and variances. They vary within those parameters established for each represented weather station.

Figure 8 contains 20 replications of the base case run using weather station 4 at Baker City, OR, as done in computing the example illustrated in the bottom of figure 7. Each of the 20 replications has a different number of initial eggs per hectare. An assumption was made that the true population mean of eggs in all three stands was exactly 400,000 eggs/ha. Furthermore, one standard deviation in the sampling error is assumed to be 100,000 eggs/ha. For each stand and replicate, a normal random number was drawn from a normal distribution with mean 400,000 and standard deviation 100,000, and the resulting random variable was used as the initial number of eggs per hectare. Table 2 lists the values by stand and replication. Random draws that were below 200,000 or above 600,000 were rejected.

The top of figure 8 displays the *Females* (females/tree) for stand Bear01 for each of the replications and the average of all replications. The bottom displays *Defol* (new foliage defoliation) for all replications. Figure 9 is exactly like figure 8 except that each of the 20 replications has a different sequence of weather.

Figure 8 illustrates variable results: replication A surely is unique, and so is replication T. A strong trend in the means for both *Females* and *Defol* is evident, however. Clearly these results indicate a need to pay attention to initial egg levels when using the Budworm Dynamics Model.

Comparing figures 8 and 9 is also interesting. The variable weather resulted in greater variation in output, as one might expect. Notice that the means are a little lower (although probably not significantly lower). Populations of some of the replications never reached outbreak conditions, when the weather patterns varied between replications.
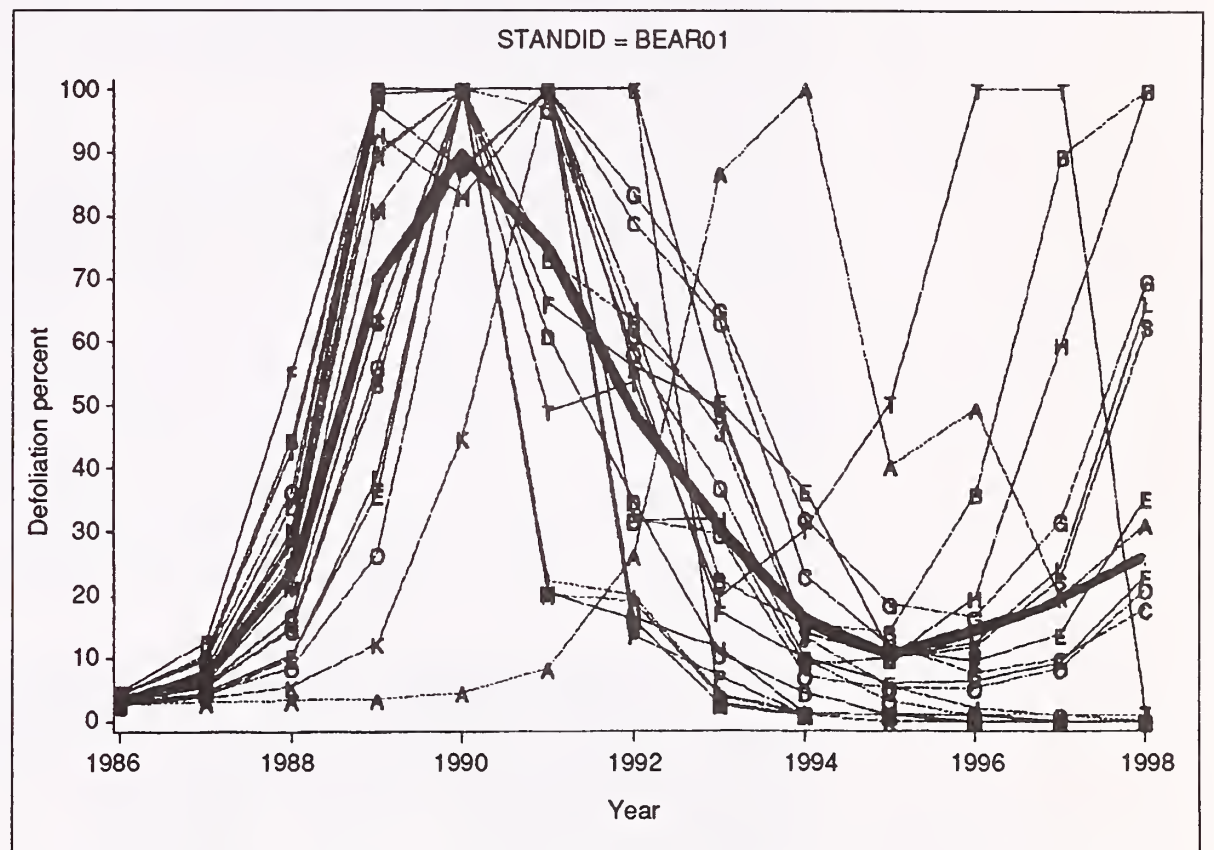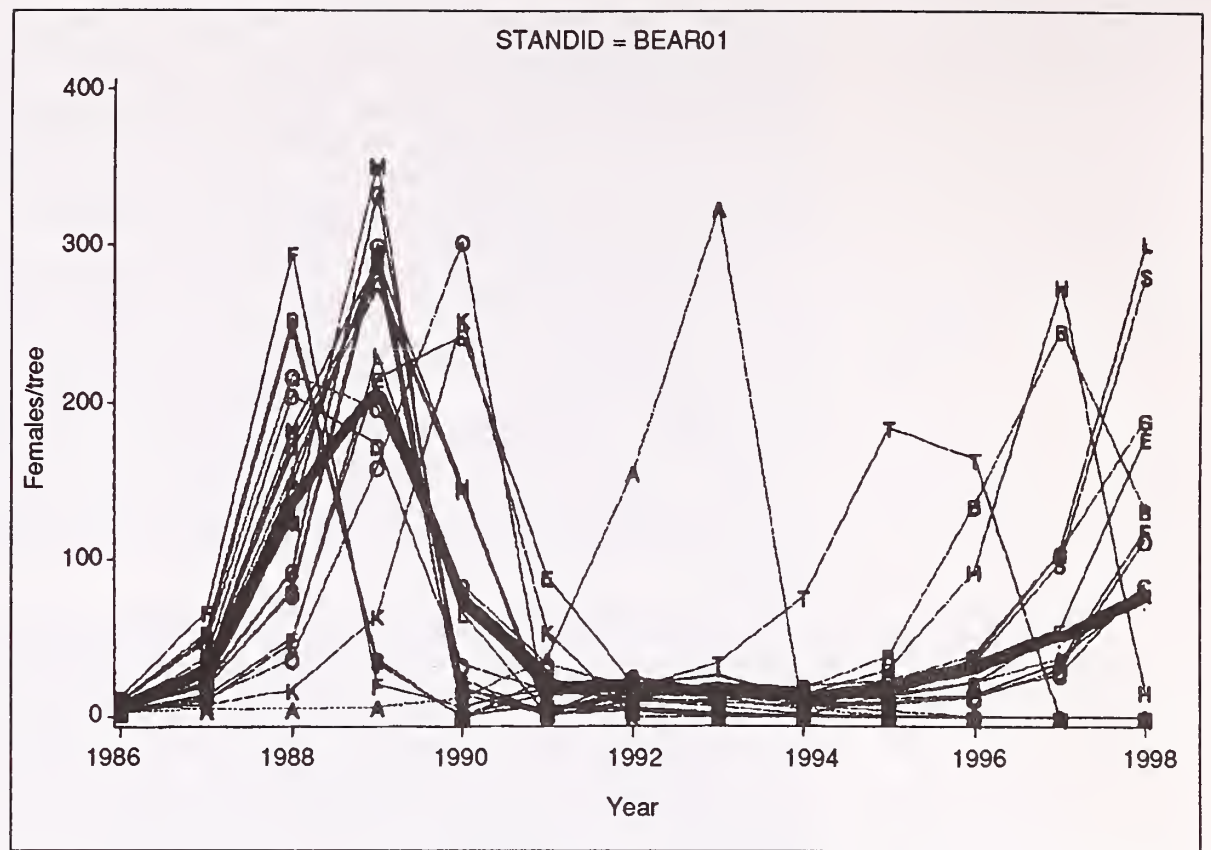
Figure 8—The number of females per tree (top, indicator variable
Females) and defoliation (bottom, indicator variable **Defol**) plotted
for 20 replications of stand Bear01 run using the base case with
total eggs per hectare set at various levels, and run using weather
station 4. The heavy line traces the average of all 20 replications.

Table 2—Thousands of eggs per hectare for stands and replications displaying stochastic milieus

Replication	Stand			Replication	Stand		
	Bear01	Bear02	Bear03		Bear01	Bear02	Bear03
A	302	247	401	K	335	286	378
B	467	485	421	L	280	332	540
C	375	439	262	M	357	442	452
D	388	559	242	N	345	528	434
E	336	324	469	O	345	326	406
F	499	448	538	P	330	538	425
G	363	352	466	Q	477	428	317
H	403	455	426	R	341	518	377
I	387	486	357	S	377	369	408
J	357	449	339	T	455	372	578
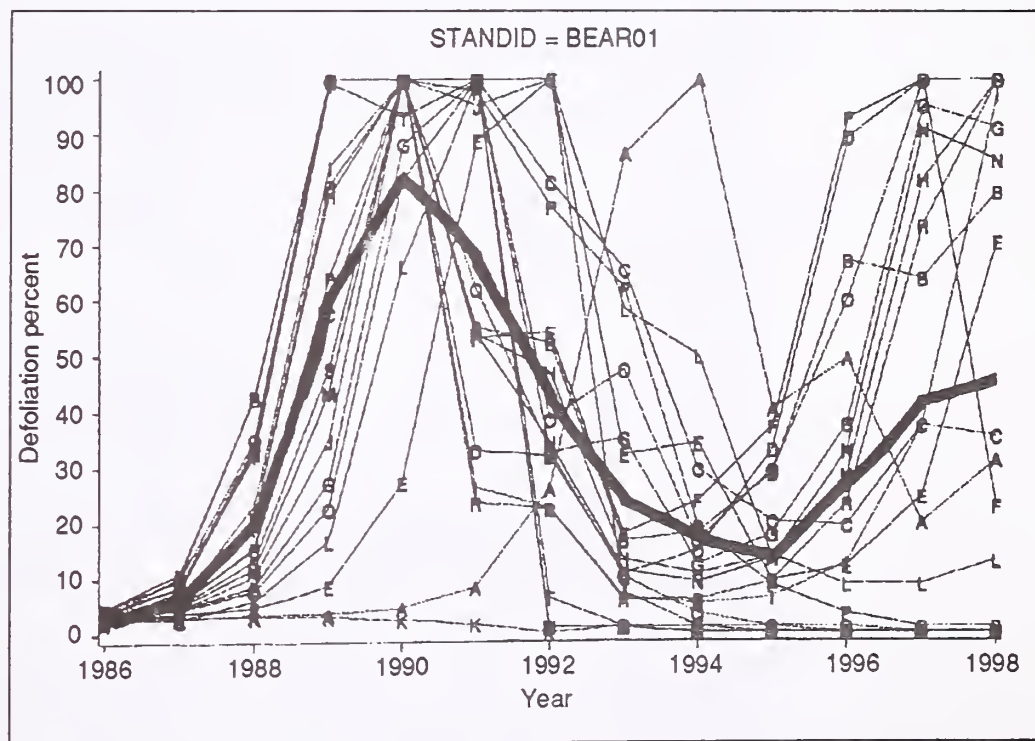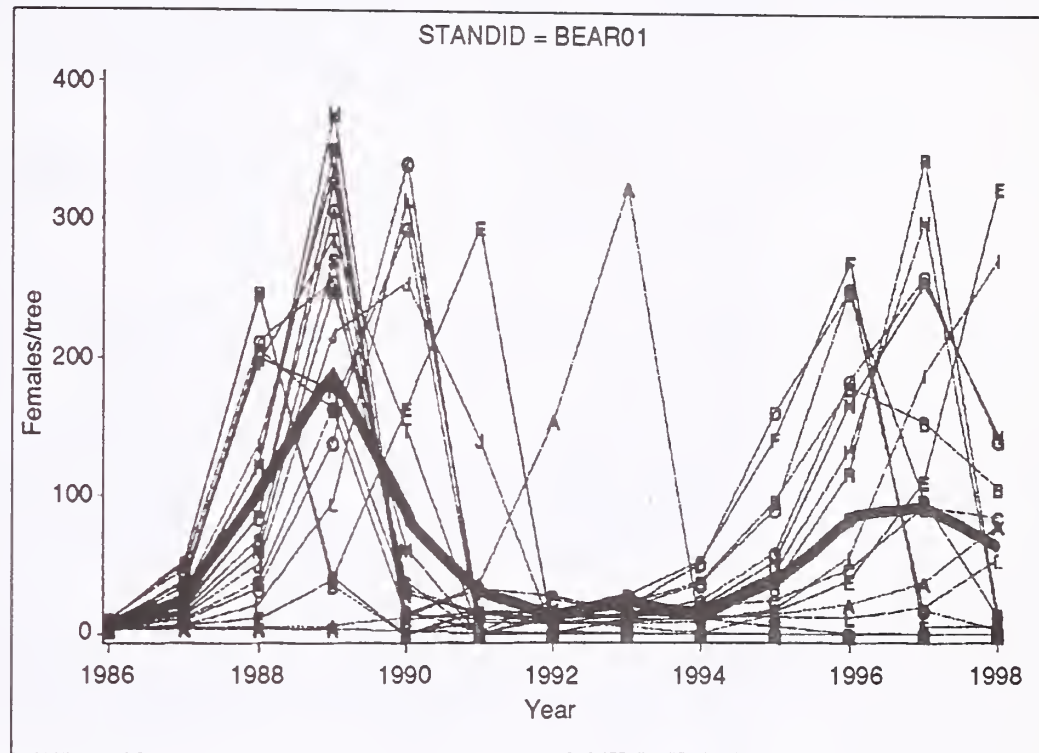
Figure 9—Like figure 8 except that a different random seed was used in the weather model for each replication.

SUMMARY

The Budworm Dynamics Model has been changed in a significant way prompting the release of version 3.1. This paper describes the changes to this model. The model exhibits varied, rich, and interesting behavior in response to changing some of the initial conditions and model options. Crookston and others (1990) list many more model options than exhibited in this paper. The influence of various stand structures and habitats, regional differences in model behavior, comparisons of model outputs to actual measured populations, formal sensitivity analyses, and other interesting work is, so far, left undone.

Models are useful in many respects. By illustrating some of this model's behavior, insight into the model, and thereby into actual populations, may be gained. The relationships between model output and reality need not be one-to-one to provide opportunities for generating useful insights.

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APPENDIX A: EXAMPLE FILES

The following files form the bases for the Budworm Dynamics Model runs described in this paper. An SAS (SAS Institute 1985) program used to read and plot budworm model STATDATA output is first. The base case (fig. 3) can be reproduced by running the keyword (second listing) file that references the foliage files (listings 3-4) presented after the keyword file.

Listing 1: SAS Program to Read and Plot STATDATA

```
data insect; infile 'insect.out';
  keep mgmtid standid tpha year adults females eggs d_cause
       t_dead disperse totmort;
  input dataid 1-2 standid $ 3-10 mgmtid $ 11-14 year 15-18
        season $ 19-22 host $ 23-24 tsize $ 25-28 crown $ 29-32 tpha 33-38
        @39 (adults females 14s eggs disperse birds ants type1 type2 folq
             spray) (11*8.);

  if not (host = 'TO' and tsize = 'TOT' and
          season = 'SUMR' and crown = 'TREE') then delete;
  d_cause  = disperse+birds+ants+type1+type2+folq+spray;
  t_dead   = eggs-adults;
  if eggs > .05 then totmort  = t_dead/eggs*100.;
                else totmort  = .;
run;


proc sort  data=insect; by standid mgmtid year; run;

data biomass; infile 'biomass.out';
  keep mgmtid standid year tpha f_totadj f_new gfoloss defol;
  input dataid 1-2 standid $ 3-10 mgmtid $ 11-14 year 15-18
        season $ 19-22 host $ 23-24 tsize $ 25-28 crown $ 29-32
        tpha 33-38 f_new 39-48 f_remain 49-58 f_total 59-68
        f_newadj 69-82 f_totadj 83-96;

  if not (host = 'TO' and tsize = 'TOT' and
          season = 'FALL' and crown = 'TREE') then delete;
  gfoloss = f_totadj-f_total;
  defol   = (1.0-(f_new/f_newadj))*100.;
  if defol < 1.0 then defol = 0.0;
run;


proc sort  data=biomass; by standid mgmtid year; run;

data adisp; infile 'adisp.out';
  drop dataid method;
  input dataid 1-2 standid $ 3-10 mgmtid $ 11-14 year 15-18
        method $ 19-21 @22 (f_gross eggspot eggslaid eggmden) (4*11.); run;

proc sort data=adisp; by standid mgmtid year; run;

data curdir.ibd;
  merge insect biomass adisp; by standid mgmtid year;
  eggspot=eggspot/tpha; eggslaid=eggslaid/tpha;
  if females = . then do; females = 0.0; eggs = 0.0; t_dead = 0.0;
     disperse = 0.0; d_cause = 0.0; totmort = .; eggpfem = .;
  end;
  if females > 0.0 then eggpfem=eggspot/females;
                   else eggpfem=0.0;
run;
```

19

```
proc means data=curdir.ibd noprint;
     by standid;
     var females eggs defol f_totadj;
     output out=maxes max=mxfem mxegg mxdef mxf_tot; run;

data plotem;
  keep  standid rvalue variable year;
  merge curdir.ibd maxes; by standid;
     rvalue=females/mxfem;    variable='Females';  output;
     rvalue=eggs/mxegg;       variable='Eggs   ';  output;
     rvalue=defol/mxdef;      variable='Defol  ';  output;
     rvalue=f_totadj/mxf_tot; variable='F_tot  ';  output; run;

data anno;
  set maxes;
  length position $ 1 text $ 13;
  position='1'; style = 'swissl'; function='label';
  size=1.2; xsys='3'; ysys='3';
  x=19.4; y=2; color='blue '; text='MAXIMUMS';                      output;
  position='3';
  x=22.4; y=2; color='blue '; text=put(mxdef,4.0)||' %';           output;
  x=38.6; y=2; color='red  '; text=put(mxegg,6.0)||'/tree';       output;
  x=56.0; y=2; color='brown'; text=put(mxf_tot,6.0)||' g/tree'; output;
  x=73.1; y=2; color='cyan '; text=put(mxfem,6.0)||'/tree';       output; run;

title; footnote h=1.5;
symbol1 c=blue  v=1 i=join l=1 f=swissl w=1;
symbol2 c=red   v=2 i=join l=3 f=swissl w=1;
symbol3 c=brown v=3 i=join l=5 f=swissl w=1;
symbol4 c=cyan  v=4 i=join l=7 f=swissl w=1;
axis1 label=(h=1.4 f=swissl c=blue 'Year')
      order=(1986 to 1998 by 2);
axis2 label=(h=1.4 f=swissl c=blue A=90 'Proportion of maximums')
      order=(0.0 to 1.0 by .1);
proc gplot data=plotem gout=bw.graphs;
     by standid;
     plot rvalue*year=variable / hminor=0 vminor=0 anno=anno
                                 vaxis=axis2 haxis=axis1; run;
```

Listing 2:
Keyword File for
Base Case

```
                                       Column rule
                 ----+----1----+----2----+----3----+----4----+----5----+----6----+----7--
FLYSUM
OPEN            31.
biomass.out
OPEN            32.
insect.out
OPEN            33.
adamage.out
OPEN            35.
adisp.out
STATDATA        31.       32.       33.                           35.
STNDLOCS
BEAR01          18.        .4        .3
BEAR02          32.       1.         .6
BEAR03          18.       1.5        .8
-999
FLYUNIT
OPEN            22.                  2.
bear01.wri
ADDSTAND        22.
END
CLOSE           22.
OPEN            22.                  2.
bear02.wri
ADDSTAND        22.
END
CLOSE           22.
OPEN            22.                  2.
bear03.wri
ADDSTAND        22.
END
CLOSE           22.
PROJECT         1998.
STOP
```

```
                                 Column rule
----+----1----+----2----+----3----+----4----+----5----+----6----+----7--

BEAR01    NONE 1986 0100001 310 51 117. 310.
West end of Bear Gulch, Malheur National Forest, Oregon.
        .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
        .0000000E+00  .4160227E+04  .1248068E+05  .1109394E+05
        .0000000E+00  .3706545E+03  .0000000E+00  .0000000E+00  .0000000E+00
        .0000000E+00  .0000000E+00  .0000000E+00  .6125225E+03  .0000000E+00
        .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
        .2285308E+03  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
        .2367467E+01
    2   .1893874E+02  .7304938E+02  .1231018E+03  .2392032E+03  .4305654E+03
        .1275750E+03  .1862993E+04  .3353386E+04  .9935962E+03
    2   .6493280E+01  .4869962E+02  .1055158E+03  .1674420E+03  .3588044E+03
        .2551496E+03  .1117794E+04  .2794490E+04  .1987190E+04
    2   .1082213E+01  .3246640E+02  .8792984E+02  .5740872E+02  .2870437E+03
        .2551496E+03  .5588972E+03  .2235590E+04  .1987190E+04
    2   .5411066E+00  .8116600E+01  .3517194E+02  .1435218E+02  .3588044E+03
        .6378745E+03  .1862993E+03  .2794490E+04  .4967984E+04
    2   .1893874E+02  .7304938E+02  .1231018E+03  .2392032E+03  .4305654E+03
        .1275750E+03  .1862993E+04  .3353386E+04  .9935962E+03
    2   .6493280E+01  .4869962E+02  .1055158E+03  .1674420E+03  .3588044E+03
        .2551496E+03  .1117794E+04  .2794490E+04  .1987190E+04
    2   .1082213E+01  .3246640E+02  .8792984E+02  .5740872E+02  .2870437E+03
        .2551496E+03  .5588972E+03  .2235590E+04  .1987190E+04
    2   .5411066E+00  .8116600E+01  .3517194E+02  .1435218E+02  .3588044E+03
        .6378745E+03  .1862993E+03  .2794490E+04  .4967984E+04
    2    .8548    .8548    .8548   1.6051   1.6051  1.6051  3.0789  3.0789  3.0789
    2   2.5474   1.6927    .8380   7.9613   6.3564  4.7514 15.7447 12.6662  9.5876
    2   1.0000   1.0000   1.0000   1.0000   1.0000  1.0000  1.0000  1.0000  1.0000
    2   1.0000   1.0000   1.0000   1.0000   1.0000  1.0000  1.0000  1.0000  1.0000
    2   1.0000   1.0000   1.0000   1.0000   1.0000  1.0000  1.0000  1.0000  1.0000
    2   1.0000   1.0000   1.0000   1.0000   1.0000  1.0000  1.0000  1.0000  1.0000
    7    .0000    .0000    .0000    .0000    .0000   .0000  2.3695  2.3695  2.3695
    7    .0000    .0000    .0000    .0000    .0000   .0000 34.3572 31.9880 29.6187
```

```
                                        Column rule
        ----+----1----+----2----+----3----+----4----+----5----+----6----+----7--

        BEAR02   NONE 1986 0100001 310 51 110. 310.
        Middle of Bear Gulch, Malheur National Forest, Oregon
            .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
            .0000000E+00  .3383242E+04  .1014973E+05  .9021984E+04
            .0000000E+00  .6989119E+02  .0000000E+00  .0000000E+00  .0000000E+00
            .0000000E+00  .0000000E+00  .0000000E+00  .3608867E+03  .0000000E+00
            .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
            .3600732E+03  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
            .5683719E+01
        2   .6589584E+02  .2541695E+03  .4283228E+03  .1020449E+03  .1836807E+03
            .5442397E+02  .8863274E+03  .1595390E+04  .4727078E+03
        2   .2259285E+02  .1694464E+03  .3671338E+03  .7143140E+02  .1530674E+03
            .1088478E+03  .5317974E+03  .1329492E+04  .9454175E+03
        2   .3765476E+01  .1129642E+03  .3059448E+03  .2449078E+02  .1224539E+03
            .1088478E+03  .2658979E+03  .1063594E+04  .9454175E+03
        2   .1882738E+01  .2824107E+02  .1223779E+03  .6122691E+01  .1530674E+03
            .2721199E+03  .8863277E+02  .1329492E+04  .2363541E+04
        2   .6589584E+02  .2541695E+03  .4283228E+03  .1020449E+03  .1836807E+03
            .5442397E+02  .8863274E+03  .1595390E+04  .4727078E+03
        2   .2259285E+02  .1694464E+03  .3671338E+03  .7143140E+02  .1530674E+03
            .1088478E+03  .5317974E+03  .1329492E+04  .9454175E+03
        2   .3765476E+01  .1129642E+03  .3059448E+03  .2449078E+02  .1224539E+03
            .1088478E+03  .2658979E+03  .1063594E+04  .9454175E+03
        2   .1882738E+01  .2824107E+02  .1223779E+03  .6122691E+01  .1530674E+03
            .2721199E+03  .8863277E+02  .1329492E+04  .2363541E+04
        2  1.1851   1.1851   1.1851   1.6505   1.6505   1.6505   2.1806   2.1806   2.1806
        2  4.5189   3.3339   2.1489   8.7581   7.1078   5.4575  18.6530  16.4727  14.2923
        2  1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
        2  1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
        2  1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
        2  1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
        7   .0000    .0000    .0000    .0000    .0000    .0000   2.5937   2.5937   2.5937
        7   .0000    .0000    .0000    .0000    .0000    .0000  23.4189  20.8255  18.2321
```

```
                                    Column rule
         ----+----1----+----2----+----3----+----4----+----5----+----6----+----7--

         BEAR03    NONE 1986 0100001 310 51 102. 310.
         East end of Bear Gulch, Malheur National Forest, Oregon.
              .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
              .0000000E+00  .7831059E+04  .2349318E+05  .2088281E+05
              .0000000E+00  .7413108E+03  .0000000E+00  .0000000E+00  .0000000E+00
              .0000000E+00  .0000000E+00  .0000000E+00  .3199446E+03  .0000000E+00
              .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
              .3476099E+03  .0000000E+00  .0000000E+00  .0000000E+00  .0000000E+00
              .3184153E+01
         2    .4335091E+01  .1672107E+02  .2817809E+02  .2139425E+03  .3850964E+03
              .1141027E+03  .1091101E+04  .1963980E+04  .5819207E+03
         2    .1486318E+01  .1114738E+02  .2415265E+02  .1497598E+03  .3209141E+03
              .2282053E+03  .6546602E+03  .1636651E+04  .1163839E+04
         2    .2477195E+00  .7431583E+01  .2012721E+02  .5134621E+02  .2567310E+03
              .2282053E+03  .3273311E+03  .1309321E+04  .1163839E+04
         2    .1238598E+00  .1857896E+01  .8050884E+01  .1283655E+02  .3209141E+03
              .5705137E+03  .1091100E+03  .1636651E+04  .2909602E+04
         2    .4335091E+01  .1672107E+02  .2817809E+02  .2139425E+03  .3850964E+03
              .1141027E+03  .1091101E+04  .1963980E+04  .5819207E+03
         2    .1486318E+01  .1114738E+02  .2415265E+02  .1497598E+03  .3209141E+03
              .2282053E+03  .6546602E+03  .1636651E+04  .1163839E+04
         2    .2477195E+00  .7431583E+01  .2012721E+02  .5134621E+02  .2567310E+03
              .2282053E+03  .3273311E+03  .1309321E+04  .1163839E+04
         2    .1238598E+00  .1857896E+01  .8050884E+01  .1283655E+02  .3209141E+03
              .5705137E+03  .1091100E+03  .1636651E+04  .2909602E+04
         2    .7396    .7396    .7396   1.6871   1.6871   1.6871   2.5763   2.5763   2.5763
         2   2.0912   1.3517    .6122   9.3640   7.6770   5.9900  17.1365  14.5604  11.9844
         2   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
         2   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
         2   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
         2   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
         7    .0000    .0000    .0000    .0000    .0000    .0000   3.0828   3.0828   3.0828
         7    .0000    .0000    .0000    .0000    .0000    .0000  30.8445  27.7619  24.6794
```

Errata

Page 22, regarding Example 4: Requesting Output, tne FOLSUM and POPSUM keywords should be inserted between lines 8 and 9 of example 3, not between lines 7 and 8.

Page 36, top of page, under the description of the DISPDIR keyword. In the sentence that describes the contents of field 1, the reference to table 9 should be to table 8.

Page 54, figure A-2. The column ruler on the top line indicates that the data records (which start with the word "BEAR01") start in the first column. In fact, all of the data records in the foliage files contain a blank in the first position. Note that the format description of this file on page 58, table B-2, is correct.

New Keyword

The management identification code for a stand is set using the Prognosis Model MGMTID keyword. When creating a foliage file using the Prognosis-Budworm Dynamics Model WRITEFOL keyword, this management identification is output in the first record of the foliage file. When running the Budworm Dynamics Model, the management identification code and other stand data are read when an ADDSTAND keyword in entered.

This technique makes it inconvenient to use the management identification code to label Budworm Dynamics Model output. The management identification code can be a useful tool to label output, particularly output created using the STATDATA option.

The Budworm Dynamics Model now offers an MGMTID keyword that works just like the MGMTID keyword used in the Prognosis Model. With it, you can change the label used to identify Budworm Dynamics Model output without having to edit or recreate the foliage file. Place the MGMTID keyword after the ADDSTAND keyword for a given stand and before the corresponding END keyword. Follow the MGMTID keyword with the new management identification code for the stand.

MGMTID   Signal that a new management identification code is entered on a supplemental data record.

Supplemental data record:

Col 1-4: The new management identification code.

The Budworm Dynamics Model, a component of the Budworm Modeling System, is
herein revised. The resulting model is called version 3.1. Illustrations display the behavior
of version 3.1 as compared to 3.0 and when run using various options and initial condi-
tions. The model exhibits interesting and rich behavior. This paper offers an opportunity
to begin exploring the model as a potential research, teaching, and management tool.

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology
to improve management, protection, and use of the forests and rangelands of the
Intermountain West. Research is designed to meet the needs of National Forest
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