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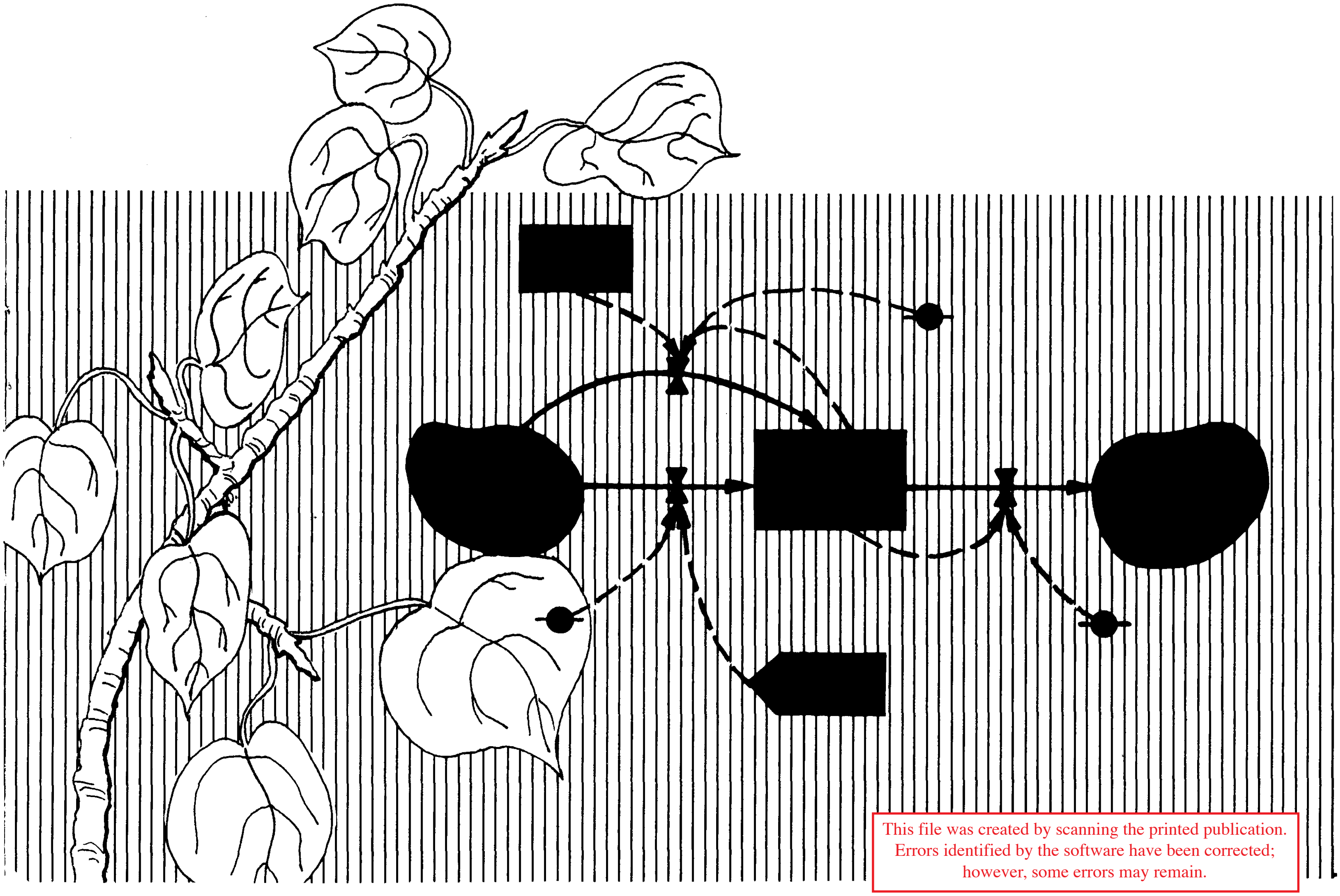
Aspen Succession in the Intermountain West: A Deterministic Model

**Dale L. Bartos, Frederick R. Ward,
and George S. Innis**



THE AUTHORS

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ACKNOWLEDGMENTS

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RESEARCH SUMMARY

A deterministic model of succession in aspen forests was developed using existing data and intuition. The degree of uncertainty, which was determined by allowing the parameter values to vary at random within limits, was larger than desired. Analysis of model sensitivity to changes in parameter values was made and the results presented. These results have indicated areas of needed research. The model responds realistically to various management techniques and could be an aid to resource managers in their decision making process.

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INTRODUCTION

The aspen (*Populus tremuloides* Michx.) ecosystem is prevalent in the mountainous West (Little 1971). This system produces multiple resources including: water, wildlife habitat, recreational sites, summer grazing for domestic livestock, wood fiber, and esthetics.

To manage the aspen system and its resources intelligently, we must understand the natural forces acting upon and within the ecosystem. When we understand the dynamics of the vegetation, we can make valid judgments concerning management of these lands for the resources mentioned above. The process of succession also needs to be better understood so that the successional position of a particular stand can be identified and the stand managed accordingly.

Much of successional theory has been developed for mesic, temperate forests. Many of these theories have been incorporated into simulation models tracking the dynamics of the forested system following disturbance. Shugart and West (1980) review much of this literature and Trimble and Shriner (1981) inventory many of the published and unpublished models.

More than 200 years is required for conifers to invade and dominate aspen forests. Long-term intensive studies are not feasible to answer pressing and current management problems. Using existing data and intuition, Bartos (1973, 1978) developed a simulation model as an aid to understanding the dynamics of the aspen system. We have revised this model by reducing the number of parameters, while still retaining the structure and behavior of the model.

The model presented here considers a site as a homogeneous unit on which plants (trees, shrubs, and herbs) are growing. Because the model addresses average conditions on an area, it is more like the model of Noble and Slatyer (1977) than the family of models produced by Botkin, his associates and followers (Botkin 1977; Botkin and others 1972a, b; Shugart and West 1977). Our model is concerned with the alternative fates of an aspen/conifer site following a major disturbance (fire or clearcut). These alternatives, described by Mueggler (1976), include succession to conifers, remaining in aspen, or succession to meadow, again suggesting the Noble and Slatyer model. To date, our model treats only the first alternative. Implementation of other alternatives is straightforward, depending only on the identification of mechanisms responsible for the alternate pathways.

Our model is most like that of Sperger (1980), although the latter model is very elaborate. Sperger includes many more size classes in his model so that he can predict the size class distribution of the forest at any age. We deal with aspen and conifer reproduction in three different size classes, and beyond that we consider only biomass. Therefore, our model requires less data than Sperger's model for a particular run.

With all the published successional models, why do we presume to build another? First, much of the utility in a modeling exercise derives from the design and construction of the model (Innis 1972; Odum 1981). This utility is denied one who attempts to use another's model. Because models are specific to their applications, model building begins with statements of the objectives. Each of the published models has different objectives and, consequently, different structure. We must appreciate this dependence on objectives when evaluating a model.

In addition to the "standard" run showing succession in the aspen forest following a disturbance, this paper includes responses of the model to common management techniques. As an aid to interpretation of model results, an indication of the distribution of the model results as a function of uncertainty of the parameter values used is presented. The model is very sensitive to changes in some parameter values, and this sensitivity is discussed.

Model Objective

Our objective was to develop a streamlined simulation model that would predict the dynamic nature of vegetation components within the aspen system and how these components change during the successional process. This model should apply to most aspen lands in the western United States and should aid natural resource managers in their decisionmaking process. In addition, a good responsive model would aid in studying the aspen system. Such a model would provide an excellent basis on which to develop a problem analysis for future research. Individual studies could be conducted to more accurately estimate the most sensitive parameters.

Several terms in this statement of objectives require further elaboration: 1. "Dynamic" implies changes over time in the various vegetation components of the system. 2. "Vegetation component" refers to only the aboveground biomass for wood (aspen and conifers) and herbage (shrub and herb species). 3. "Successional process" is the dynamics of a vegetation unit as it progresses towards a community that is in a steady state (climax) relationship with the environment. We are concerned only with secondary succession—where the soil may remain at a fairly advanced stage of development while the plant community is set back to an earlier stage because of a disturbance.

4. "General model" implies flexibility to apply the model to different sites which have similar environmental conditions. The model needs to assimilate disconnected bits of information and predict within reason the results of management practices.

While this objective statement sets the general tone of the modeling effort, a more explicit set of issues must be addressed:

1. Does the modeled successional pattern fit the intuition of experts?
2. Does the model respond reasonably to management actions?
3. Without major influences from conifers and herbs, is an aspen community able to stabilize for long periods of time?
4. What are the sensitivities of these predictions to parameter estimates, site condition assignments, initial conditions, and functional forms of flows?
5. What additional research is needed to make this model a more accurate simulation of the consequences of succession?

Assumptions

Several assumptions were made to facilitate initial model development and subsequent updates. The initial assumptions are: 1. The system stressed will have conifers on or near it to provide a seed source when the site is disturbed. 2. Aspen are present; therefore, a root source exists to provide a flush of aspen suckers when the site is disturbed. 3. The damaged site will be small enough to be homogeneous with respect to soil characteristics and abiotic factors. 4. Disturbance will be by burning; some root crowns of perennial herbs will not be killed and total herb production will be temporarily stimulated when the site is disturbed. (The community could quite conceivably be stressed by cutting the overstory trees and similar responses might be observed.)

MODEL STRUCTURE

The major components of interest in this model are aspen, conifers, shrubs, and herbs. These regenerate, grow, and die at rates affected by the various components (fig. 1). Soil and climate are not explicitly treated in the model but are reflected in site-specific parameters such as growth rate, regeneration rate, and maximum biomass of the various compartments. The mathematical model is a set of simultaneous difference equations. The model was coded in FORTRAN V and runs on a variety of computers. (A complete listing of the computer program is presented in appendix A.) The model is deterministic, not stochastic, in nature. Parameter values used (see appendix C) reflect long-term averages adjusted for the step size, which we set at 1 year.

Primary concern is aboveground biomass (kg/ha) of the four major state variables. Aspen suckers and conifer seedlings, however, are treated in three size categories on the basis of density because growth, mortality, and interactions with other compartments are very different for the suckers and seedlings than for mature individuals and should be handled in a different fashion.

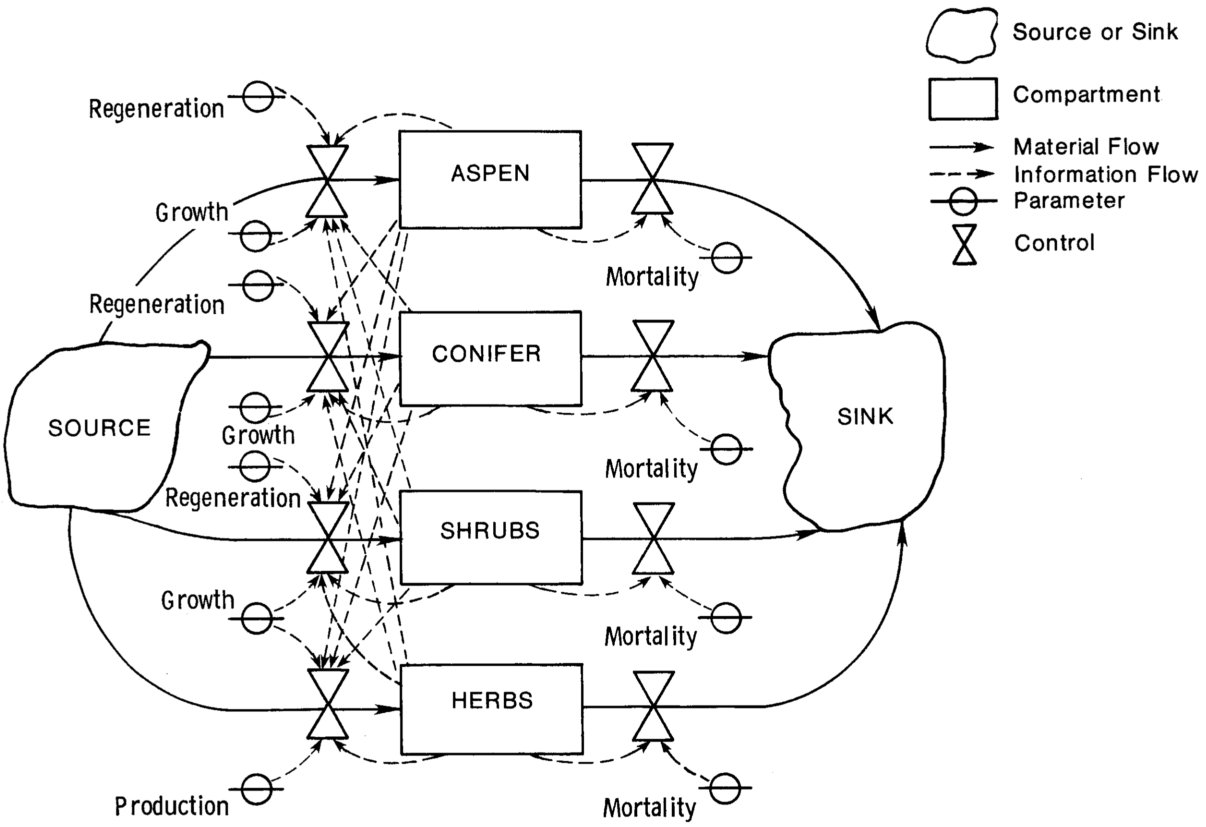


Figure 1.—Summary flow diagram of major compartments in the ASPEN model.

The aspen reproduction categories are: ASP1, aspen suckers less than 0.5 meters tall; ASP2, suckers between 0.5 and 2 meters tall; and ASP3, suckers over 2 meters tall but less than 5 cm d.b.h. All aspen reproduction is considered to be vegetative. For conifers the three categories of seedlings are CON1, CON2, and CON3, defined according to the same size structure as the aspen suckers. CON1 seedlings are considered to be established (to have persisted on the site for at least 3 years) to avoid dividing them into several subgroups. Time for passage through these subgroups is accounted for by a time delay. Thus, no regeneration into CON1 is allowed for a few years (3 to 10 depending on the site) after the initial disturbance. The numbers of individuals graduating from ASP3 and CON3 are converted to biomass using average weights of 5 cm d.b.h. aspen and conifer and constitute the regeneration flows from the source to the biomass compartments of aspen and conifer. These two major compartments contain the biomass only of individuals larger than 5 cm d.b.h.

In the case of shrubs, mature plants were not considered sufficiently different from the young ones to warrant separate treatments; so the shrub compartment contains individuals of all sizes.

The herb compartment was subdivided into annuals and perennials. Because only the aboveground biomass is considered, these compartments are totally depleted each year. Production was not separated into reproduction and growth.

Flows representing regeneration, growth, production, or graduation are controlled by the product of a maximum rate with two or more inhibiting functions having values which range over the interval from 0 to 1. For example, the graduation of conifer seedlings from CON3 to CON is given by FLOW27 = CON3 * P(101) * Z1 * Z2 where P(101) gives the maximum graduation rate allowed, Z1 = 1 – 0.5 * PASP gives the restriction of the aspen, and Z2 = 1 – 0.7 * PCON gives the restriction of the conifers. The maximum rates are given by parameters reflecting site characteristics, and the functions represent restrictions imposed on that flow by various compartments. The independent variable for each restricting function is taken to be the ratio of the present value to the maximum possible value of the inhibiting compartments, rendering these functions independent of site.

With one exception, the influence of aspen on conifer reproduction which will be discussed later, these inhibiting functions are nonincreasing. When the inhibiting compartment has a value of zero, the ratio of present to maximum value is zero and the inhibiting function has a value of 1 (no restriction). As the value of the inhibiting compartment increases, the ratio of that value to the maximum increases and the value of the inhibiting function decreases below 1 so that there is a more stringent restriction.

The inhibiting functions were suggested in graphic form by members of the Aspen Ecosystem Project (INT-RWU-1751) at the Intermountain Station's Forestry Sciences Laboratory in Logan, Utah. We then fitted these curves with functions and they were approved by consensus of the project scientists as exhibiting appropriate behavior.

All compartments other than sources and sinks were considered to have potential influence on a flow. If this influence was considered quite minor, as in the case of herbage on growth of large conifers, it was omitted. In cases where intensive investigation has yielded more detailed knowledge, the influences were considered separately, but where less was known the influences were pooled. For instance, the three aspen sucker compartments separately affect the regeneration of ASP1, but the three conifer seedling compartments are pooled into one compartment, which has a single restriction on ASP1 regeneration. The detailed discussion of the model structure includes graphs of the functions restricting the flows into the various compartments. Each graph is accompanied by its equation, and the flow equations into and out of each compartment are given.

Each mortality flow in the model is a fixed percentage of the value of the compartment from which the flow originates; for example, the mortality of conifers is given by the equation FLOW6 = CON * P(105). In the biomass compartments "mortality" is interpreted to include the loss of portions of a plant as well as of entire plants. These mortality rates are site-specific parameters. During the model building process there was much discussion concerning the mechanisms which limit a compartment to some maximum value. In the absence of firm knowledge as to whether (1) the mortality rate increases to surpass the growth rate, (2) the growth rate drops to the mortality rate, or (3) the growth rate decreases over time as the mortality rate increases, it was decided to hold mortality constant and decrease growth from some maximum value by means of the various restrictions. In the aspen compartment, for example, maximum growth rate is set at 8 percent per annum and mortality rate is set at 3 percent per annum. This allows for a net growth of 8 percent – 3 percent = 5 percent per annum in the extreme case that little aspen and no conifer is present to curtail the growth rate. A heavy conifer stand, however, would restrict aspen growth rate to nearly zero, yielding a net growth of 0 percent – 3 percent = – 3 percent per annum, the mortality rate.

Large-scale losses, such as those induced by disease or insect infestation, are outside the purview of the model. One could treat such high mortality, however, by stopping the simulation and restarting with new initial values that reflect the appropriate loss.

At the beginning of a simulation run the computer assigns and prints the maximum possible values of various compartments (code 11100–13700). The maximum value of a compartment represents the level that compartment could contain in the absence of any competition from other compartments. Input parameters give the maximum values of mature aspen, mature conifer, shrubs, annuals, perennials, the three aspen sucker classes, the three conifer seedling categories, the pooled biomass equivalent of the conifer seedlings, the pooled biomass equivalent of the aspen suckers, and the combined biomass possible for shrubs and aspen suckers. Maximum herbage is the sum of the maxima of the annual and perennial compartments.

Some initial values are assigned through parameters and others are computed from those values assigned (code 14400–18100). Those assigned are for aspen and its three sucker classes, conifer and its three seedling classes, annuals, perennials, shrubs, and number of mature conifers. Those computed include total herbs and other combinations of compartments with assigned initial values.

Computation of flows requires that ratios of present value to maximum possible value for numerous compartments be computed at each time step (code 24700–27700). The FORTRAN name for such a ratio is the FORTRAN name for the compartment with a prefix of P; for instance, PASP stands for the ratio of aspen present to aspen possible. Should such a ratio exceed 1, the value of the corresponding inhibitor function becomes negative, which causes anomalous behavior; so a check is made to reset the ratio to 1 in case its computed value exceeds 1.

Regeneration and mortality of ASP1 (code 28000–29600) are diagramed in figure 2. ASP1 mortality is given by FLOW15 = ASP1 * P(41), where P(41) is the site-specific mortality rate. ASP1 regeneration is given by FLOW14 = P(40) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6 * Z7 where P(40) is the site specific rate and the factors Z1, Z2, Z3, Z4, Z5, Z6, and Z7 are the restrictions contributed by ASP, CON, SHU, ASP1, ASP2, ASP3, and CONN respectively (fig. 3). Note that as the ratio of present to maximum possible biomass goes from 0 to 1, the corresponding restriction increases from 1 (no restriction) to a fraction nearer 0.

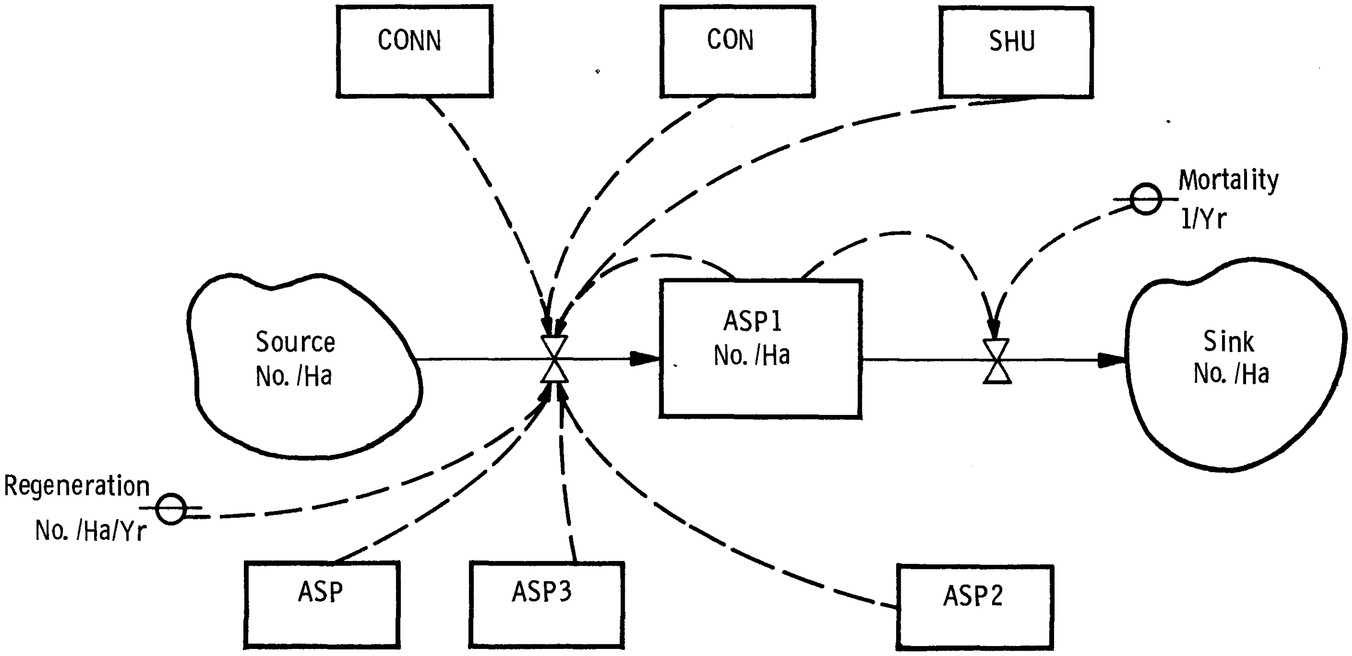
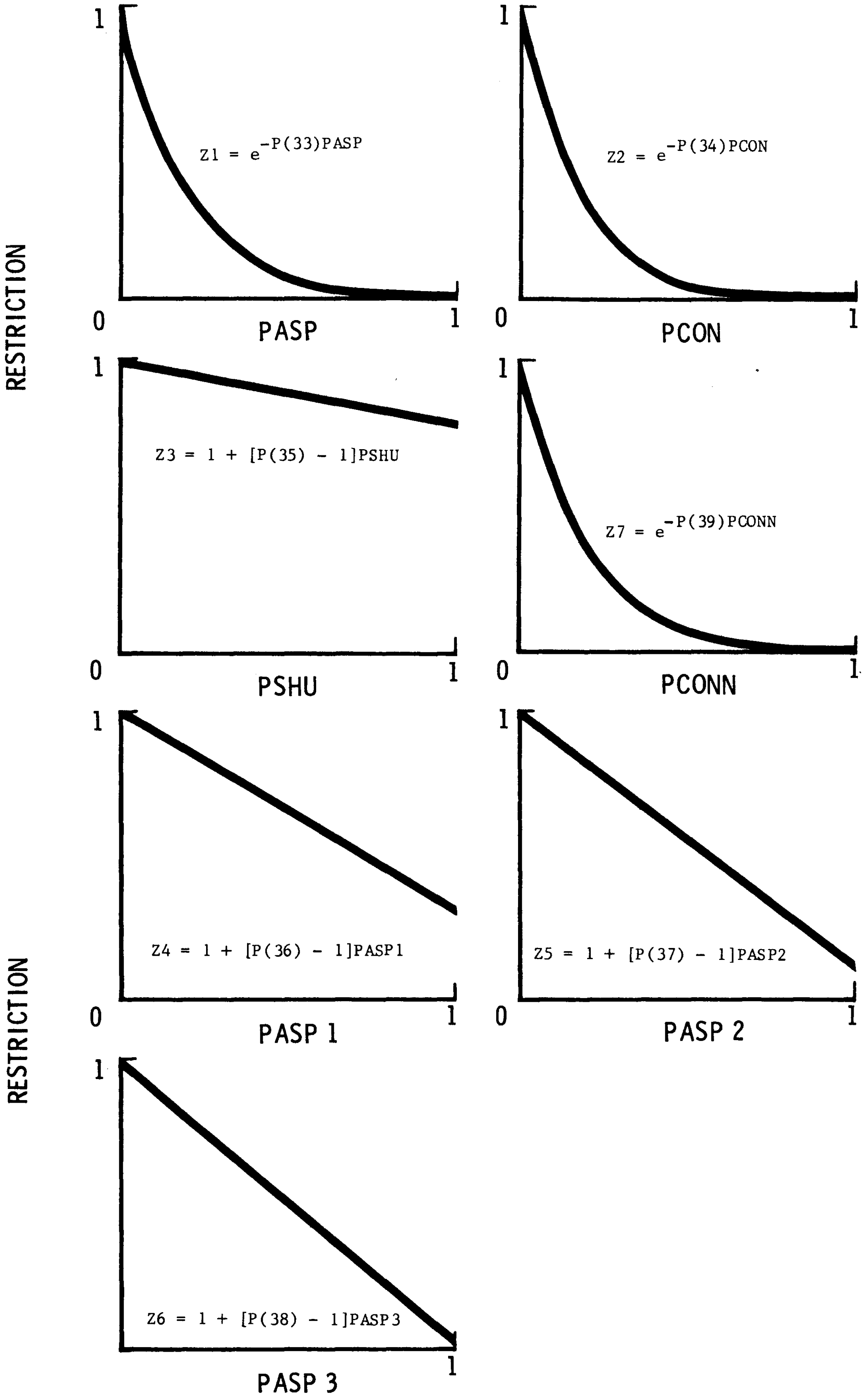


Figure 2.—Flow diagram depicting regeneration and mortality of ASP1.



FLOW 14 = P(40) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6 * Z7

Figure 3.—Functions that inhibit the regeneration of ASP1.

Each year some fraction of the ASP1 is allowed to graduate to ASP2 and a fixed proportion of the ASP2 die (code 29700–31300). The flows are diagramed (fig. 4) and the nature of the restrictions is shown in figure 5. The ASP1 restriction is considered negligible in this case, but the herbs are not. While the herbs may not restrict suckering of aspen, they do compete with the young suckers for light.

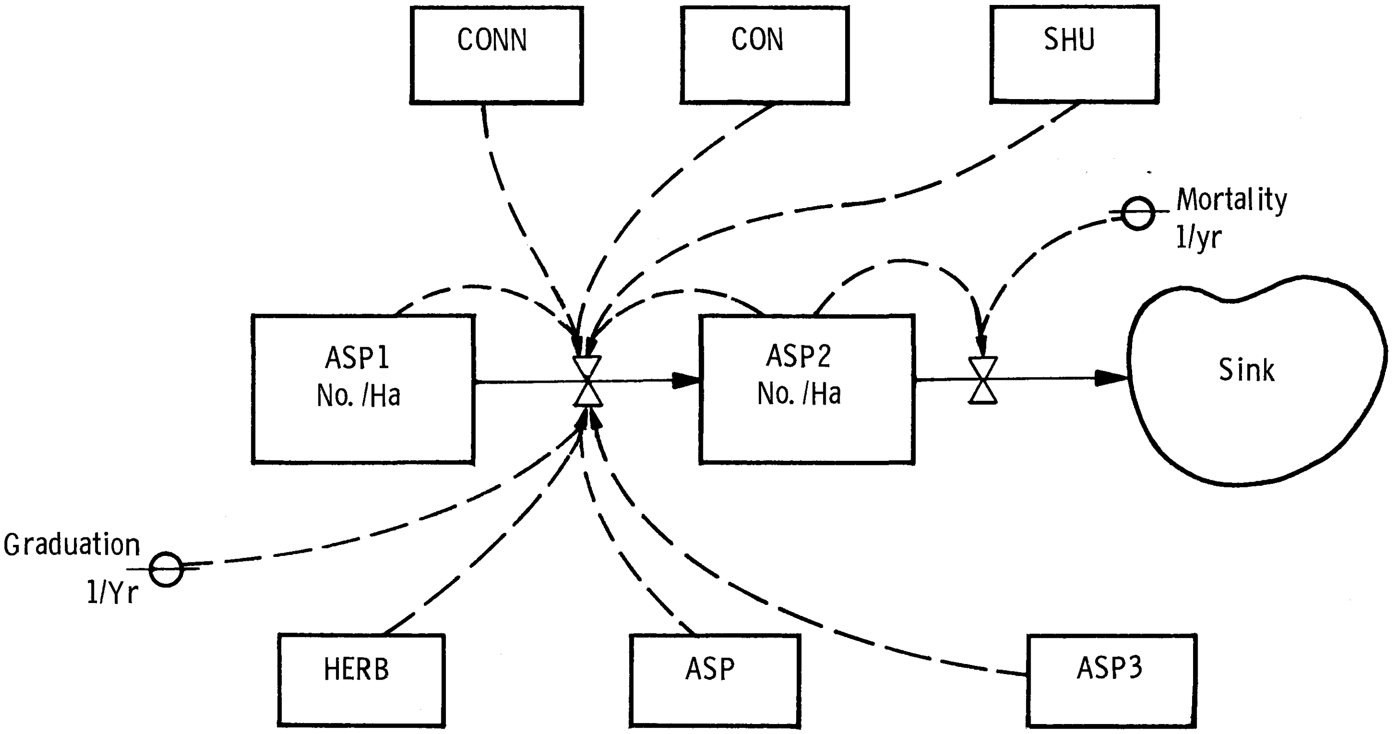
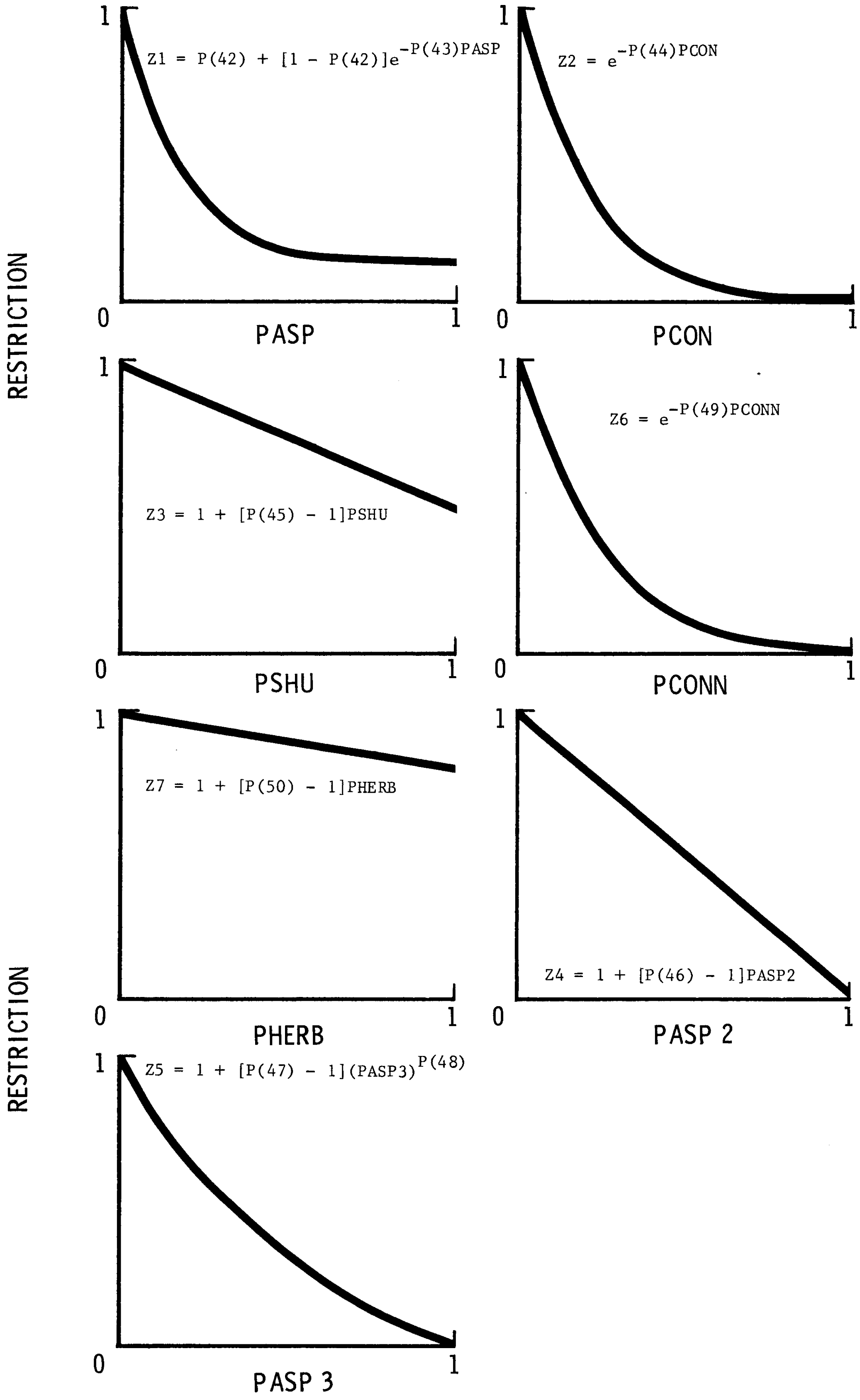


Figure 4.—Flow diagram depicting graduation from ASP1 to ASP2 and mortality from ASP2.



FLOW 16 = ASP1 * P(51) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6 * Z7

Figure 5.—Functions that inhibit the graduation of ASP1.

Graduation from ASP2 to ASP3 and mortality of ASP3 (code 31400–32800) are shown in figure 6. At this point restrictions due to herbs and ASP2 are considered negligible. Inhibitions from the other compartments are graphed in figure 7.

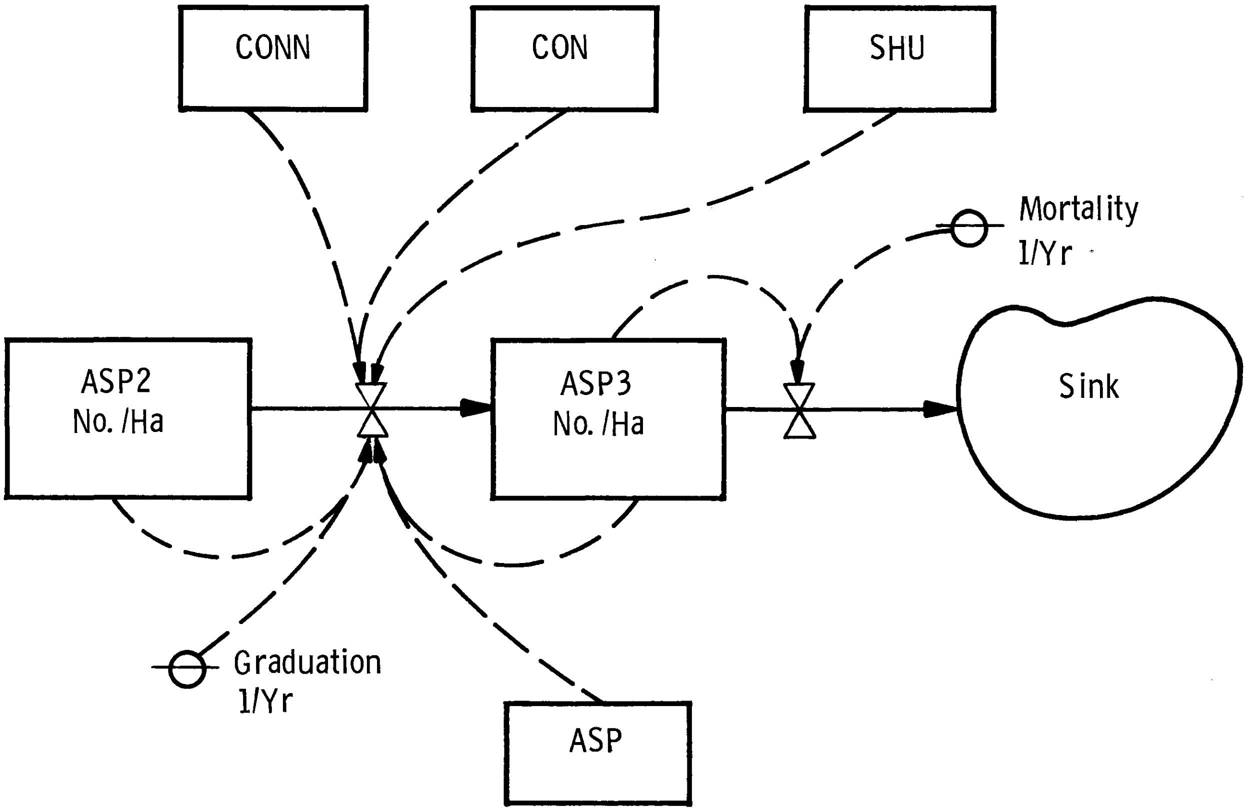
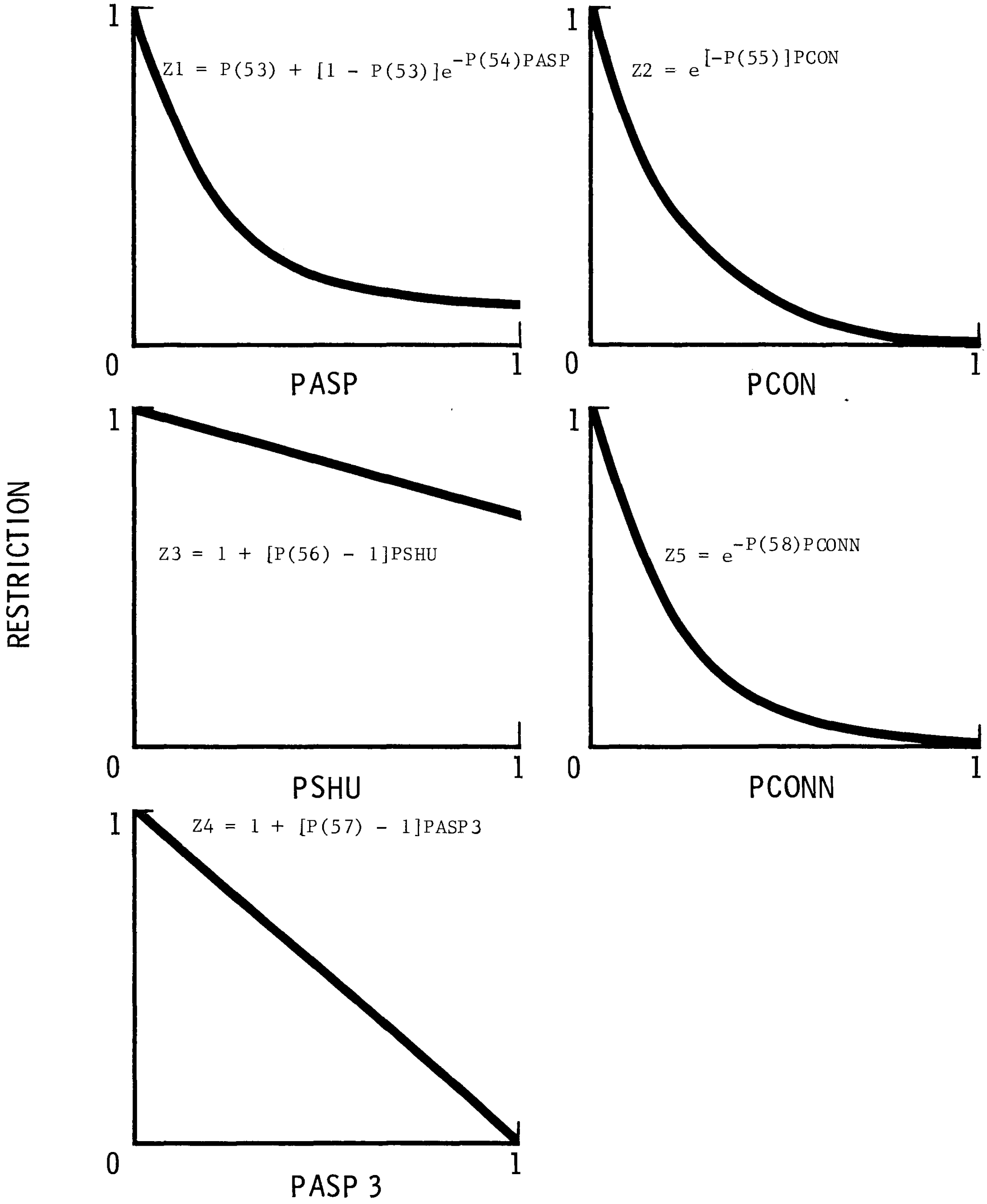


Figure 6.—Flow diagram depicting graduation from ASP2 to ASP3 and mortality from ASP3.



FLOW 18 = ASP2 * P(59) * Z1 * Z2 * Z3 * Z4 * Z5

Figure 7.—Functions that inhibit the graduation of ASP2.

To ensure a conservative system, graduation from ASP3 (code 32900–33600) is shown in figure 8 as going to the sink. The sum of the values in the three aspen sucker compartments and their source and sink should remain constant. Only the conifer, aspen, and shrub compartments have identifiable restrictions on the flow (fig. 9).

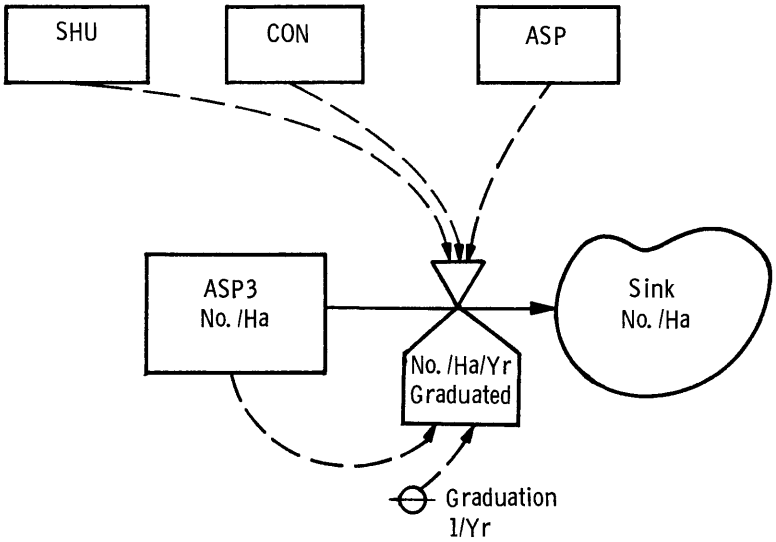
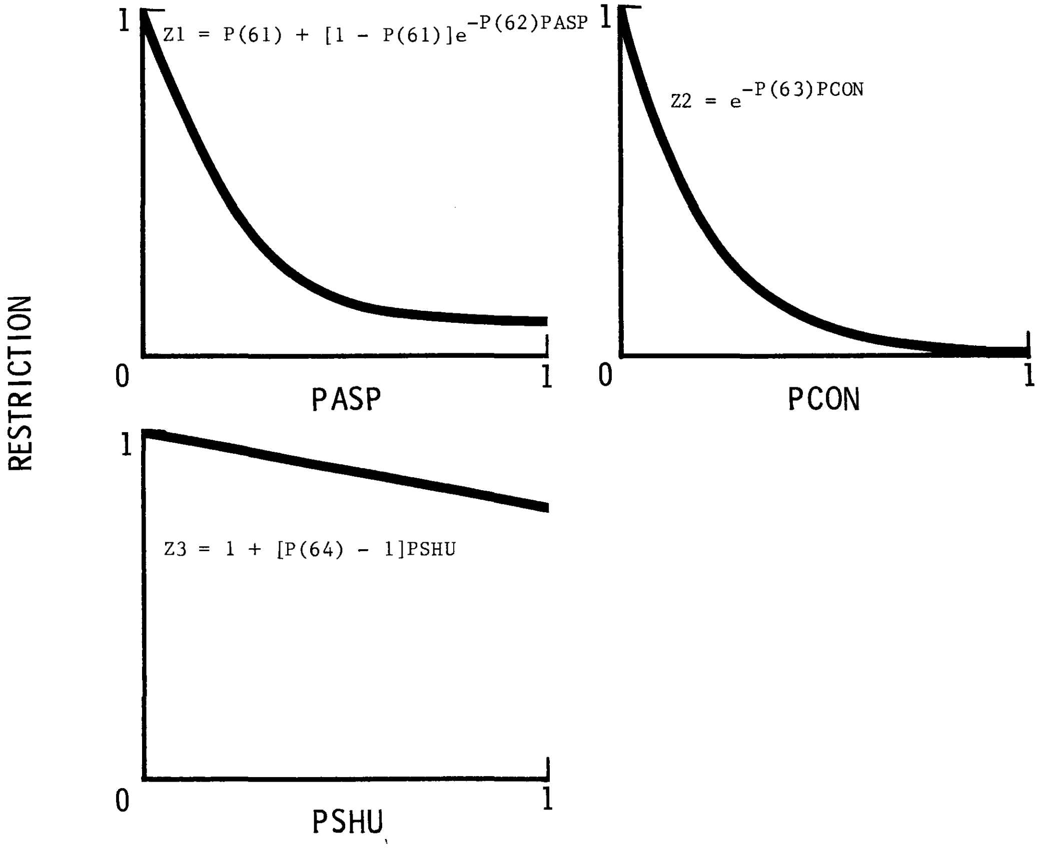


Figure 8.—Flow diagram depicting graduation of ASP3.



$FLOW\ 20 = ASP3 * P(65) * Z1 * Z2 * Z3$

Figure 9.—Functions that inhibit the graduation of ASP3.

There are two flows from the source to ASP in figure 10. The lower flow is simply the conversion of ASP3 graduation from numbers to biomass (code 33700–34100). The upper flow from the source and the flow to the sink represent aspen growth and mortality (code 34200–35300). The restrictions of the aspen and conifer on aspen growth are shown in figure 11. The restriction due to aspen itself is such that the product of the restriction with the growth rate would equal the mortality rate slightly before maximum biomass is reached. This produces a net mortality as aspen biomass approaches maximum so that aspen biomass will not continue to increase past maximum due to graduation from ASP3.

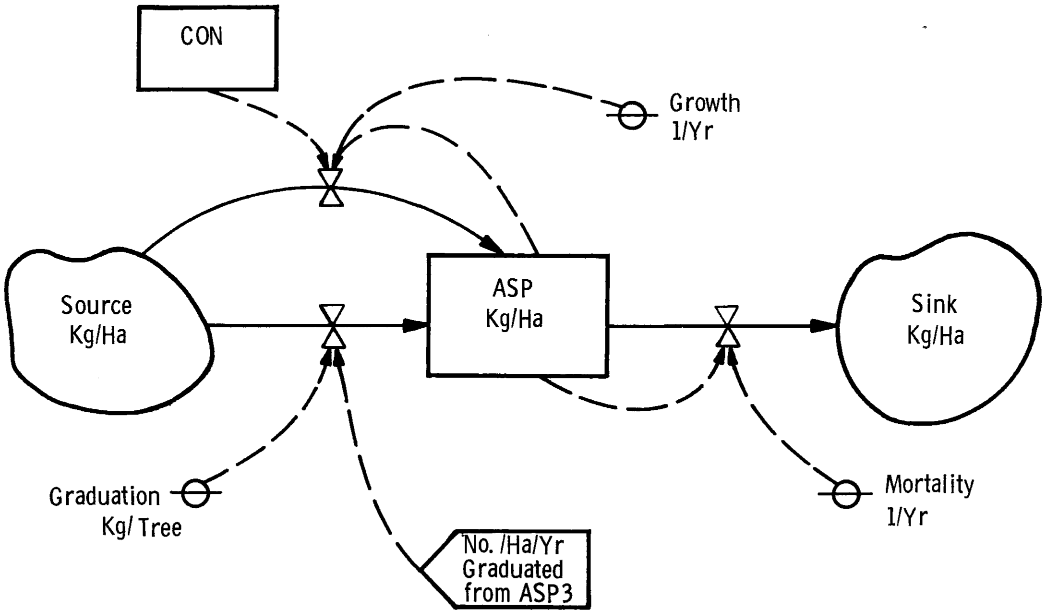
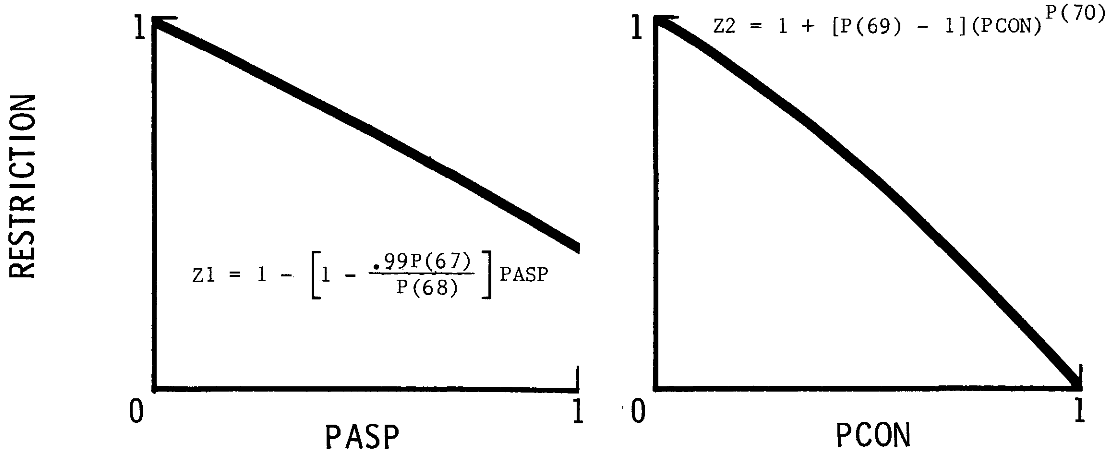


Figure 10.—Flow diagram depicting regeneration, growth, and mortality of aspen (ASP).



FLOW 2 = ASP * P(68) * Z1 * Z2

Figure 11.—Functions that inhibit the growth of aspen.

Regeneration and mortality of CON1 (code 35400–37600) are diagramed in figure 12. As in the case of ASP1, the relative mortality and maximum rate of regeneration are site specific. All compartments except CON1 affect the regeneration rate, though annuals and perennials are pooled as a single effect in HERB and the aspen suckers are converted to biomass and pooled with shrubs as SHUH (fig. 13). The restriction of aspen on CON1 regeneration is the only inhibiting function which is not strictly decreasing. This deviation from the norm was designed to account for a "nurse" effect of aspen on conifer regeneration. Controversy revolves around this point, however, with some arguing that there is no positive effect from aspen on the conifer seedlings.

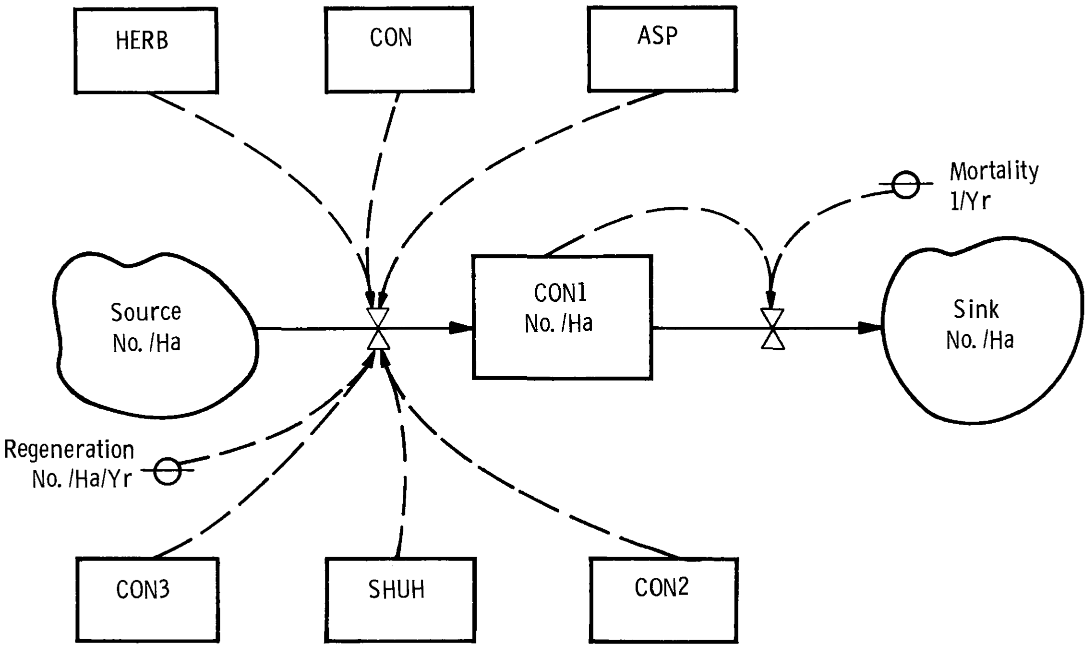
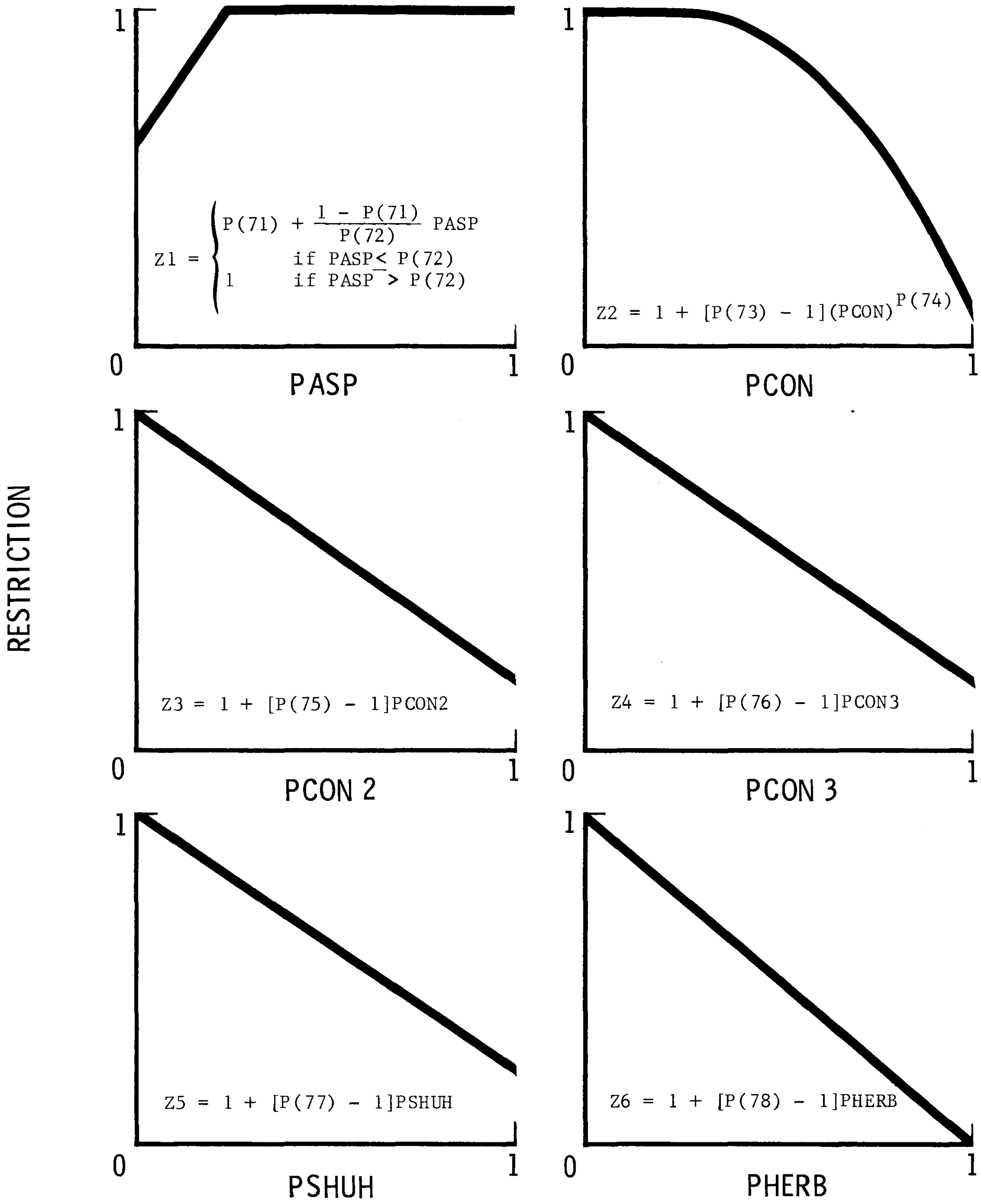


Figure 12.—Flow diagram depicting regeneration and mortality of CON1.



FLOW 21 = P(79) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6

Figure 13.—Functions that inhibit the regeneration of CON1.

Graduation of CON1 to CON2 and mortality of CON2 (code 37500–39000) are diagramed in figure 14. The graduation is affected by the same compartments as is regeneration (fig. 15).

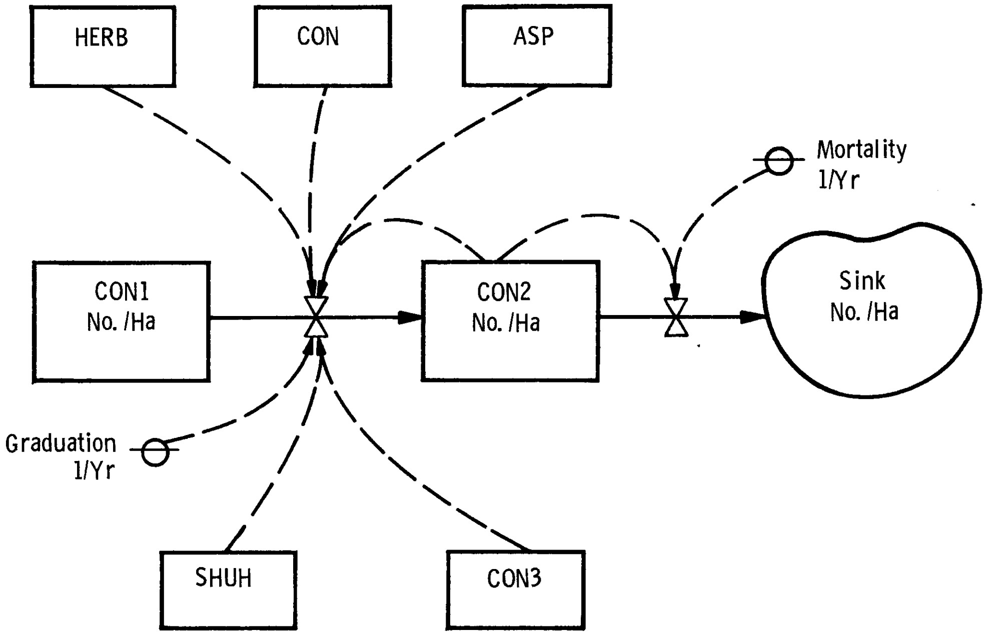
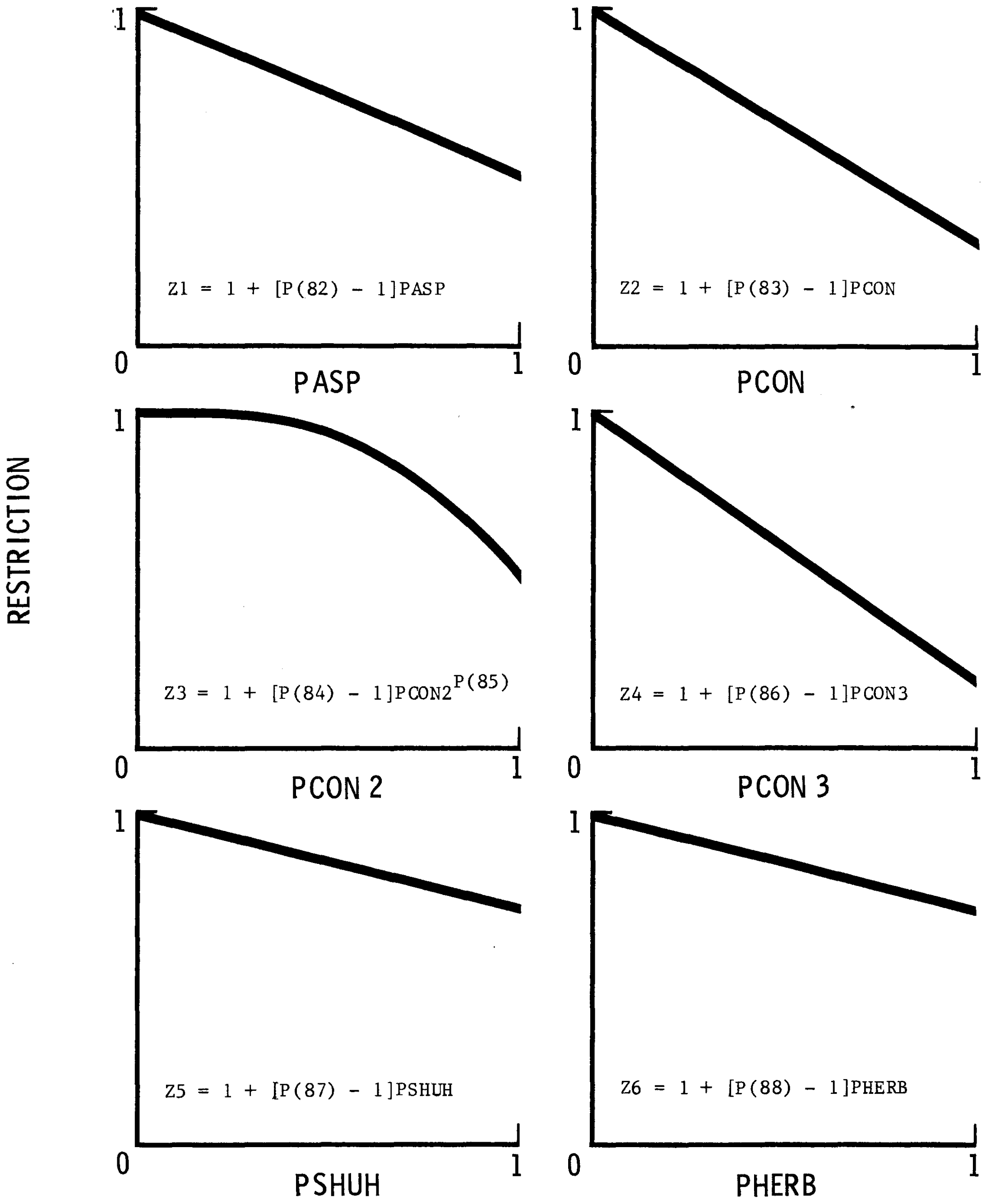


Figure 14.—Flow diagram depicting graduation of CON1 to CON2 and mortality of CON2.



FLOW 23 = CON1 * P(89) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6

Figure 15.—Functions that inhibit the graduation of CON1.

The diagram of CON2 graduation and CON3 mortality (code 39100–40400) is in figure 16. In the graduation of CON2 the herbs, shrubs, and aspen suckers are no longer considered significant factors. The remaining inhibitions are shown in figure 17.

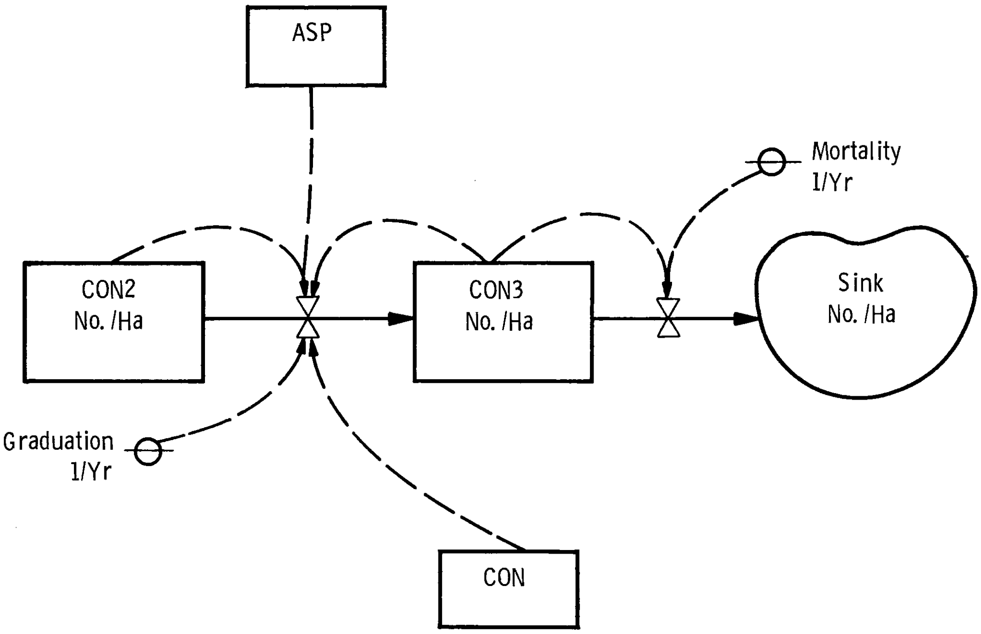
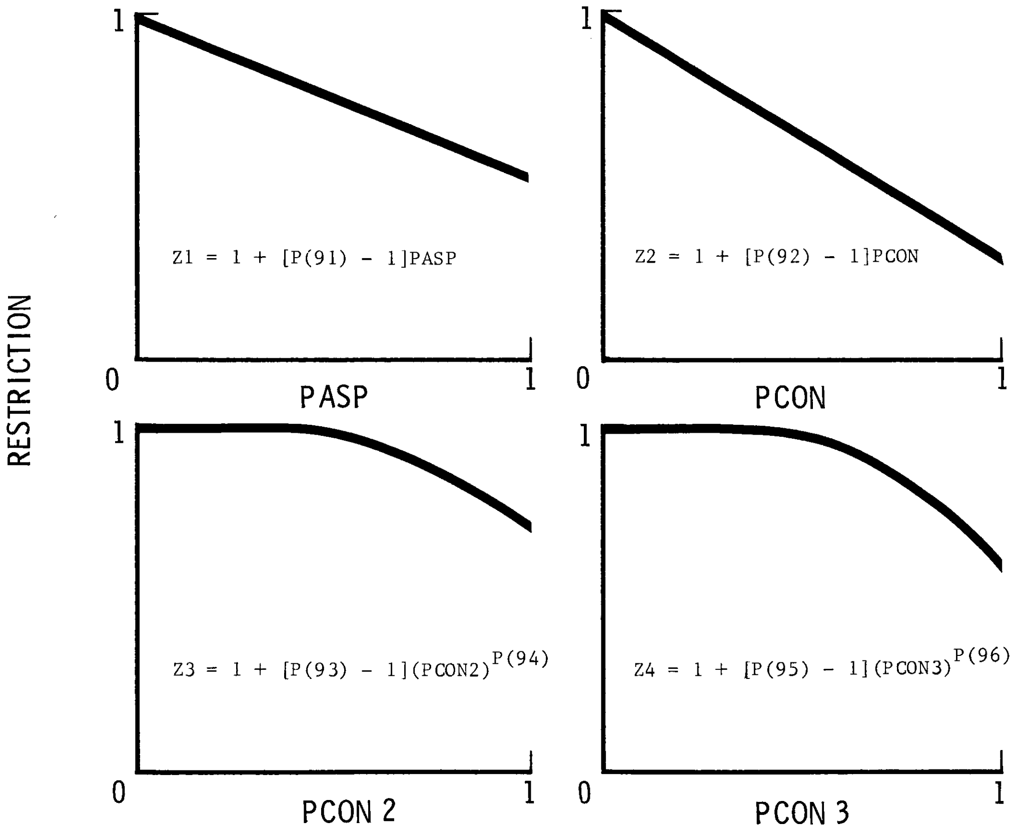


Figure 16.—Flow diagram depicting graduation of CON2 to CON3 and mortality of CON3.



FLOW 25 = CON2 * P(97) * Z1 * Z2 * Z3 * Z4

Figure 17.—Functions that inhibit the graduation of CON2.

Like ASP3, the CON3 seedlings graduate to a numbers sink (code 40500–41100) (fig. 18) with restrictions (fig. 19). The sum of the values in the source, the sink, and the three seedling compartments should remain constant over the years. Because the mortality applied to the conifer numbers (code 42400–42800) is the same fraction as that applied to the conifer biomass, all the loss of smaller limbs shows up as loss of tree numbers, so that the numbers estimate grows continually smaller and average tree size estimates are too large.

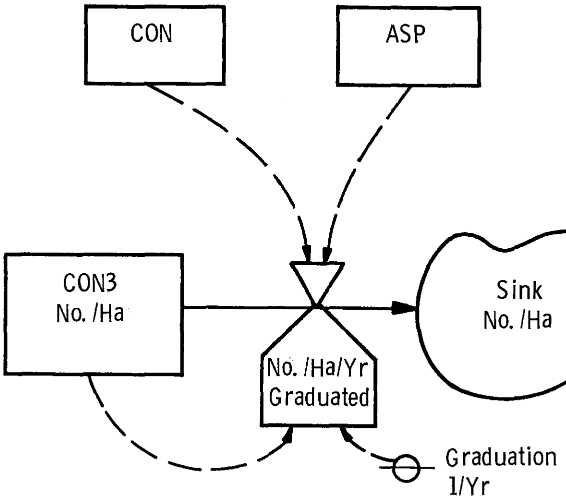
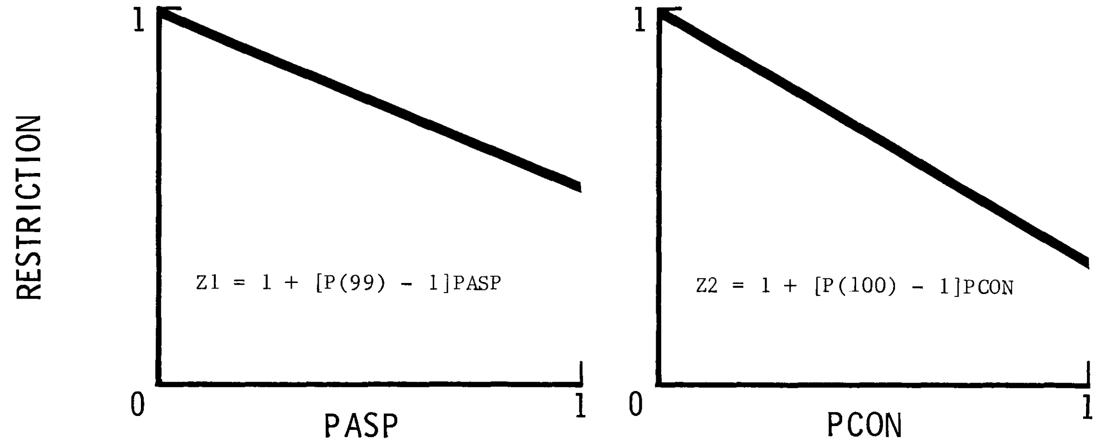


Figure 18.—Flow diagram depicting graduation of CON3.



FLOW 27 = CON3 * P(101) * Z1 * Z2

Figure 19.—Functions that inhibit the graduation of CON3.

The two flows into the conifer compartment from the source and the single flow out to the sink are shown in figure 20. The lower flow from the source is the conversion of CON3 graduation to biomass (code 41200–41600). The outflow is mortality (code 42900–43300), and the upper flow is in conifer growth (code 41700–42300), which is affected only by aspen and the conifer itself (fig. 21). The manner in which aspen affects conifer growth is quite critical and parameter 103, which gives the maximum restriction of aspen on conifer growth, is probably the one to which the model is most sensitive. Changing this curve can drastically alter the response of the system. The inhibition of CON on CON growth is designed, as in the case with aspen, to prevent an increase beyond maximum biomass in the CON compartment due to influx from CON3 graduation.

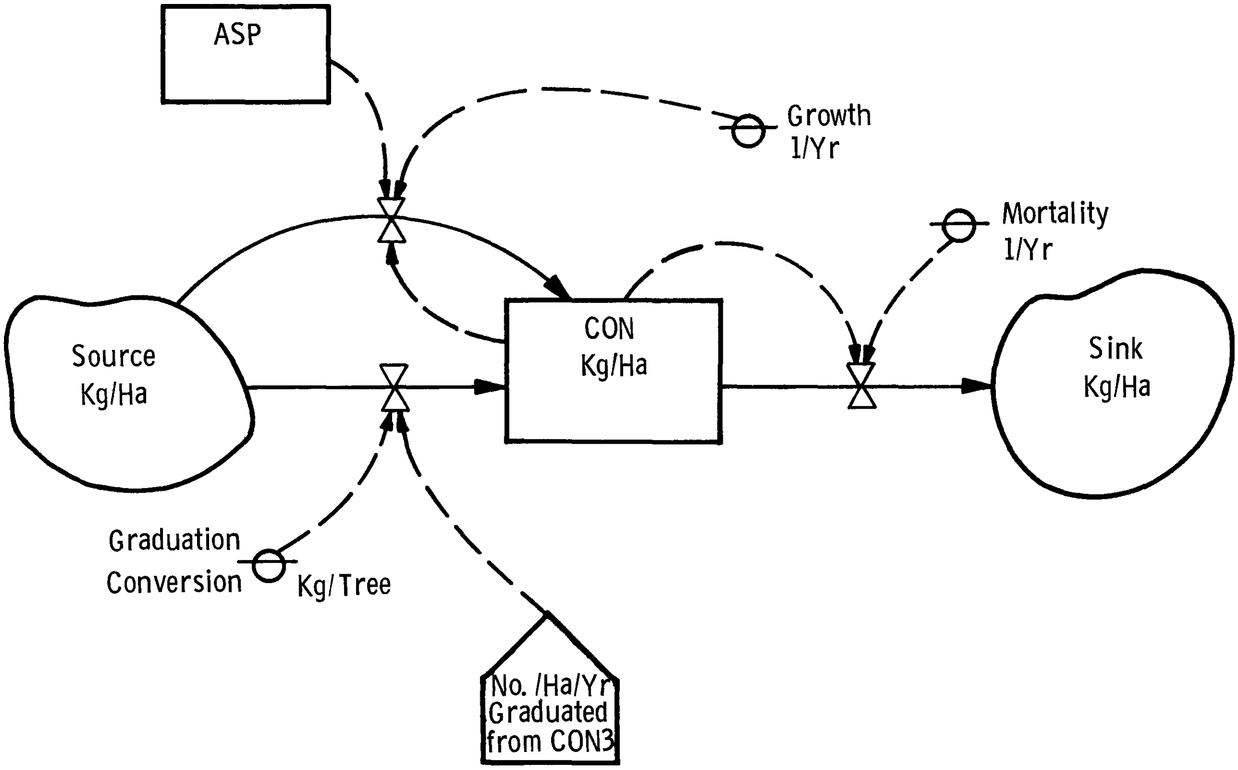
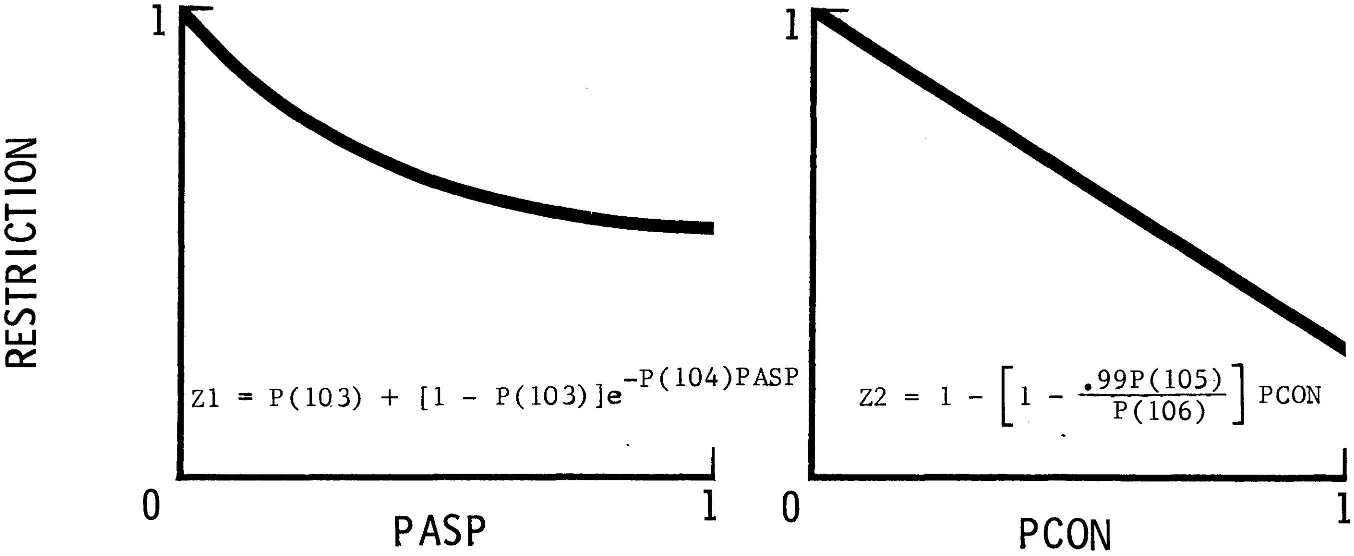


Figure 20.—Flow diagram depicting regeneration, growth, and mortality of conifer (CON).



FLOW 5 = CON * P(106) * Z1 * Z2

Figure 21.—Functions that inhibit the growth of conifer.

Production and mortality of annuals (code 43400–44700) are diagramed in figure 22. All other compartments affect production, but the conifer seedling effects are pooled into CONN and the aspen suckers act together with the shrubs. These restrictions are graphed in figure 23. Because the time step is 1 year, the relative mortality is 1. Sensitivity of the system to the various parameters in this portion of the program is very slight, and the herbs should probably not be subdivided into the two compartments.

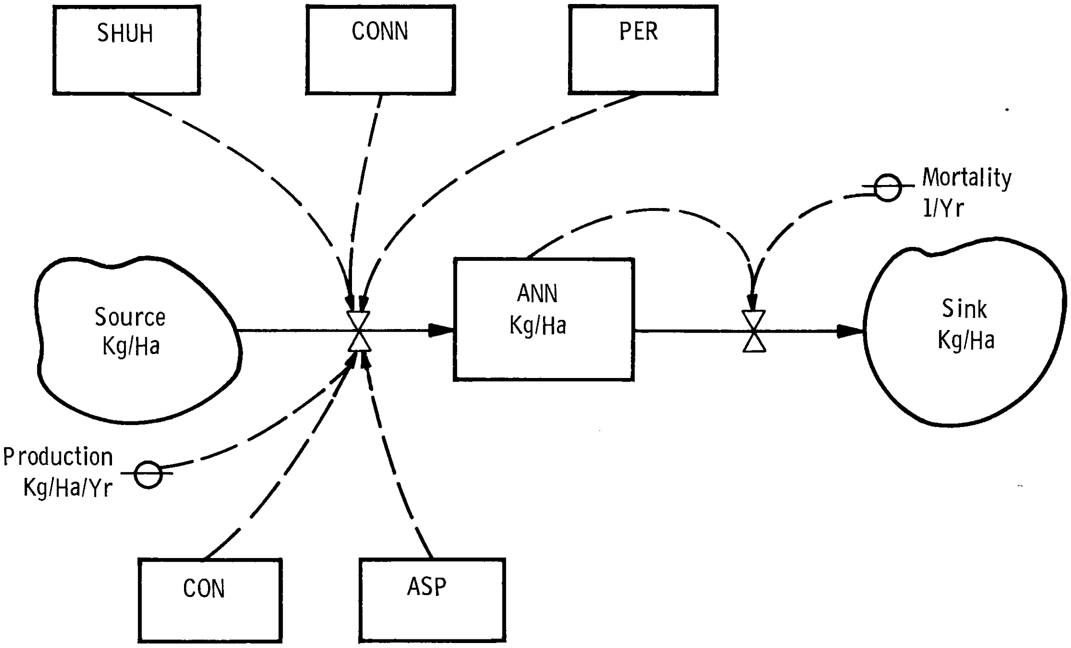
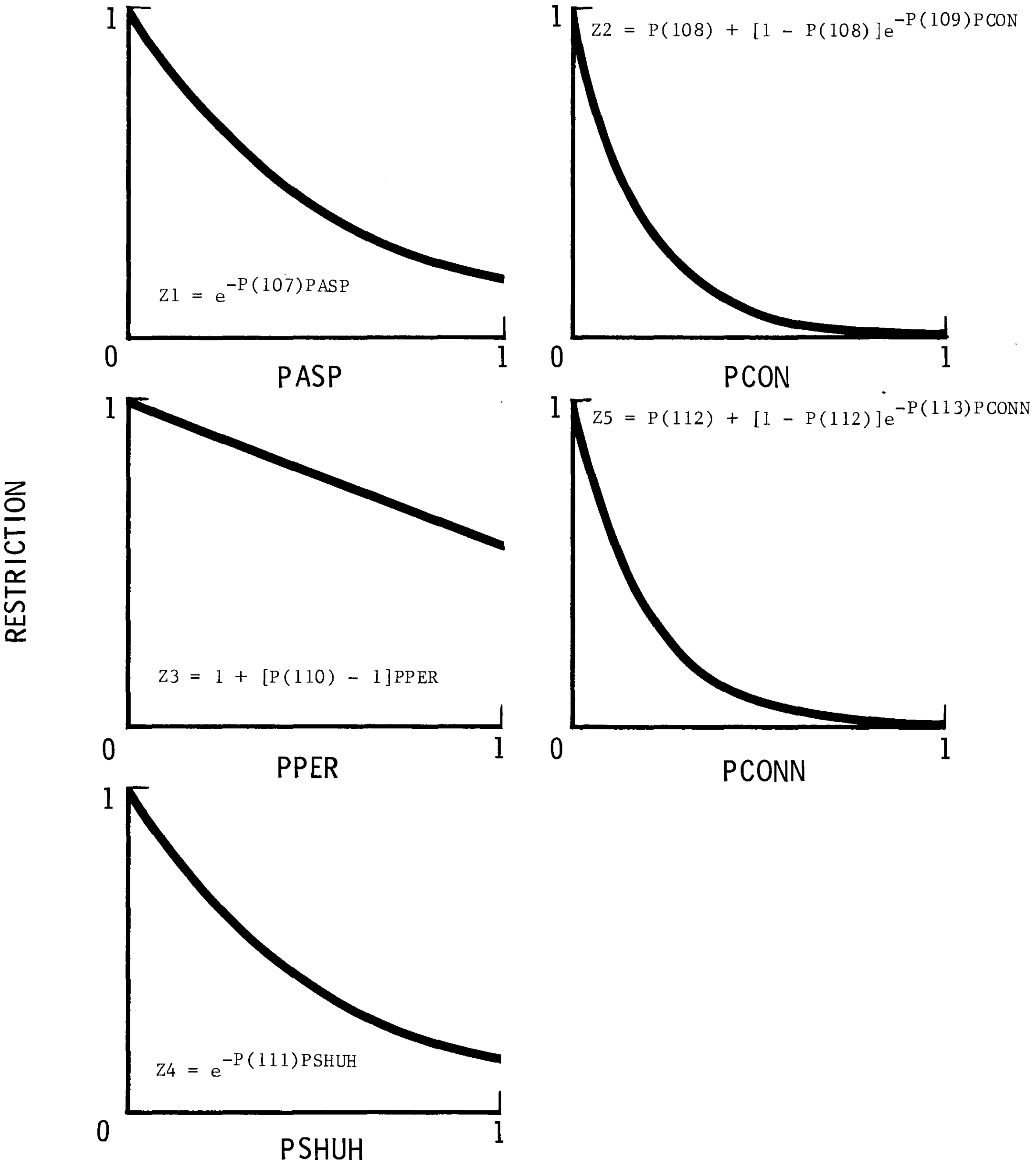


Figure 22.—Flow diagram depicting production and mortality of annuals.



FLOW 7 = P(114) * Z1 * Z2 * Z3 * Z4 * Z5

Figure 23.—Functions that inhibit the production of annual herbs.

Perennial production and mortality flows (code 44800–46100) are shown in figure 24. Since only the aboveground biomass is considered, mortality is considered to be 100 percent per annum. Restrictions on production are graphed in figure 25.

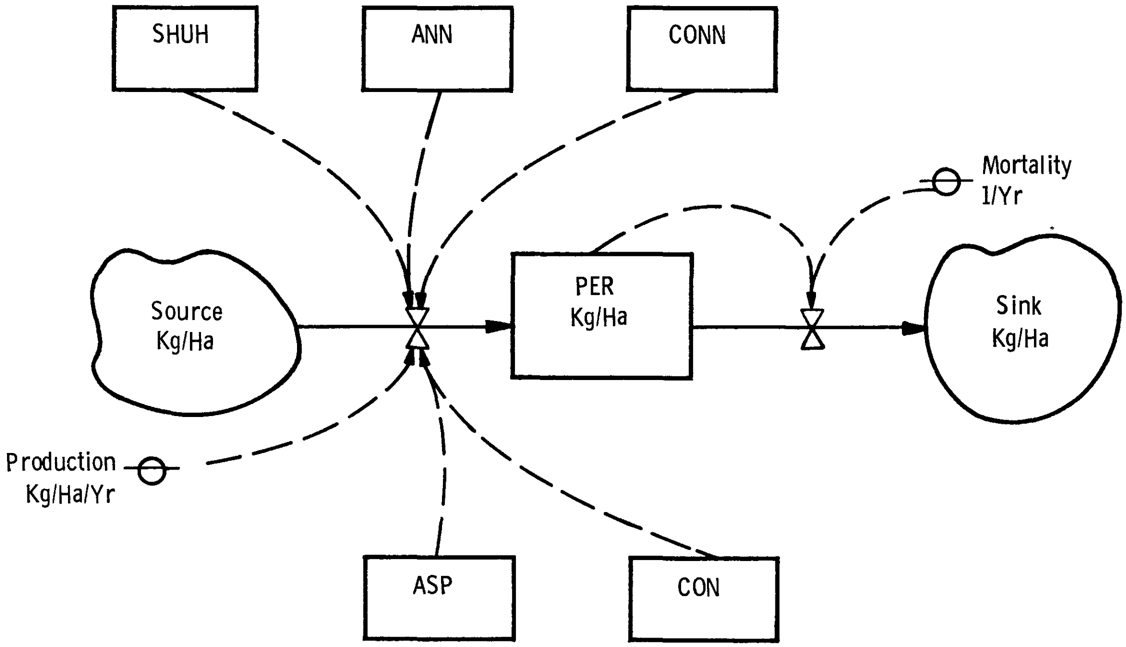
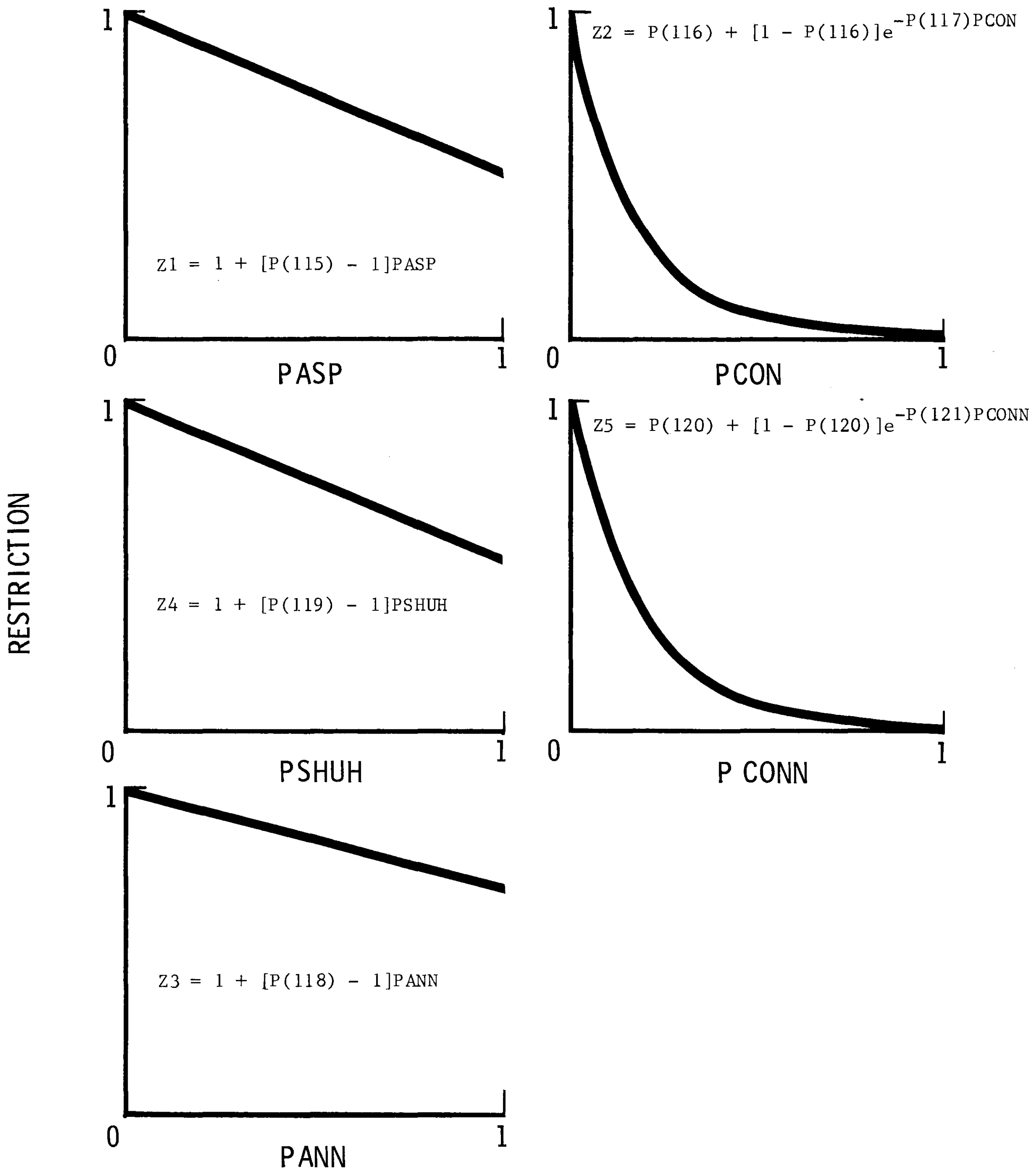


Figure 24.— Flow diagram depicting production and mortality of perennials.



FLOW 9 = P(122) * Z1 * Z2 * Z3 * Z4 * Z5

Figure 25.—Functions that inhibit the production of perennial herbs.

Regeneration, growth, and mortality (code 46200–48800) of shrubs are diagramed in figure 26 with restrictions shown in figures 27 and 28. Regeneration is on a biomass basis, rather than a numbers basis as it was for aspen and conifer reproduction. All compartments including the shrub compartment affect the regeneration rate. All compartments also inhibit the growth of shrubs, though effects of some are pooled. The restriction of shrubs on shrub growth is similar to that of aspen and conifer on their respective growths—net growth is blocked just prior to maximum possible biomass so that new input from regeneration will not raise the biomass beyond the maximum stated, as might happen if aspen and conifer were absent from the site.

After all the flows for one time step have been computed, time and the compartment values are updated (code 48900–53200). Thus, all values in one step are completely determined by the values in the preceding step, except that time may influence CON1 regeneration because a few years are required for seedlings to become established.

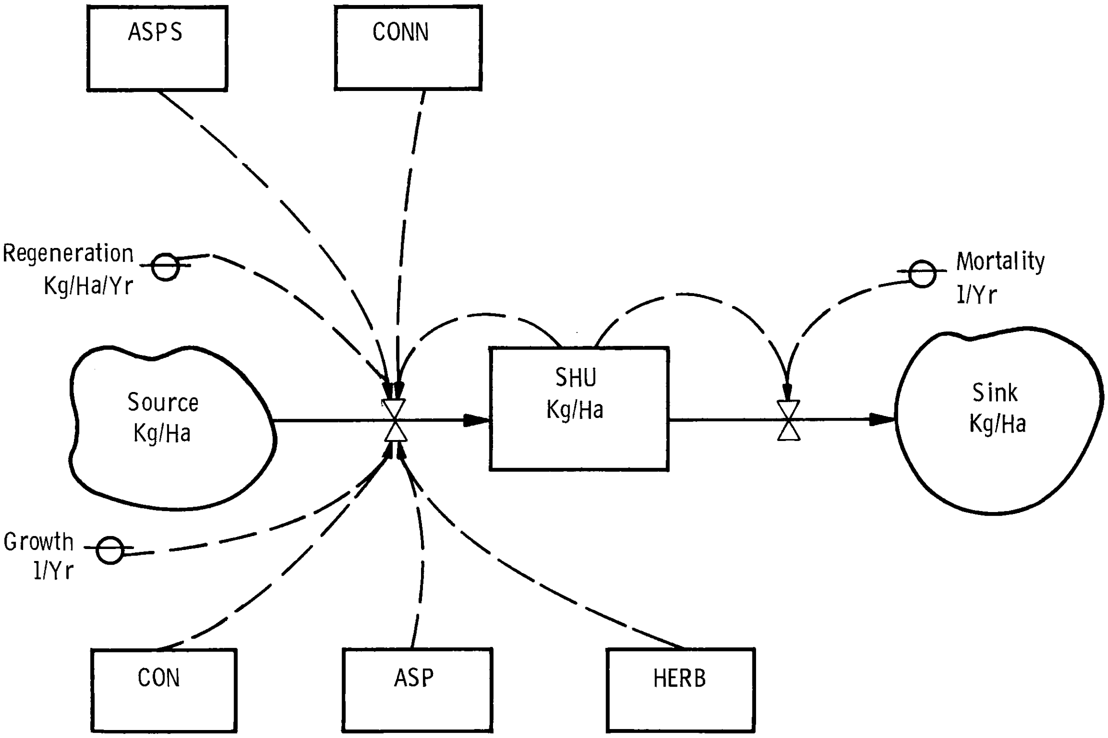
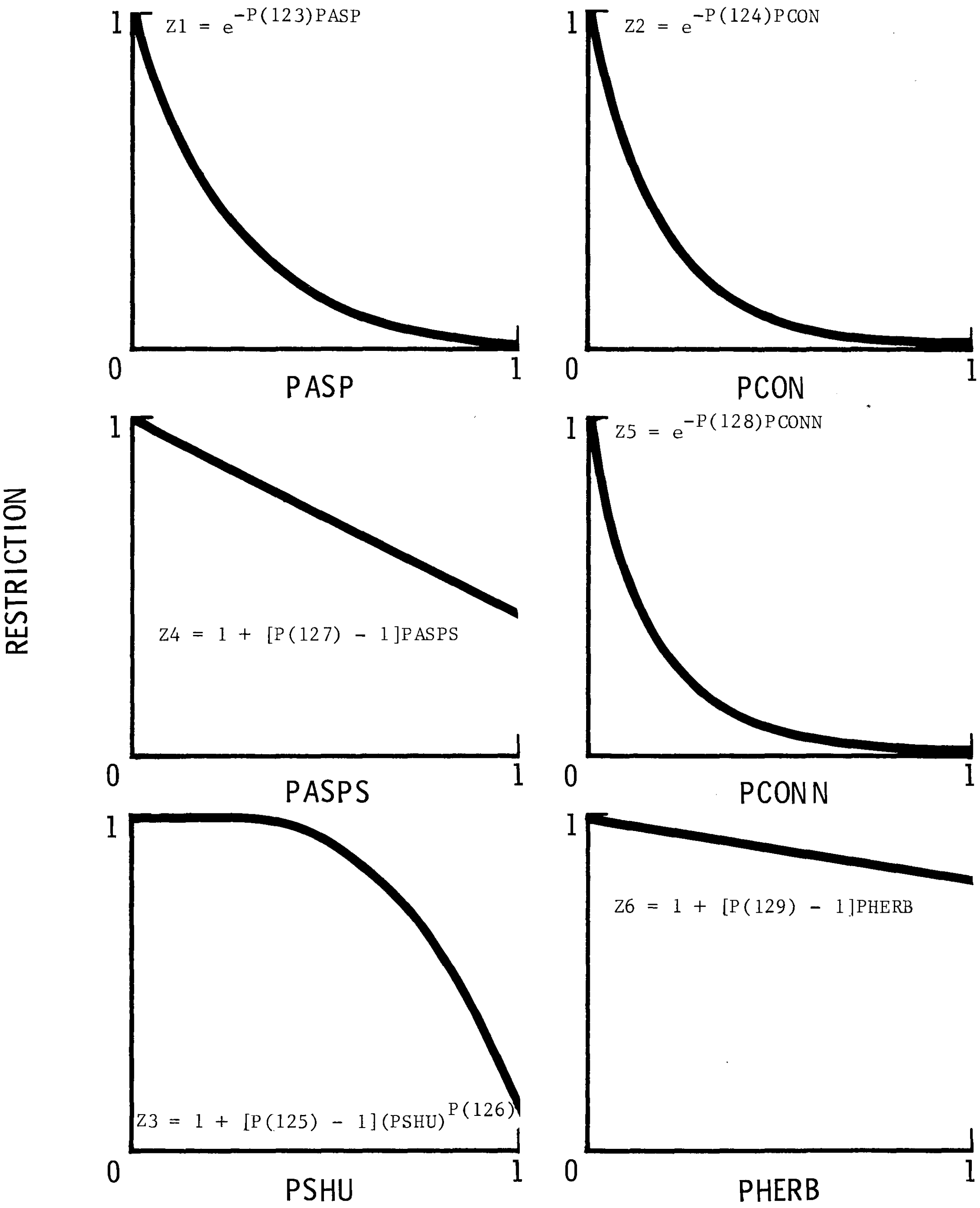
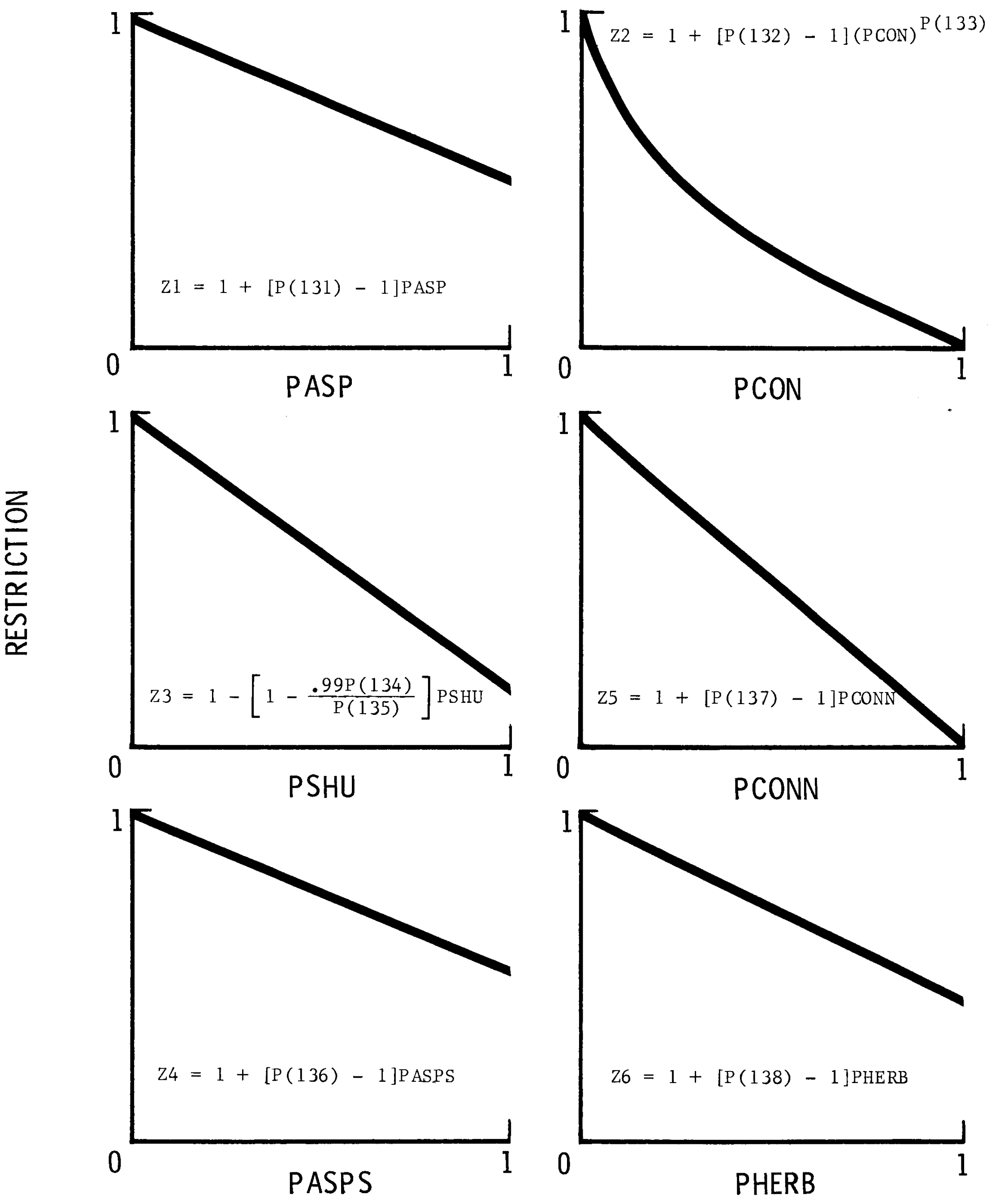


Figure 26.—Flow diagram depicting regeneration, growth, and mortality of shrubs.



FLOW 11 = P(130) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6

Figure 27.—Functions that inhibit the regeneration of shrubs.



FLOW 12 = SHU * P(135) * Z1 * Z2 * Z3 * Z4 * Z5 * Z6

Figure 28.—Functions that inhibit the growth of shrubs.

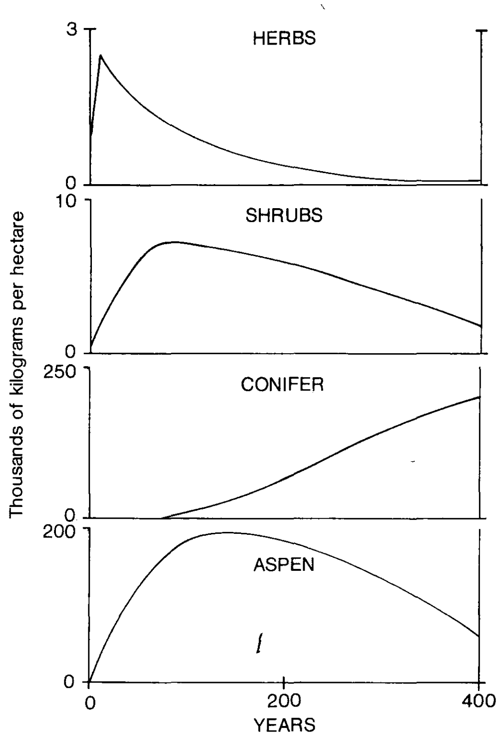


Figure 29a.—Biomass of four major system components graphed against time for "standard run" in which all parameters are at nominal levels.

MODEL RESULTS

The model results are quite realistic. Although no one has directly observed 400 years of succession in the Intermountain West, experts agree that the model output for a typical site fits their expectations developed from observations of a series of existing sites.

Results of the model for 400 years following a hot fire are shown in figure 29 (a, b, c). In this "standard run" it is assumed that maximum biomass possible for the major compartments is 200 000 kg/ha for aspen, 250 000 kg/ha for conifer, 10 000 kg/ha for shrubs, and 4 000 kg/ha for herbs. While peak aspen biomass (191 000 kg/ha) occurs in the 132d year, the aspen biomass exceeds 190 000 kg/ha for approximately 40 years. The conifers come in much more slowly and conifer biomass does not exceed aspen biomass until nearly 300 years after the disturbance. After 400 years the conifer biomass is 202 000 kg/ha and still increasing slightly. The shrubs peak in the 80th year with 7 050 kg/ha and herbs peak the eighth year with a biomass of 2 700 kg/ha. Graphs of biomass versus time for these major compartments are shown in figure 29a. Aspen suckers come in quite rapidly (fig. 29b), peaking within the first few years, but then they decline rapidly. The smallest size class (ASP1) is the most numerous. The number of conifer seedlings gradually increases to a peak value about 300 years following the disturbance and then decreases again, the small seedlings being more numerous (fig. 29c).

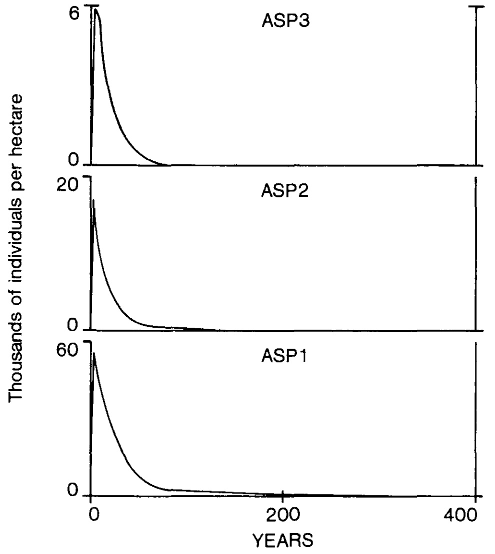


Figure 29b.—Density of three classes of aspen suckers graphed against time for "standard run" in which all parameters are at nominal levels.

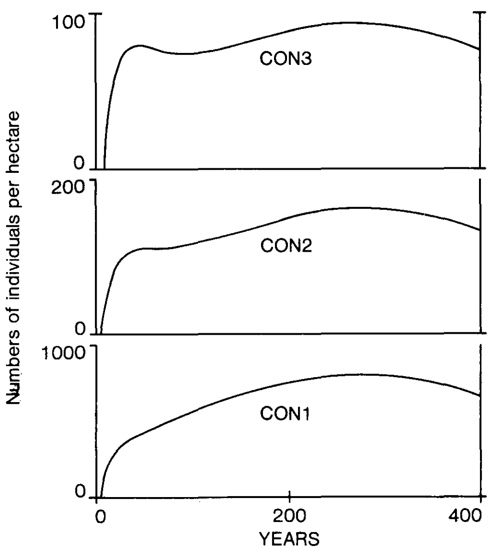


Figure 29c.—Density of three classes of conifer seedlings graphed against time for "standard run" in which all parameters are at nominal levels.

By changing the maximum rate at which conifer seedlings become established (parameter 79), from 1,000 to 10,000, an earlier dominance of conifers is obtained (fig. 30). This results in an earlier suppression of the other compartments and a shorter time period for conifers to approach maximum. Although such behavior may occur in the Intermountain area, it is probably more typical of aspen woodlands of the Upper Midwest.

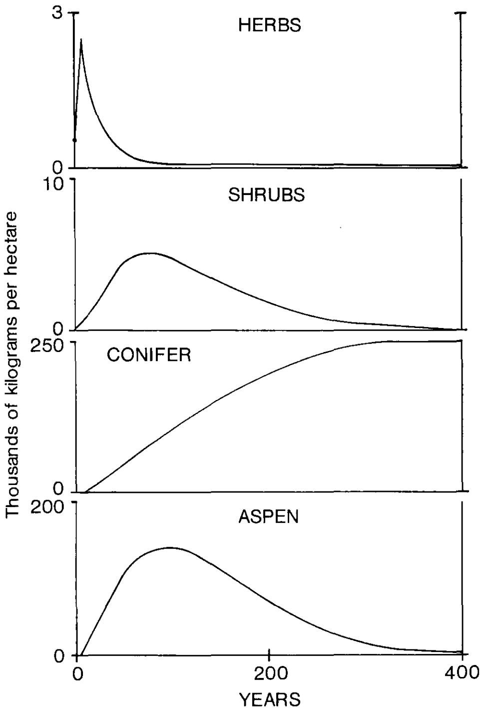


Figure 30.—Biomass of four major system components graphed against time for case simulating rapid regeneration of conifers.

If other disturbances are not allowed and if conifer seedlings do not become established (no seed source), the values in the other compartments remain much higher (fig. 31) throughout the simulation run.

In figure 32 an aspen harvest is simulated at 90 years in the successional process to favor conifer production on the site. Conifer growth is shown to be enhanced by that harvest; in just 270 years it attains the value achieved in 400 years in the "standard run," and after 400 years it is close to its maximum biomass. Immediately after the aspen harvest, the shrubs and herbs increase but are quickly suppressed again by the rapidly growing conifers. Aspen comes in again after the harvest but peaks at only 85 000 kg/ha and is almost eliminated by the 400th year. Aspen regeneration is stimulated by the harvest of aspen overstory, but establishment of conifer seedlings is suppressed (fig. 33). This situation brings up a controversial point in the model: the effect of aspen on conifer seedling regeneration. Foresters differ as to the influence of aspen on conifer regeneration, and it was decided to use a positive influence in this model. This positive effect on conifer regeneration is partially due to the ameliorating effects aspen has on soil surface temperatures (Sperger 1980). It is accomplished by having the aspen restriction on conifer regeneration **decrease** as aspen

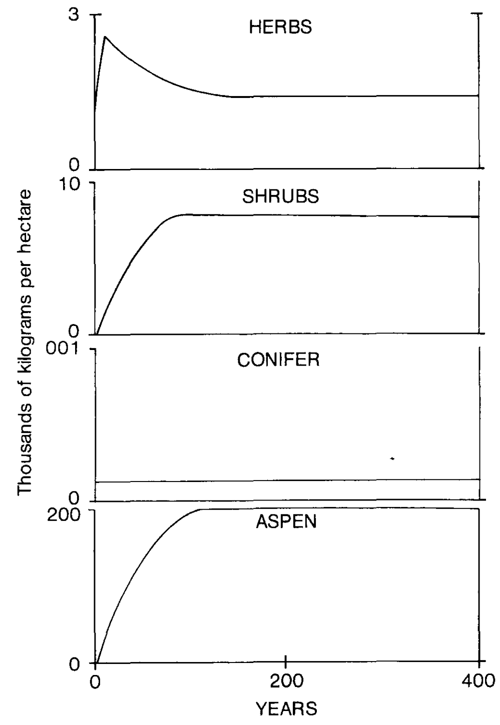


Figure 31.—Biomass of four major system components graphed against time for case in which there is no conifer regeneration.

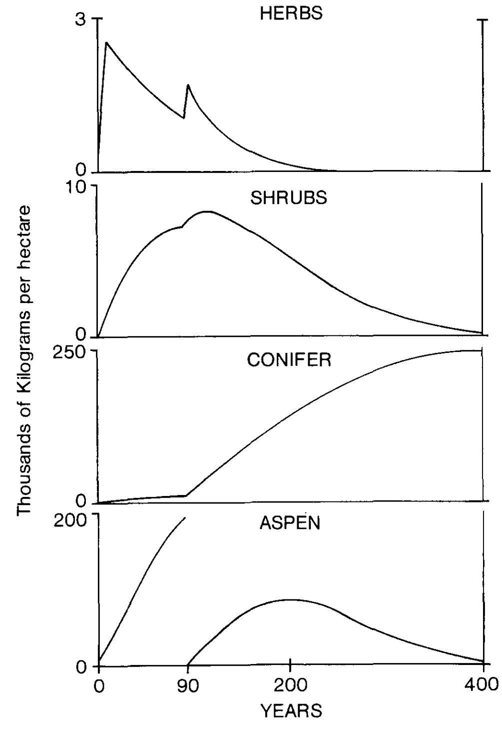


Figure 32.—Biomass of four major system components graphed against time for case in which aspen is harvested at 90 years.

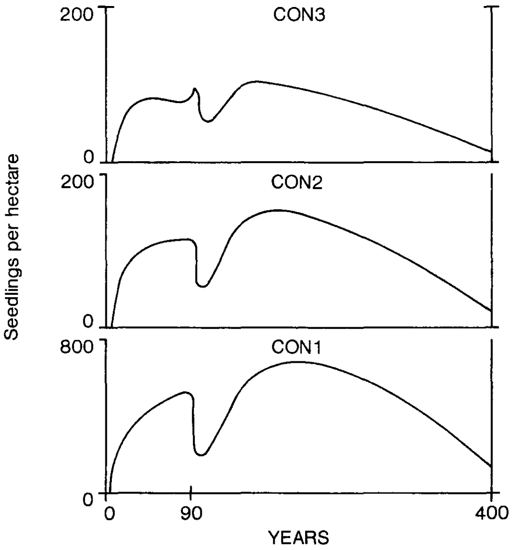


Figure 33.—Density of conifer seedlings in case where aspen overstory is harvested at 90 years.

biomass increases. Thus, harvest of the aspen overstory imposes a restriction on the regeneration of conifer. This influence merits further investigation. However, even if no influence of aspen on conifer regeneration is allowed, the conifer biomass in the 300th year is only 1.9 percent higher for the " standard run," while peak biomass for shrubs, aspen, and herbs changes very little.

A more typical clearcutting situation is shown in figure 34. Here all the overstory conifers and half the conifer seedlings are removed at 300 years. Also, half the mature aspen biomass is removed by harvesting. The next 300 years are very similar to the first 300 except that aspen peaks a little more quickly and at a somewhat higher value. One should bear in mind that this second peak does not represent the even-aged stand represented by the first peak.

The major shortcoming of the model is lack of confidence in the parameter values used. It is quite possible that widely differing sets of parameters can give very similar model results. On the other hand, slightly differing parameters can yield widely differing results. To demonstrate the degree of uncertainty in the model, 32 simulation runs (variations on the " standard run") were made. Parameters for the maximum production rates of annuals and perennials and for the maximum values of the aspen, conifer, shrub, annual, and perennial compartments were fixed for the "typical" site investigated and the initial value for number of conifers was held at zero. At the start of each of these 32 runs, each of the remaining 130 parameter values was picked at random from a uniform distribution over the range of values considered possible for that parameter (appendix C) and held for the duration of the run. Choice of parameters was not always completely random, however; checks were made to ascertain that the sum of relative flow rates from a compartment did not exceed 1 and that aspen growth rate never exceeded the conifer growth rate. The basic shapes of the resulting graphs were much the same in all cases. That is, if appropriately different scales were used for the 32 graphs of any major compartment, they would be quite similar in appearance. Some idea of the distribution of these 32 runs can be gained from figure 35, which shows for each point in time the minimum and maximum values of each of the four major compartments as well as the 25th, 50th, and 75th percentile values.

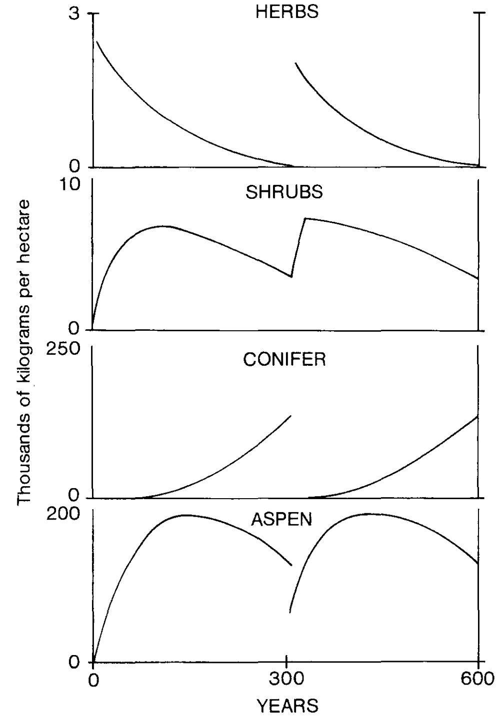


Figure 34.—Biomass of four major system components graphed against time for case in which conifer and aspen are harvested at 300 years.

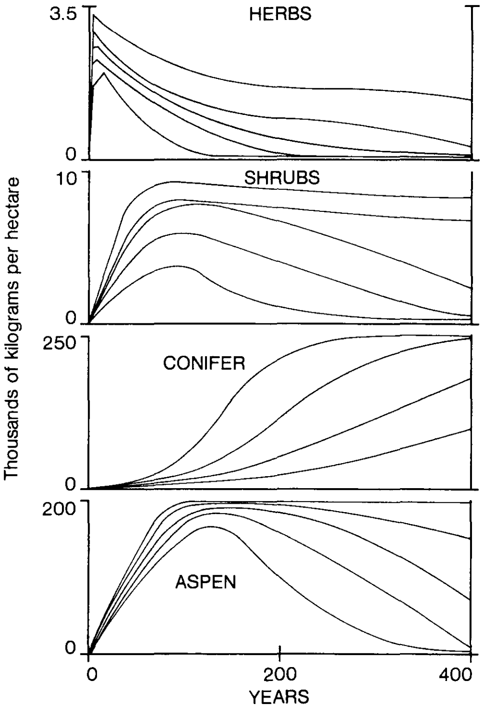


Figure 35.—Results from 32 computer runs with randomly varying parameters showing maximum, 75th percentile, 50th percentile, 25th percentile, and minimum values at each point in time.

Sensitivity Analysis

To test parameter sensitivity, the same 130 parameters mentioned in the preceding section were altered one at a time from the nominal value to the more remote end point in the range of possible values. Change in the peak value for each of the four major compartments was recorded, as was the change in time at which the peak occurred. This exercise showed that the model is fairly insensitive to changes in many of the parameters, indicating that the model may be overdetermined; however, it is still quite sensitive to changes in others. The change in time at which peaks occurred varied little, and the peak biomass of herbs also did not indicate much sensitivity except to the initial value of annuals. Parameters to which the peak values of aspen, conifers, and shrubs are most sensitive are those involving the growth and mortality rates of those compartments, the restriction of aspen on conifer growth, the restriction of conifers on aspen growth, and regeneration into or mortality from CON1. For instance, an increase in the annual growth rate of conifers from 7 percent to 7.5 percent reduces the peak value of aspen biomass by 0.7 percent and increases the peak conifer biomass by 19.7 percent. If the maximum restriction of aspen on conifer growth is lessened from 0.5 to 0.7, the peak aspen biomass is decreased 3.1 percent while the peak conifer biomass is increased 70.9 percent.

Further investigations of these relationships indicated that one could raise conifer growth rates from 7 percent to 8 percent, raise conifer mortality from 2 to 3 percent, lighten the restriction of aspen on conifer growth from 0.5 to 0.5625, and get almost no change at all in the model results! Therefore, the parameter values are not unique, but it appears that, so long as there is some method of bringing growth and mortality rates together, the conifer biomass will show appropriate sigmoidal growth.

Some two-way interactions were also tested. The three indicators chosen were peak aspen and peak shrub biomass in 400 years and conifer biomass at 300 years. Because graphs of a compartment's size are very similar if scales are adjusted appropriately, it was felt that maximum values would be good indicators. Because the peak of herbs is almost never affected, it was dropped as an indicator. Peak conifer biomass always occurred at 400 years and differences at that time could be slight while differences earlier were much greater; so biomass at 300 years was a more appropriate indicator for conifer biomass.

Of the 130 parameters allowed to vary it was found that 32 caused at least 1 of those 3 indicators to change from its nominal value by at least 2 percent (table 1). For these 32 parameters, all 496 paired interactions were evaluated. For I, I(A), I(B), and I(AB) (defined, respectively, as the values of the

Table 1.—Parameters (identified in appendix C) to which the ASPEN model is most sensitive, their nominal and perturbed values, and the effect of those perturbations on the three indicators

Parameter number	Nominal value	Perturbed value	Peak aspen % change	Conifer at 300 % change	Peak shrub % change
13	15000.	20000.	-0.3	2.8	-2.0
67	.03	.035	-1.9	4.7	2.0
70	1.2	1.4	1.2	-2.6	-.1
77	.2	.4	-.4	3.6	-.4
78	.001	.2	-.7	3.8	-.8
79	1000.	1250.	-.9	7.6	-.8
80	5.	10.	.4	-3.4	.7
81	.7	.9	.6	-7.0	.6
82	.5	.7	-.3	4.1	-.2
87	.7	.9	-.2	2.3	-.2
88	.7	.9	-.3	2.5	-.3
89	.3	.4	-.9	7.8	-.8
90	.45	.6	.6	-7.1	.6
91	.5	.7	-.3	3.8	-.2
97	.25	.4	-1.3	10.8	-1.2
98	.1	.15	.5	-6.0	.5
99	.5	.7	-.2	2.6	-.2
101	.2	.3	-.6	5.8	-.9
102	6.	7.	-.6	3.7	-.7
103	.5	.7	-3.1	70.9	-1.5
104	3.	4.	.4	-13.6	.3
105	.02	.025	1.0	-42.5	.6
106	.07	.075	.7	19.7	.4
115	.5	.7	.3	-2.9	-4.8
119	.5	.4	3.1	-3.1	-2.6
123	4.	6.	.0	.4	-2.3
130	100.	125.	.1	-.5	2.6
131	.5	.6	.0	-.8	8.3
133	.5	1.	.1	-1.5	10.6
134	.03	.04	-.1	1.9	-17.9
135	.2	.25	.2	-2.0	14.2
138	.4	.6	.1	-1.2	9.3

indicator with no parameters perturbed, only parameter A perturbed, only parameter B perturbed, and both A and B perturbed), the effect of the interaction of A with B is defined to be [I(AB) – I] – [I(A) – I] – [I(B) – I]. In only 24 of these 496 cases did effect of the interaction on an indicator exceed 2 percent of the nominal value of the indicator. In every case it was the 300-year biomass of the conifer that was changed by at least 2 percent. In 20 of the 24 cases the parameter giving the maximum restriction of aspen on conifer growth was involved. The other four cases involved growth or mortality of aspen or conifer. In none of the cases investigated did the effect of the interaction exceed the larger of the two main effects. Because parameters having the greatest effect on the indicators were investigated, it is likely that a similar result would have held if the other 5,000+ pairs had been checked. Thus, the strongest interactions affecting the selected indicators probably are the 24 listed in table 2.

The main effects and interactions previously mentioned involved altering just one or two parameters at a time. Another concept of effect involves a factorial design in which all combinations of parameters are perturbed and the average effect over all combinations of other factors is considered. (A discussion of factorial designs and fractional factorial designs can be found in Cochran and Cox, 1975.) A complete factorial design for 130 factors, or even 30 factors, would have been too expensive; however, a fractional factorial design for a set of 36 parameters, which included the 32 previously found to have the largest main effects, was possible. These were divided into six groups called macroparameters because each is treated as a unit in the factorial analysis. These macroparameters, named A, B, C, D, E, and F, contain six parameters each. Care was taken to separate closely related parameters into different macroparameters. Then a 0.5 replication of a 2**6 factorial design was done using ABCDEF as the defining contrast. The three indicators of interest were again the peak values of aspen and shrubs over 400 years and the value of conifer at 300 years. Contents of the macroparameters are shown in table 3. The ones perturbed in each repetition of the experiment and corresponding values of the three indicators are shown in table 4.

The effect of a factor on an indicator is defined to be 1/32 of the sum of all values of that indicator obtained from experiments in which an odd number of the macroparameters within that factor were perturbed, minus 1/32 of the sum of all values of the indicator obtained from experiments in which an even number of the macroparameters within that factor were perturbed. Each main effect has an alias with a 5-way interaction; each 2-way interaction has an alias with a 4-way interaction; and each 3-way interaction has an alias with another 3-way interaction. The various factors, their aliases, corresponding change, and percentage change in values of the three indicators are given in table 5. From this table one can observe that for all three indicators the effects of the 1-way (5-way) interactions are in general greater than the effects of the 2-way (4-way) interactions, which are in general larger than the effects of the 3-way interactions. This observation and intuition indicate that the larger effects are associated with the lower rather than the

Table 2.—Parameter pairs to which the system is most sensitive, their nominal and perturbed values, and the effect of each perturbation, due to the interaction, on the conifer biomass in the 300th year

Parameter number	Nominal value	Perturbed value	Parameter number	Nominal value	Perturbed value	Percent change in CON (300) due to interaction
13	15000.	20000.	103	0.5	0.7	-2.2
67	.03	.035	104	3.	4.	-2.2
67	.03	.035	105	.02	.025	-2.4
67	.03	.035	106	.07	.075	2.1
77	.2	.4	103	.5	.7	-2.7
78	.001	.2	103	.5	.7	-3.7
79	1000.	1250.	103	.5	.7	-5.6
80	5.	10.	103	.5	.7	2.1
81	.7	.9	103	.5	.7	5.1
82	.5	.7	103	.5	.7	-3.3
89	.3	.4	103	.5	.7	-5.8
90	.45	.6	103	.5	.7	5.2
91	.5	.7	103	.5	.7	-3.1
97	.25	.4	103	.5	.7	-8.1
98	.1	.15	103	.5	.7	4.5
99	.5	.7	103	.5	.7	-2.1
101	.2	.3	103	.5	.7	-4.3
102	6.	7.	103	.5	.7	-3.8
103	.5	.7	104	3.	4.	8.1
103	.5	.7	105	.02	.025	23.3
103	.5	.7	106	.07	.075	-14.5
103	.5	.7	119	.5	.7	2.1
103	.5	.7	115	.5	.7	2.1
104	3.	4.	105	.02	.025	3.8

higher order interactions. In other words this fractional factorial design serves to reinforce the previous results determining which parameters the system is most sensitive to without giving as much detail. The effect of a macroparameter corresponds roughly to the effects of its constituent parts but is not the mean of those separate effects.

Table 3.—Elements of a macroparameter used in the fractional factorial design

Macroparameter	Parameters					
A	36	68	97	104	115	135
B	70	80	82	98	130	134
C	13	67	77	88	99	123
D	58	78	89	101	106	133
E	32	79	90	102	103	131
F	71	81	91	105	119	138

Table 4.—Treatment combinations in the fractional factorial design and corresponding values of the three indicators

Treatment combinations	Peak aspen biomass	Conifer biomass at 300 years	Peak shrub biomass
none	191431.	136588.	7050.
AB	195503.	118820.	6928.
AC	187023.	143652.	7497.
AD	187145.	165280.	8307.
AE	185432.	230285.	8005.
AF	195483.	62685.	8181.
BC	189827.	147357.	5792.
BD	190058.	172190.	6975.
BE	188938.	230019.	6646.
BF	196333.	67952.	6944.
CD	172764.	211782.	7859.
CE	171980.	243178.	7198.
CF	189226.	92279.	7522.
DE	171926.	244791.	8316.
DF	189439.	121772.	8175.
EF	188281.	206687.	7974.
ABCD	184586.	175282.	7593.
ABCE	183182.	235315.	7121.
ABCF	194369.	80309.	7514.
ABDE	183155.	238680.	8150.
ABDF	194563.	105379.	8065.
ABEF	193766.	190216.	7968.
ACDE	158185.	247128.	8679.
ACDF	182953.	129373.	8621.
ACEF	181381.	215800.	8325.
ADEF	181111.	225440.	8884.
BCDE	167716.	246617.	7526.
BCDF	186895.	134833.	7472.
BCEF	185712.	214236.	7136.
BDEF	185898.	225754.	7990.
CDEF	162565.	243121.	8545.
ABCDEF	177484.	232844.	8444.

Table 5.—Factors, their aliases, and interactive effects on the three indicators as determined by the fractional factorial design

Defining contrast ABCDEF		Peak aspen biomass		Conifer biomass at 300 years		Peak shrub biomass	
Factor	Alias	Effect	% from nominal	Effect	% from nominal	Effect	% from nominal
A	BCDEF	1135.	0.6	-4458.	-3.3	286.	4.1
B	ACDEF	3177.	1.7	-3251.	-2.4	-340.	-4.8
C	ABDEF	-4457.	-2.3	7830.	5.7	-54.	-.8
D	ABCEF	-4419.	-2.3	15778.	11.6	369.	5.2
E	ABCDF	-5028.	-2.6	50143.	36.7	200.	2.8
F	ABCDE	2394.	1.3	-19946.	-14.6	254.	3.6
AB	CDEF	-183.	-.1	576.	.4	45.	.6
AC	BDEF	270.	.1	-148.	-.1	10.	.1
AD	BCEF	235.	.1	-633.	-.5	-44.	-.6
AE	BCDF	157.	.1	2040.	1.5	-21.	-.3
AF	BCDE	-88.	0.	422.	.3	-21.	-.3
BC	ADEF	804.	.4	-469.	-.3	-13.	-.2
BD	ACEF	840.	.4	-318.	-.2	17.	.2
BE	ACDF	885.	.5	579.	.4	31.	.4
BF	ACDE	-391.	-.2	399.	.3	46.	.7
CD	ABEF	-1178.	-.6	-224.	-.2	46.	.7
CE	ABDF	-1187.	-.6	-2432.	-1.8	-6.	-.1
CF	ABDE	439.	.2	727.	.5	16.	.2
DE	ABCF	-1245.	-.7	-7113.	-5.2	16.	.2
DF	ABCE	442.	.2	2244.	1.6	-79.	-1.1
EF	ABCD	461.	.2	9827.	7.2	-27.	-.4
ABC	DEF	-38.	0.	1618.	1.2	2.	0.
ABD	CEF	-34.	0.	1113.	.8	-2.	0.
ABE	CDF	56.	0.	-604.	-.4	-12.	-.2
ABF	CDE	-196.	-.1	-793.	-.6	-4.	-.1
ACD	BEF	19.	0.	-1227.	-.9	-11.	-.2
ACE	BDF	-30.	0.	558.	.4	-5.	-.1
ACF	BDE	157.	.1	917.	.7	3.	0.
ADE	BCF	-48.	0.	1027.	.8	1.	0.
ADF	BCE	132.	.1	614.	.4	7.	.1
AEF	BCD	206.	.1	-1190.	-.9	3.	0.

Use of the Program

To run the program ASPEN one must specify from which device to read the data and on which device to print the results. Appendix A contains a listing of the program as it is run with a card deck at Utah State University (USU) and the input device, file 5, is specified as the card reader while the output device on file 6 is specified as the printer (code 200–300).

A brief flow chart of the program is given in figure 36. It does not describe the flow equations in detail because they are handled in the section on model structure.

The first information required from the data file concerns time. The values of DT, TEND, STEP, and PSTSZ are read and then printed as part of the program output (code 9300–9900). DT is the step size of the difference equations. Although it is a parameter, it was always used as 1 year in our work at USU. While it is conceivable that one might want to increase step size to save computation, some of the parameters would need to be altered to compensate. For instance, a growth rate of 8 percent per year is not quite the same as a growth rate of 16 percent over 2 years, and the difference can be pronounced after 400 years. The length of the run in years is TEND; the number of years between printout of state variables is STEP; and PSTSZ specifies the number of years between points on the graphical output. The graphing subroutines (code 56000–65200) allow for only 101 points (including the point at time 0) plotted across the page; so PSTSZ must be an integer no smaller than the quotient TEND divided by 100. In a run of 100 years or fewer, each year's values can be graphed, but for a run of 400 years, no more than every fourth year can be graphed (PSTSZ = 400/100 = 4 or larger). The printed output is fairly voluminous, and printing every year's values can be expensive. A sample output is shown in appendix B.

Immediately following the time information are the 138 parameter values. The program reads these values and prints them with the other output (code 10000–11000). Parameter values are read in free format, five to the line. The last two values, P(139) = P(140) = 0, are simply space fillers. It is not easy to find a particular value from the listing, but it is possible if it is remembered that the four values on the first line are for time and that the parameter values follow in order, five to the line.

Time is always initiated at zero by the program. If the program is stopped and restarted again at a later year, the later year does not show up in the output; time is reinitiated to zero. The time delay for conifer seedling establishment, parameter 80, tells how many years into the run to delay. For example if the run is stopped for some reason and restarted at 100 years and if a 5-year time delay on conifer seedling establishment is desired, parameter 80 should be set at 5, not 105.

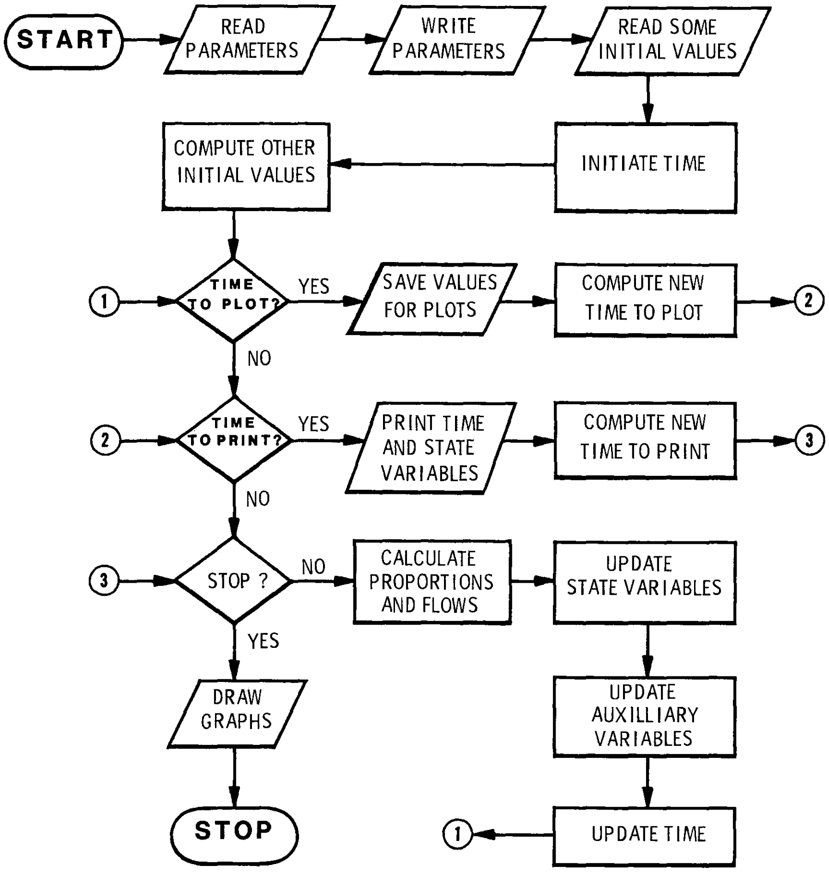


Figure 36.—A brief flow chart of the program ASPEN.

CONCLUSIONS

For trajectory analysis of orbiting satellites, a flat-earth theory is woefully inadequate, but for consideration of baseball trajectories at a ball park, that theory is quite adequate. Similarly, the succession model presented in this paper, while certainly incomplete, might help a land manager identify the successional stage of a forest and determine how its composition might change in the future.

The model yields believable results for the forest system simulated, whether that forest was undisturbed or subjected to various manipulations. It could be of some aid in making forest management decisions if managers bear in mind that the model is a partial truth and not the whole truth.

The distressing shortcoming of the model is that good estimates do not exist for most of the parameters used. Many parameter values were chosen from a range which scientists in our project estimated to include the actual value. To some of these parameters the model is quite sensitive, giving vastly different simulation results depending on which value in that range is chosen. One should not rely on the model as a predictor until closer estimates of these parameters are obtained.

Sensitivity analysis has also shown that the model is quite insensitive to many parameter estimates, indicating that a simplification effort might substantially reduce the model complexity while keeping the essential features. We have also isolated those parameters (growth and mortality rates of aspen and conifer and the restrictive effect of aspen on conifer growth) that have the most drastic effects on the model output. Further research in these areas would be most valuable to our understanding of the system and would lend confidence to the model as a predictive tool.

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APPENDIX A

Program Listing for ASPEN

```
? USER 950012001/SONJA
? CLASS 60
? COMPILE ASPEN FORTRAN LIBRARY
? DATA
 $ RESET FREE
FILE  5(KIND=READER)
FILE  6(KIND=PRINTER)
C.....   PROGRAM ASPEN
C.....THIS FORTRAN PROGRAM WAS REVISED FROM AN EARLIER SIMCOMP
C.....3.0 VERSION WHICH WAS RUN AT CSU.  IT WAS INITIALLY
C.....WRITTEN BY BARTOS AND JAMESON IN 1972 AND REVISED IN
C.....JANUARY 1977 BY BARTOS WITH THE AID OF INNIS TO RUN
C.....ON THE BURROUGHS SYSTEM AT USU.
C.....SUBSTANTIAL MODIFICATIONS WERE MADE IN 1980-81 BY BARTOS
C.....AND WARD.
C.....
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....
C.....       THE FOLLOWING DATA CARDS ARE NEEDED TO RUN THIS PROGRAM.
C.....       ALL ARE DONE IN FREE FORMAT.
C.....
C.....     1 = DT, TEND, STEP, PSTSZ
C.....  2-29 = VARIOUS PARAMETERS (5 PER CARD)
C.....
C.....
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....
C.....       LIST OF STATE VARIABLES
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....            ASP  = ASPEN BIOMASS      KG/HEC
C.....            CON  = CONIFER BIOMASS      KG/HEC
C.....            ANN  = ANNUAL BIOMASS      KG/HEC
C.....            PER  = PERENNIAL BIOMASS      KG/HEC
C.....            SHU  = SHRUB BIOMASS      KG/HEC
C.....          BIOSOR = BIOMASS LEFT IN SOURCE     KG/HEC
C.....          BIOSIN = BIOMASS GONE TO SINK         KG/HEC
C.....            ASP1 = ASPEN SUCKERS LESS THAN .5 M TALL      #/HEC
C.....            ASP2 = ASPEN SUCKERS .5 M - 2 M TALL        #/HEC
C.....            ASP3 = ASPEN SUCKERS OVER 2 M TALL BUT
C.....                   LESS THAN 5.08 CM DBH              #/HEC
C.....          SUCSOR = ASPEN SUCKERS LEFT IN SOURCE     #/HEC
C.....          SUCSIN = ASPEN SUCKERS GONE TO SINK       #/HEC
C.....            CON1 = CONIFER SEEDLINGS LESS THAN .5 M TALL      #/HEC
C.....            CON2 = CONIFER SEEDLINGS .5 M TO 2 M TALL     #/HEC
C.....            CON3 = CONIFER SEEDLINGS OVER 2 M TALL BUT
C.....                   LESS THAN 5.08 CM DBH              #/HEC
C.....          SEESOR = CONIFER SEEDLINGS LEFT IN SOURCE   #/HEC
C.....          SEESIN = CONIFER SEEDLINGS GONE TO SINK     #/HEC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....
C.....        LIST OF AUXILIARY VARIABLES
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....           NOCON = NUMBER TREES IN CON      #/HEC
C.....            AWPC = AVERAGE MASS OF CONIFERS    KG/TREE
C.....                   CON/NOCON    OR -1 IF NOCON=0
C.....            HERB = PERENNIALS + ANNUALS      KG/HEC
C.....            ASPS = MASS OF ASPEN SUCKERS     KG/HEC
C.....            SHUH = MASS OF SHRUBS & ASPEN SUCKERS     KG/HEC
```

APPENDIX A (cont.)

```
C.....             SUC = TOTAL ASPEN SUCKERS      #/HEC
C.....            SEED = TOTAL CONIFER SEEDLINGS  #/HEC
C.....            CONN = MASS OF CONIFER SEEDLINGS   KG/HEC
C.....          BIOSUM = SUM OF BIOMASS STATE VARIABLES
C.....                       (SHOULD BE ZERO)     KG/HEC
C.....          SUCSUM = SUM OF ASPEN SUCKER STATE VARIABLES
C.....                       (SHOULD BE ZERO)     #/HEC
C.....          SEESUM = SUM OF CONIFER SEEDLING STATE VARIABLES
C.....                       (SHOULD BE ZERO)     #/HEC
C.....        AN M PRECEDING THE VARIABLE NAME REPRESENTS
C.....          THE MAXIMUM POSSIBLE VALUE OF THAT VARIABLE.
C.....
C.....        A P PRECEDING THE VARIABLE NAME REPRESENTS THE
C.....          PROPORTION THAT VARIABLE IS OF ITS MAXIMUM
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....
C.....          LIST OF TIME VARIABLES
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....            TIME = ELAPSED TIME             YEARS
C.....              DT = COMPUTATION STEPSIZE     YEARS
C.....            TEND = TIME AT WHICH RUN ENDS   YEARS
C.....            TTPR = TIME OF PRINTOUT         YEARS
C.....            STEP = TIME BETWEEN PRINTOUTS   YEARS
C.....            TTPL = TIME OF PLOT POINT       YEARS
C.....           PSTSZ = TIME BETWEEN PLOT POINTS YEARS
C.....            INDX = NUMBER OF STORED VALUE FOR PLOT
C.....         T(INDX) = TIME OF STORED VALUE FOR PLOT      YEARS
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
      REAL NOCON,MHERB,MASP,MCON,MSHU,MCON1,MCON2,MCON3
      REAL MASP1,MASP2,MASP3,MCONN,MASPS,MSHUH,MANN,MPER
      DIMENSION P(140),T(101),Y1(2,101),Y2(2,101),Y3(2,101)
      DIMENSION Y4(3,101),Y5(3,101)
C.....
C.....     READ IN AND WRITE OUT TIME INFORMATION
C.....
      READ(5,/) DT,TEND,STEP,PSTSZ
      WRITE(6,31)DT,TEND,STEP,PSTSZ
   31 FORMAT(1H0,' DT = ',F5.1,5X,' TEND = ',F5.1,5X,' STEP = ',F5.1,
     /5X,'PSTSZ = ',I3)
C.....
C.....     READ IN AND WRITE OUT PARAMETERS FOR FLOW EQUATIONS
C.....
      DO 1114 M=1,140,5
 1114 READ(5,/)(P(M+MM),MM=0,4)
      WRITE(6,1005)
 1005 FORMAT('0')
      DO 1010 I = 1,140,5
      WRITE(6,1020)I,P(I),I+1,P(I+1),I+2,P(I+2),I+3,P(I+3),I+4,P(I+4)
 1010 CONTINUE
 1020 FORMAT(' ',5(2X,'P('I3') = 'F13.6))
C.....
C.....     ASSIGN AND WRITE OUT MAXIMUM VALUES OF STATE VARIABLES
C.....
      MASP = P(1)
      MCON = P(2)
      MSHU = P(3)
      MPER = P(4)
      MANN = P(5)
      MASP1 = P(6)
```

```
      MASP2 = P(7)
      MASP3 = P(8)
      MCON1 = P(9)
      MCON2 = P(10)
      MCON3 = P(11)
      MASPS = P(12)
      MSHUH = P(13)
      MCONN = P(14)
      MHERB = MANN + MPER
      WRITE(6,32)MASP,MCON,MHERB,MSHU,MCONN,MSHUH
   32 FORMAT(1H0,' MASP =',F10.2,2X,' MCON =',F10.2,2X,
     /'MHERB =',F10.2,2X,' MSHU =',F10.2,2X,'MCONN =',F10.2,
     /2X,'MSHUH =',F10.2)
      WRITE(6,33)MASP1,MASP2,MASP3,MCON1,MCON2,MCON3
   33 FORMAT(1H ,'MASP1 =',F10.2,2X,'MASP2 ='F10.2,2X,'MASP3 =',
     /F10.2,2X,'MCON1 ='F10.2,2X,'MCON2 =',F10.2,2X,'MCON3 =',F10.2)
      WRITE(6,34)MASPS,MPER,MANN
   34 FORMAT(1H ,'MASPS =',F10.2,2X,' MPER =',F10.2,2X,' MANN =',F10.2)
C.....
C.....      SET TIME AND COUNT TO 0.0
C.....
      TIME = 0.0
      TTPR = 0.0
      TTPL = 0.0
C.....
C.....      ASSIGN THE INITIAL VALUES OF THE STATE VARIABLES
C.....
      ASP = P(15)
      CON = P(16)
      SHU = P(17)
      PER = P(18)
      ANN = P(19)
      ASP1 = P(20)
      ASP2 = P(21)
      ASP3 = P(22)
      CON1 = P(23)
      CON2 = P(24)
      CON3 = P(25)
      NOCON = P(26)
C.....
C.....      UPDATE CORRESPONDING VALUES OF OTHER VARIABLES
C.....
      HERB = ANN + PER
      SUC  = ASP1+ASP2+ASP3
      SEED = CON1+CON2+CON3
      ASPS = P(27)*ASP1 + P(28)*ASP2 + P(29)*ASP3
      SHUH = SHU + ASPS
      CONN = P(30)*CON1 + P(31)*CON2 + P(32)*CON3
      BIOSOR = -ASP - CON - ANN - PER - SHU
      BIOSIN = 0.0
      SUCSOR = -ASP1 - ASP2 - ASP3
      SUCSIN = 0.0
      SEESOR = -CON1 - CON2 - CON3
      SEESIN = 0.0
      BIOSUM = BIOSOR + ASP + CON + ANN + PER + SHU + BIOSIN
      SUCSUM = SUCSOR + ASP1 + ASP2 + ASP3 + SUCSIN
      SEESUM = SEESOR + CON1 + CON2 + CON3 + SEESIN
      IF (NOCON.GT.0.0) GO TO 77
      AWPC = -1
      GO TO 78
   77 AWPC = CON/NOCON
```

```
   78 CONTINUE
C.....
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....
C.....     MAIN LOOP OF PROGRAM STARTS  HERE
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....     CHECK IF TIME TO STORE VALUES FOR PLOT
C.....
  250 IF(TIME.LT.TTPL) GO TO 35
      INDX = TIME/PSTSZ + 1
      T(INDX) = TIME
      Y1(1,INDX) = ASP
      Y1(2,INDX) = CON
      Y2(1,INDX) = ANN
      Y2(2,INDX) = PER
      Y3(1,INDX) = HERB
      Y3(2,INDX) = SHU
      Y4(1,INDX) = ASP1
      Y4(2,INDX) = ASP2
      Y4(3,INDX) = ASP3
      Y5(1,INDX) = CON1
      Y5(2,INDX) = CON2
      Y5(3,INDX) = CON3
C.....
C.....     UPDATE TTPL FOR NEXT PLOT TIME
C.....
      TTPL = TTPL + PSTSZ
C.....
C.....     CHECK IF TIME TO PRINT
C.....
   35 IF (TIME.LT.TTPR)GO TO 300
C.....
C.....     WRITE OUT VARIOUS VARIABLES AND TIME
C.....
      WRITE(6,500)TIME
  500 FORMAT(1H0,10X,'TIME',F7.2)
      WRITE(6,501)ASP,CON,SHU
  501 FORMAT(1H0,'    ASP =',F20.6,5X,'   CON =',F20.6,5X,
     /'    SHU =',F20.6)
      WRITE(6,502)ANN,PER,HERB
  502 FORMAT(1H ,'    ANN =',F20.6,5X,'   PER =',F20.6,5X,
     /'  HERB ='F20.6)
      WRITE(6,507)ASP1,ASP2,ASP3
  507 FORMAT(1H ,'  ASP1 ='F20.6,5X,'  ASP2 =',F20.6,5X,
     /'  ASP3 =',F20.6)
      WRITE(6,508)CON1,CON2,CON3
  508 FORMAT(1H ,'  CON1 =',F20.6,5X,'  CON2 =',F20.6,5X,
     /'  CON3 =',F20.6)
      WRITE(6,509)NOCON,SUC,SEED
  509 FORMAT(1H ,' NOCON ='F20.6,5X,'   SUC =',F20.6,5X,
     /'  SEED =',F20.6)
      WRITE(6,510)BIOSUM,SUCSUM,SEESUM
  510 FORMAT(1H ,'BIOSUM ='F20.6,5X,'SUCSUM =',F20.6,5X,
     /'SEESUM =',F20.6)
      WRITE(6,511)AWPC
  511 FORMAT(1H ,'  AWPC =',F20.6)
C.....
C.....     UPDATE TTPR FOR NEXT PRINT TIME
C.....
```

```
      TTPR = TTPR + STEP
C...
C.....     CHECK IF TIME TO STOP RUN
C.....
  300 IF(TEND.LE.TIME) GO TO 45
C.....
C.....     CALCULATE PROPORTIONS TO PUT ON A RELATIVE BASIS,
      PSHUH = SHUH/MSHUH
      IF(PSHUH.GT.1.)PSHUH = 1.
      PASPS = ASPS/MASPS
      IF(PASPS.GT.1.)PASPS=1.
      PHERB = HERB/MHERB
      IF(PHERB.GT.1.)PHERB=1.
      PASP = ASP/MASP
      IF(PASP.GT.1.)PASP=1.
      PCON = CON/MCON
      IF(PCON.GT.1.)PCON=1.
      PSHU = SHU/MSHU
      IF(PSHU.GT.1.)PSHU=1.
      PASP1 = ASP1/MASP1
      IF(PASP1.GT.1.)PASP1=1.
      PASP2 = ASP2/MASP2
      IF(PASP2.GT.1.)PASP2=1.
      PASP3 = ASP3/MASP3
      IF(PASP3.GT.1.)PASP3=1.
      PCON1 = CON1/MCON1
      IF(PCON1.GT.1.)PCON1=1.
      PCON2 = CON2/MCON2
      IF(PCON2.GT.1.)PCON2=1.
      PCON3 = CON3/MCON3
      IF(PCON3.GT.1.)PCON3=1.
      PCONN = CONN/MCONN
      IF (PCONN.GT.1.)PCONN=1.
      PPER = PER/MPER
      IF(PPER.GT.1.)PPER=1.
      PANN = ANN/MANN
      IF(PANN.GT.1.)PANN=1.
C.....      CALCULATE THE VARIOUS FLOWS
C.....
C.....      COMPUTE FLOW 14    ASP1 REGENERATION
C.....      AFFECTED BY ASP, CON, SHU, ASP1, ASP2, ASP3, CONN
C.....
      Z1=EXP(-P(33)*PASP)
      Z2=EXP(-P(34)*PCON)
      Z3=1.+(P(35)-1.)*PSHU
      Z4=1.+(P(36)-1.)*PASP1
      Z5=1.+(P(37)-1.)*PASP2
      Z6=1.+(P(38)-1.)*PASP3
      Z7=EXP(-P(39)*PCONN)
      FLOW14 = P(40)*Z1*Z2*Z3*Z4*Z5*Z6*Z7
C.....
C.....     COMPUTE FLOW 15     ASP1 MORTALITY
C.....     AFFECTED BY ASP1
C.....
      FLOW15 = ASP1*P(41)
C.....
C.....      COMPUTE FLOW16    ASP1 GRADUATION
C.....      AFFECTED BY ASP,CON,SHU,ASP1,ASP2,ASP3,CONN,HERB
C.....
      Z1=P(42)+(1.-P(42))*EXP(-P(43)*PASP)
      Z2=EXP(-P(44)*PCON)
```

```
      Z3=1.+(P(45)-1.)*PSHU                                             00030200
      Z4=1.+(P(46)-1.)*PASP2                                            00030300
      Z5=1.+(P(47)-1.)*PASP3**P(48)                                     00030400
      Z6=EXP(-P(49)*PCONN)                                              00030500
      Z7=1.+(P(50)-1.)*PHERB                                            00030600
      FLOW16 = ASP1*P(51)*Z1*Z2*Z3*Z4*Z5*Z6*Z7                          00030700
C.....                                                                  00030800
C.....      COMPUTE FLOW17    ASP2 MORTALITY                            00030900
C.....      AFFECTED BY ASP2                                            00031000
C.....                                                                  00031100
      FLOW17 = ASP2*P(52)                                               00031200
C......                                                                 00031300
C.....      COMPUTE FLOW18    ASP2 GRADUATION                           00031400
C.....      AFFECTED BY ASP, CON, SHU, ASP2, ASP3, CONN                 00031500
C.....                                                                  00031600
      Z1=P(53)+(1.-P(53))*EXP(-P(54)*PASP)                              00031700
      Z2=EXP(-P(55)*PCON)                                               00031800
      Z3=1.+(P(56)-1.)*PSHU                                             00031900
      Z4=1.+(P(57)-1.)*PASP3                                            00032000
      Z5=EXP(-P(58)*PCONN)                                              00032100
      FLOW18 = ASP2*P(59)*Z1*Z2*Z3*Z4*Z5                                00032200
C.....                                                                  00032300
C.....      COMPUTE FLOW19     ASP3 MORTALITY                           00032400
C.....      AFFECTED BY ASP3                                            00032500
C.....                                                                  00032600
      FLOW19 = ASP3*P(60)                                               00032700
C.....                                                                  00032800
C.....      COMPUTE FLOW20     ASP3 GRADUATION                          00032900
C.....      AFFECTED BY ASP, CON, SHU, ASP3                             00033000
C.....                                                                  00033100
      Z1=P(61)+(1.-P(61))*EXP(-P(62)*PASP)                              00033200
      Z2=EXP(-P(63)*PCON)                                               00033300
      Z3=1.+(P(64)-1.)*PSHU                                             00033400
      FLOW20 = ASP3*P(65)*Z1*Z2*Z3                                      00033500
C.....                                                                  00033600
C.....      COMPUTE FLOW1    ASP3 GRADUATION CONVERSION                 00033700
C.....                      (ASP GENERATION)                            00033800
C.....                                                                  00033900
      FLOW1 = FLOW20*P(66)                                              00034000
C.....                                                                  00034100
C.....      COMPUTE FLOW2     ASP GROWTH                                00034200
C.....      AFFECTED BY ASP, CON                                        00034300
C.....                                                                  00034400
      Z1=1.-(1.-P(67)*.99/P(68))*PASP                                   00034500
      Z2=1.+(P(69)-1.)*PCON**P(70)                                      00034600
      FLOW2 = ASP*P(68)*Z1*Z2                                           00034700
C.....                                                                  00034800
C.....      COMPUTE FLOW3     ASP MORTALITY                             00034900
C.....      AFFECTED BY ASP                                             00035000
C.....                                                                  00035100
      FLOW3 = ASP*P(67)                                                 00035200
C.....                                                                  00035300
C.....      COMMMPUTE FLOW21     CON1 REGENERATION                      00035400
C.....      AFFECTED BY ASP, CON, CON2, CON3, SHUH,HERB                 00035500
C.....                                                                  00035600
      Z1=P(71)+(1.-P(71))/P(72)*PASP                                    00035700
      IF (Z1.GT.1.) Z1=1.                                               00035800
      Z2=1.+(P(73)-1.)*PCON**P(74)                                      00035900
      Z3=1.+(P(75)-1.)*PCON2                                            00036000
      Z4=1.+(P(76)-1.)*PCON3                                            00036100
      Z5=1.+(P(77)-1.)*PSHUH                                            00036200
```

```
      Z6=1.+(P(78)-1.)*PHERB
      FLOW21 = P(79)*Z1*Z2*Z3*Z4*Z5*Z6
C.....
C.....     P(80) YEAR TIME DELAY IN CONIFER REPRODUCTION
C.....
      IF (TIME.LE.P(80)) FLOW21=0.
C.....
C.....      COMPUTE FLOW22     CON1 MORTALITY
C.....      AFFECTED BY CON1
C.....
      FLOW22 = CON1*P(81)
C.....
C.....      COMPUTE FLOW23     CON1 GRADUATION
C.....      AFFECTED BY ASP, CON,CON1,CON2,CON3,SHUH,HERB
C.....
      Z1=1.+(P(82)-1.)*PASP
      Z2=1.+(P(83)-1.)*PCON
      Z3=1.+(P(84)-1.)*PCON2**P(85)
      Z4=1.+(P(86)-1.)*PCON3
      Z5=1.+(P(87)-1.)*PSHUH
      Z6=1.+(P(88)-1.)*PHERB
      FLOW23 = CON1*P(89)*Z1*Z2*Z3*Z4*Z5*Z6
C.....
C.....     COMPUTE FLOW24     CON2 MORTALITY
C.....     AFFECTED BY CON2
C.....
      FLOW24 = CON2*P(90)
C.....
C.....      COMPUTE FLOW25   CON2 GRADUATION
C.....      AFFECTED BY ASP,CON,CON2,CON3,
C.....
      Z1=1.+(P(91)-1.)*PASP
      Z2=1.+(P(92)-1.)*PCON
      Z3=1.+(P(93)-1.)*PCON2**P(94)
      Z4=1.+(P(95)-1.)*PCON3**P(96)
      FLOW25 = CON2*P(97)*Z1*Z2*Z3*Z4
C.....
C.....      COMPUTE FLOW26     CON3 MORTALITY
C.....      AFFECTED BY CON3
C.....
      FLOW26 = CON3*P(98)
C.....
C.....      COMPUTE FLOW27     CON3 GRADUATION (NOCON GENERATION)
C.....      AFFECTED BY ASP, CON, CON3
C.....
      Z1=1.+(P(99)-1.)*PASP
      Z2=1.+(P(100)-1.)*PCON
      FLOW27 = CON3*P(101)*Z1*Z2
C.....
C.....     COMPUTE FLOW4     CON3 GRADUATION CONVERSION
C.....                       (CON GENERATION)
C.....
      FLOW4 = FLOW27*P(102)
C.....
C.....     COMPUTE FLOWS5     CON GROWTH
C.....     AFFECTED BY ASP, CON
C.....
      Z1=P(103)+(1.-P(103))*EXP(-P(104)*PASP)
      Z2=1.-(1.-P(105)*.99/P(106))*PCON
      FLOW5 = CON*P(106)*Z1*Z2
C.....
```

```
C.....      COMPUTE FLOW30       NOCON MORTALITY
C.....     AFFECTED BY  NOCON
C.....
      FLOW30 = NOCON*P(105)
C.....
C.....      COMPUTE FLOW6      CON MORTALITY
C.....     AFFECTED BY CON
C.....
      FLOW6 = CON*P(105)
C.....
C.....      COMPUTE FLOW7      ANN PRODUCTION
C.....     AFFECTED BY ASP, CON, PER, SHUH,CONN
C.....
      Z1 = EXP(-P(107)*PASP)
      Z2 = P(108)+(1.-P(108))*EXP(-P(109)*PCON)
      Z3 = 1.+(P(110)-1.)*PPER
      Z4 = EXP(-P(111)*PSHUH)
      Z5 = P(112)+(1.-P(112))*EXP(-P(113)*PCONN)
      FLOW7 = P(114)*Z1*Z2*Z3*Z4*Z5
C.....
C.....     ANNUAL MORTALITY ASSUMED TO BE 100% EACH YEAR
C.....
      FLOW8 = ANN/DT
C.....
C.....     COMPUTE FLOW9      PER PRODUCTION
C.....     AFFECTED BY ASP, CON, ANN, SHUH, CONN
C.....
      Z1 = 1.+(P(115)-1.)*PASP
      Z2 = P(116)+(1.-P(116))*EXP(-P(117)*PCON)
      Z3 = 1.+(P(118)-1.)*PANN
      Z4 = 1.+(P(119)-1.)*PSHUH
      Z5 = P(120)+(1.-P(120))*EXP(-P(121)*PCONN)
      FLOW9 = P(122)*Z1*Z2*Z3*Z4*Z5
C.....
C.....     PER MORTALITY (ABOVE GROUND) ASSUMED TO BE 100% EACH YEAR
C.....
      FLOW10 = PER/DT
C.....
C.....     COMPUTE FLOW11      SHU REGENERATION
C.....     AFFECTED BY ASP,CON,SHU, ASPS, CONN,HERB
C.....
      Z1=EXP(-P(123)*PASP)
      Z2=EXP(-P(124)*PCON)
      Z3 = 1.+(P(125)-1.)*PSHU**P(126)
      Z4 = 1.+(P(127)-1.)*PASPS
      Z5 = EXP(-P(128)*PCONN)
      Z6 = 1.+(P(129)-1.)*PHERB
      FLOW11 = P(130)*Z1*Z2*Z3*Z4*Z5*Z6
C.....
C.....     COMPUTE FLOW12      SHU GROWTH
C.....     AFFECTED BY ASP, CON, SHU, ASPS, CONN, HERB
C.....
      Z1 = 1.+(P(131)-1.)*PASP
      Z2 = 1.+(P(132)-1.)*PCON**P(133)
      Z3 = 1.-(1.-P(134)*.99/P(135))*PSHU
      Z4 = 1.+(P(136)-1.)*PASPS
      Z5 = 1.+(P(137)-1.)*PCONN
      Z6 = 1.+(P(138)-1.)*PHERB
      FLOW12 = SHU*P(135)*Z1*Z2*Z3*Z4*Z5*Z6
C.....
C.....     COMPUTE FLOW13      SHU MORTALITY
```

```
C.....     AFFECTED BY SHU
C.....
      FLOW13 = SHU*P(134)
C.....
C.....     UPDATE STATE VARIABLES
C.....
      ASP = ASP + DT * (FLOW1 + FLOW2 - FLOW3)
      CON = CON + DT * (FLOW4 + FLOW5 - FLOW6)
      ANN = ANN + DT * (FLOW7 - FLOW8)
      PER = PER + DT * (FLOW9 - FLOW10)
      SHU = SHU + DT * (FLOW11 + FLOW12 - FLOW13)
      BIOSOR = BIOSOR + DT * (-FLOW1-FLOW2-FLOW4-FLOW5-
     1FLOW7-FLOW9-FLOW11-FLOW12)
      BIOSIN = BIOSIN + DT * (FLOW3+FLOW6+FLOW8+FLOW10+FLOW13)
      ASP1 = ASP1 + DT * (FLOW14 - FLOW15 - FLOW16)
      ASP2 = ASP2 + DT * (FLOW16 - FLOW17 - FLOW18)
      ASP3 = ASP3 + DT * (FLOW18 - FLOW19 - FLOW20)
      SUCSOR = SUCSOR + DT * (-FLOW14)
      SUCSIN = SUCSIN + DT * (FLOW15+FLOW17+FLOW19+FLOW20)
      CON1 = CON1 + DT * (FLOW21 - FLOW22 - FLOW23)
      CON2 = CON2 + DT * (FLOW23 - FLOW24 - FLOW25)
      CON3 = CON3 + DT * (FLOW25 - FLOW26 - FLOW27)
      SEESOR = SEESOR + DT * (-FLOW21)
      SEESIN = SEESIN + DT * (FLOW22+FLOW24+FLOW26+FLOW27)
C.....
C.....      UPDATE VARIOUS AUXILIARY VARIABLES
C.....
      HERB = ANN + PER
      ASPS = P(27)*ASP1 + P(28)*ASP2 + P(29)*ASP3
      SHUH = SHU + ASPS
      CONN = P(30)*CON1 + P(31)*CON2 + P(32)*CON3
      NOCON = NOCON + DT * (FLOW27 -FLOW30)
      SUC = ASP1 + ASP2 + ASP3
      SEED = CON1 + CON2 + CON3
      BIOSUM = BIOSOR + ASP + CON + ANN + PER + SHU + BIOSIN
      SUCSUM = SUCSOR + ASP1 + ASP2 + ASP3 + SUCSIN
      SEESUM = SEESOR + CON1 + CON2 + CON3 + SEESIN
      IF(NOCON.GT.0.0) GO TO 240
      AWPC=.1.
      GO TO 242
  240 AWPC=CON/NOCON
  242 CONTINUE
C.....
C.....     UPDATE TIME
C.....
 249  TIME  = TIME  + DT
C.....
      GO TO 250
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....      MAIN LOOP OF PROGRAM ENDS HERE
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....      DRAW GRAPHS OF SELECTED STATE VARIABLES
C.....
   45 WRITE(6,512)
  512 FORMAT(1H1,30X,'1 = ASP      2 = CON',/)
      CALL PLOTS(2,INDX,T,Y1)
      WRITE(6,513)
  513 FORMAT(1H1,30X,'1 = ANN      2 = PER',/)
      CALL PLOTS(2,INDX,T,Y2)
      WRITE(6,514)
```

```
 514 FORMAT(1H1,30X,'1 = HERB      2 = SHU',/)
     CALL PLOTS(2,INDX,T,Y3)
     WRITE(6,515)
 515 FORMAT(1H1,30X,'1 = ASP1      2 = ASP2      3 = ASP3',/)
     CALL PLOTS(3,INDX,T,Y4)
     WRITE(6,516)
 516 FORMAT(1H1,30X,'1 = CON1      2 = CON2      3 = CON3',/)
     CALL PLOTS(3,INDX,T,Y5)
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....     END OF MAIN PROGRAM
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C.....
C.....
C.....     GRAPHING SUBROUTINES
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
     SUBROUTINE PLOTS(NPLOTS,NPTS,X,Y)
     COMMON/IO/NI,NO
     DIMENSION X(NPTS),Y(NPLOTS,NPTS),XSCL(101),YSCL(52),ILINE(101)
     NI = 5
     NO = 6
     XMIN=X(1)
     XMAX=X(1)
     DO 1 I=1,NPTS
     IF(X(I).GT.XMAX)XMAX=X(I)
1    IF(X(I).LT.XMIN)XMIN=X(I)
     YMIN=Y(1,1)
     YMAX=Y(1,1)
     DO 2 I=1,NPLOTS
     DO 2 J=1,NPTS
     IF(Y(I,J).LT.YMIN)YMIN=Y(I,J)
2    IF(Y(I,J).GT.YMAX)YMAX=Y(I,J)
7    SCALX=(XMAX-XMIN)/100.
     SCALY=(YMAX-YMIN)/50.
     DO 3 I=1,101
     XSCL(I)=XMIN+FLOAT(I-1)*SCALX
     IF(I.GT.52)GO TO 3
     YSCL(I)=YMAX-FLOAT(I-1)*SCALY
3    CONTINUE
C.....
     CALL GZRO(0,ILINE)
C.....
     DO 5 K=1,51
     CALL GZRO(K,ILINE)
     CALL SKPT(NPLOTS,NPTS,K,X,Y,YSCL,XMIN,SCALX,ILINE)
5    CALL TYPIT(K,YSCL,ILINE)
     CALL GZRO(0,ILINE)
     WRITE(NO,6)(XSCL(I),I=1,101,20)
6    FORMAT(17X,F7.2,5(13X,F7.2))
     RETURN
     END
C.....
     SUBROUTINE SKPT(NPLOTS,NPTS,K,X,Y,YSCL,XMIN,SCALX,ILINE)
C.....
     DIMENSION X(NPTS),Y(NPLOTS,NPTS),ILINE(1),YSCL(1),ISYM(11)
     DATA ISYM/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9,1H0,1HC/
     DATA IBLK/1H /
     DO 1 I=1,NPLOTS
     DO 1 J=1,NPTS
     IF(Y(I,J).GT.YSCL(K))GO TO 1
     IF(Y(I,J).LE.YSCL(K+1))GO TO 1
```

```
      M=INT((X(J)-XMIN)/SCALX+1.5)                                      00060700
      IF(M.LT.1)GO TO 1                                                 00060800
      IF(M.GT.101)GO TO 1                                               00060900
      IF(ILINE(M).EQ.IBLK)GO TO 2                                       00061000
      ILINE(M)=ISYM(11)                                                 00061100
      GO TO 1                                                           00061200
2     ILINE(M)=ISYM(I)                                                  00061300
1     CONTINUE                                                          00061400
      RETURN                                                            00061500
      END                                                               00061600
C.....                                                                  00061700
      SUBROUTINE TYPIT(K,YSCL,ILINE)                                    00061800
C.....                                                                  00061900
      COMMON/IO/NI,NO                                                   00062000
      DIMENSION YSCL(1),ILINE(1)                                        00062100
      JS=K+4                                                            00062200
      IF((JS-JS/5*5).NE.0)GO TO 1                                       00062300
      WRITE(NO,6) YSCL(K)                                               00062400
    6 FORMAT(10X,E10.3,2H +)                                            00062500
      WRITE(NO,2)(ILINE(I),I=1,101)                                     00062600
2     FORMAT(1H+,20X,101A1,2X,2H+I)                                     00062700
      GO TO 3                                                           00062800
    1 WRITE(NO,5)                                                       00062900
    5 FORMAT(21X,1H-)                                                   00063000
      WRITE(NO,4)(ILINE(I),I=1,101)                                     00063100
4     FORMAT(1H+,20X,101A1,2X,2H-I)                                     00063200
3     RETURN                                                            00063300
      END                                                               00063400
C.....                                                                  00063500
      SUBROUTINE GZRO(K,ILINE)                                          00063600
C.....                                                                  00063700
      COMMON/IO/NI,NO                                                   00063800
      DIMENSION ILINE(1)                                                00063900
      DATA IPER,IN,IBLK/1H.,1H1,1H /                                    00064000
      IF(K.EQ.0)GO TO 2                                                 00064100
      DO 1 I=1,101                                                      00064200
1     ILINE(I)=IBLK                                                     00064300
      RETURN                                                            00064400
2     DO 3 I=1,101                                                      00064500
3     ILINE(I)=IPER                                                     00064600
      DO 4 I=1,101,10                                                   00064700
4     ILINE(I)=IN                                                       00064800
      WRITE(NO,5)(ILINE(I),I=1,101)                                     00064900
5     FORMAT(19X,2H..,101A1,2H..)                                       00065000
      RETURN                                                            00065100
      END                                                               00065200
```

APPENDIX A (cont.)

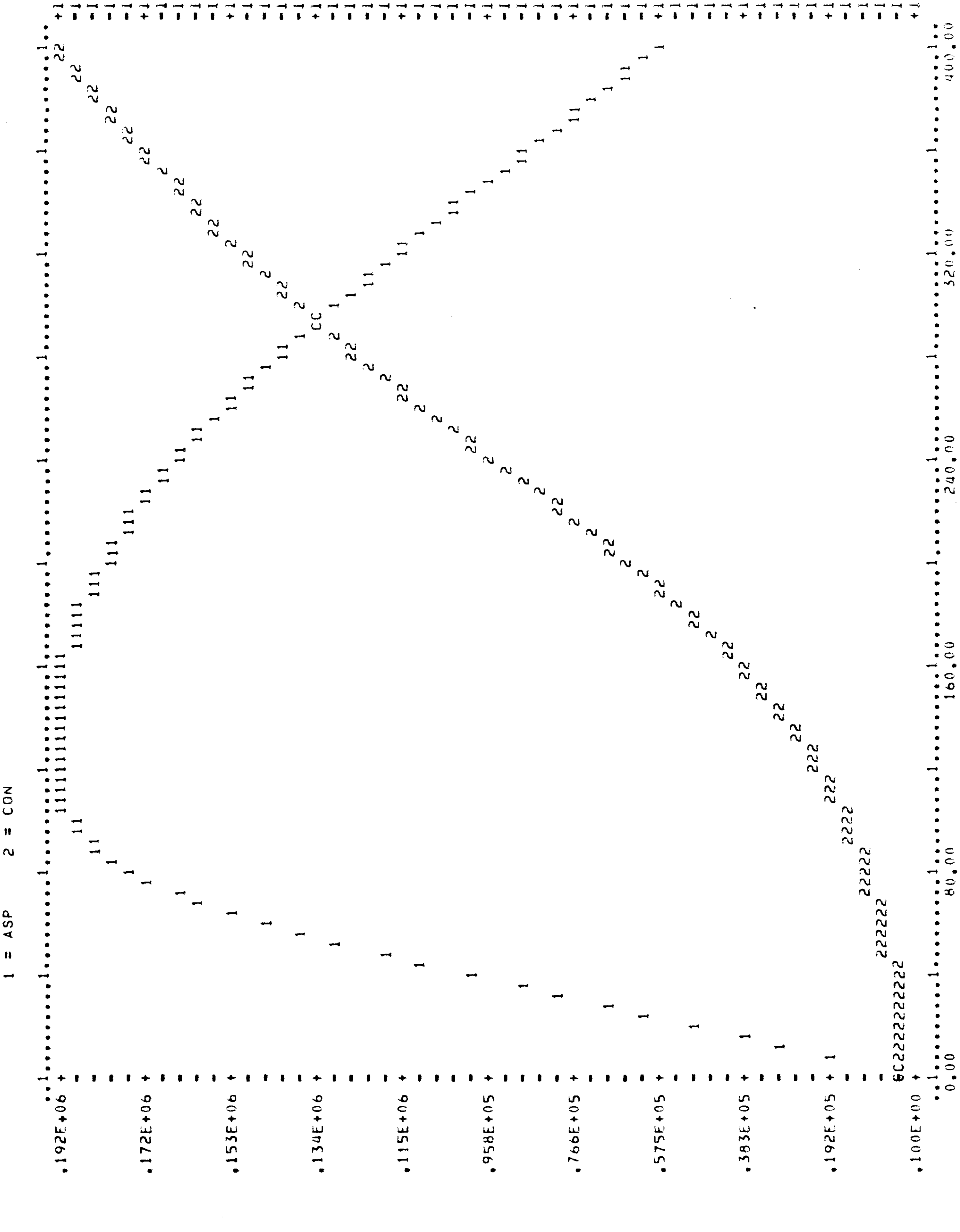
```
? DATA
1.,400.,100.,4.
200000.,250000.,10000.,3500.,500.
100000.,50000.,15000.,100000.,10000.
2500.,15000.,15000.,15000.,.1
.1,.1,.1,500.,.1
.1,.1,.1,.1,.1
0.,.006,.1,.8,.02
.4,2.4,5.,6.,.8
.3,.1,.001,6.,100000.
.45,.1,5.,5.,.5
.001,.001,.67,5.,.8
.25,.25,.1,5.,5.
.7,.001,5.,.2,.1
.1,5.,5.,.8,.15
4.,.03,.08,.001,1.2
.6,.25,.1,3.,.2
.2,.2,.001,1000.,5.
.7,.5,.3,.5,3.
.2,.7,.7,.3,.45
.5,.3,.7,3.,.5
3.,.25,.1,.5,.3
.2,6.,.5,3.,.02
.07,2.,.005,6.,.6
2.,.005,6.,500.,.5
.007,6.,.7,.5,.007
6.,3500.,4.,6.,.1
3.5,.4,6.,.8,100.
.5,.001,.5,.03,.2
.5,.01,.4,0,0
? END
```

APPENDIX B

Sample Output from ASPEN Program

```
DT =    1.0       TEND = 400.0       STEP = 100.0       PSTSZ =    4

 P(  1) = 200000.000000  P(  2) = 250000.000000  P(  3) =   10000.000000  P(  4) =    3500.000000  P(  5) =      500.000000
 P(  6) = 100000.000000  P(  7) =  50000.000000  P(  8) =   15000.000000  P(  9) =  100000.000000  P( 10) =    10000.000000
 P( 11) =   2500.000000  P( 12) =  15000.000000  P( 13) =   15000.000000  P( 14) =   15000.000000  P( 15) =        0.100000
 P( 16) =      0.100000  P( 17) =      0.100000  P( 18) =       0.100000  P( 19) =     500.000000  P( 20) =        0.100000
 P( 21) =      0.100000  P( 22) =      0.100000  P( 23) =       0.100000  P( 24) =       0.100000  P( 25) =        0.100000
 P( 26) =      0.000000  P( 27) =      0.006000  P( 28) =       0.100000  P( 29) =       0.800000  P( 30) =        0.020000
 P( 31) =      0.400000  P( 32) =      2.400000  P( 33) =       5.000000  P( 34) =       6.000000  P( 35) =        0.800000
 P( 36) =      0.300000  P( 37) =      0.100000  P( 38) =       0.001000  P( 39) =       6.000000  P( 40) =   100000.000000
 P( 41) =      0.450000  P( 42) =      0.100000  P( 43) =       5.000000  P( 44) =       5.000000  P( 45) =        0.500000
 P( 46) =      0.001000  P( 47) =      0.001000  P( 48) =       0.670000  P( 49) =       5.000000  P( 50) =        0.800000
 P( 51) =      0.250000  P( 52) =      0.250000  P( 53) =       0.100000  P( 54) =       5.000000  P( 55) =        5.000000
 P( 56) =      0.700000  P( 57) =      0.001000  P( 58) =       5.000000  P( 59) =       0.200000  P( 60) =        0.100000
 P( 61) =      0.100000  P( 62) =      5.000000  P( 63) =       5.000000  P( 64) =       0.800000  P( 65) =        0.150000
 P( 66) =      4.000000  P( 67) =      0.030000  P( 68) =       0.080000  P( 69) =       0.001000  P( 70) =        1.200000
 P( 71) =      0.600000  P( 72) =      0.250000  P( 73) =       0.100000  P( 74) =       3.000000  P( 75) =        0.200000
 P( 76) =      0.200000  P( 77) =      0.200000  P( 78) =       0.001000  P( 79) =    1000.000000  P( 80) =        5.000000
 P( 81) =      0.700000  P( 82) =      0.500000  P( 83) =       0.300000  P( 84) =       0.500000  P( 85) =        3.000000
 P( 86) =      0.200000  P( 87) =      0.700000  P( 88) =       0.700000  P( 89) =       0.300000  P( 90) =        0.450000
 P( 91) =      0.500000  P( 92) =      0.300000  P( 93) =       0.700000  P( 94) =       3.000000  P( 95) =        0.500000
 P( 96) =      3.000000  P( 97) =      0.250000  P( 98) =       0.100000  P( 99) =       0.500000  P(100) =        0.300000
 P(101) =      0.200000  P(102) =      6.000000  P(103) =       0.500000  P(104) =       3.000000  P(105) =        0.020000
 P(106) =      0.070000  P(107) =      2.000000  P(108) =       0.005000  P(109) =       6.000000  P(110) =        0.600000
 P(111) =      2.000000  P(112) =      0.005000  P(113) =       6.000000  P(114) =     500.000000  P(115) =        0.500000
 P(116) =      0.007000  P(117) =      6.000000  P(118) =       0.700000  P(119) =       0.500000  P(120) =        0.007000
 P(121) =      6.000000  P(122) =   3500.000000  P(123) =       4.000000  P(124) =       6.000000  P(125) =        0.100000
 P(126) =      3.500000  P(127) =      0.400000  P(128) =       6.000000  P(129) =       0.800000  P(130) =      100.000000
 P(131) =      0.500000  P(132) =      0.001000  P(133) =       0.500000  P(134) =       0.030000  P(135) =        0.200000
 P(136) =      0.500000  P(137) =      0.010000  P(138) =       0.400000  P(139) =       0.000000  P(140) =        0.000000
 MASP = 200000.00    MCON = 250000.00   MHERB =    4000.00    MSHU =  10000.00   MCONN =   15000.00   MSHUH =   15000.00
MASP1 = 100000.00   MASP2 =  50000.00   MASP3 =   15000.00   MCON1 = 100000.00   MCON2 =   10000.00   MCON3 =    2500.00
MASPS =  15000.00    MPER =   3500.00    MANN =     500.00

          TIME    0.00

    ASP =           0.100000          CON =            0.100000          SHU =            0.100000
    ANN =         500.000000          PER =            0.100000         HERB =          500.100000
   ASP1 =           0.100000         ASP2 =            0.100000         ASP3 =            0.100000
   CON1 =           0.100000         CON2 =            0.100000         CON3 =            0.100000
  NOCON =           0.000000          SUC =            0.300000         SEED =            0.300000
 BIOSUM =          -0.000000       SUCSUM =           -0.000000       SEESUM =           -0.000000
   AWPC =          -1.000000
```

```
          TIME 100.00

   ASP =       186676.798394       CON =       13964.229435       SHU =        6919.736938
   ANN =           18.009987       PER =         934.533414      HERB =         952.543401
  ASP1 =         1172.351872      ASP2 =          57.372357      ASP3 =          10.187821
  CON1 =          563.676260      CON2 =         116.566561      CON3 =          73.493727
 NOCON =          384.043300       SUC =        1239.912050      SEED =         753.736548
BIOSUM =           -0.000015    SUCSUM =           0.000000    SEESUM =           0.000000
  AWPC =           36.361081

          TIME 200.00

   ASP =       179628.487203       CON =       42396.969088       SHU =        5578.318924
   ANN =            7.780726       PER =         323.676584      HERB =         331.457309
  ASP1 =          443.274035      ASP2 =           9.618390      ASP3 =           0.627259
  CON1 =          746.153445      CON2 =         151.408757      CON3 =          89.396066
 NOCON =          391.575932       SUC =         453.519683      SEED =         986.958268
BIOSUM =            0.000000    SUCSUM =           0.000000    SEESUM =           0.000003
  AWPC =          159.348326

          TIME 300.00

   ASP =       128042.435857       CON =      136588.431256       SHU =        3587.097254
   ANN =            3.226571       PER =          83.181603      HERB =          86.408175
  ASP1 =          277.830569      ASP2 =           1.860322      ASP3 =           0.032086
  CON1 =          796.257013      CON2 =         161.884557      CON3 =          92.714297
 NOCON =          399.206707       SUC =         279.722977      SEED =        1050.855867
BIOSUM =            0.000019    SUCSUM =           0.000004    SEESUM =           0.000003
  AWPC =          342.149640

          TIME 400.00

   ASP =        56772.348892       CON =      191580.371622       SHU =        1565.700478
   ANN =            3.110401       PER =          43.975450      HERB =          47.085851
  ASP1 =          466.263862      ASP2 =           2.617593      ASP3 =           0.028442
  CON1 =          643.561039      CON2 =         132.709094      CON3 =          75.393348
 NOCON =          348.911140       SUC =         468.909897      SEED =         851.663481
BIOSUM =           -0.000031    SUCSUM =           0.000000    SEESUM =           0.000003
  AWPC =          549.080697
```


1 = ASP
2 = CON
.192E+06
.172E+06
.153E+06
.134E+06
.115E+06
.958E+05
.766E+05
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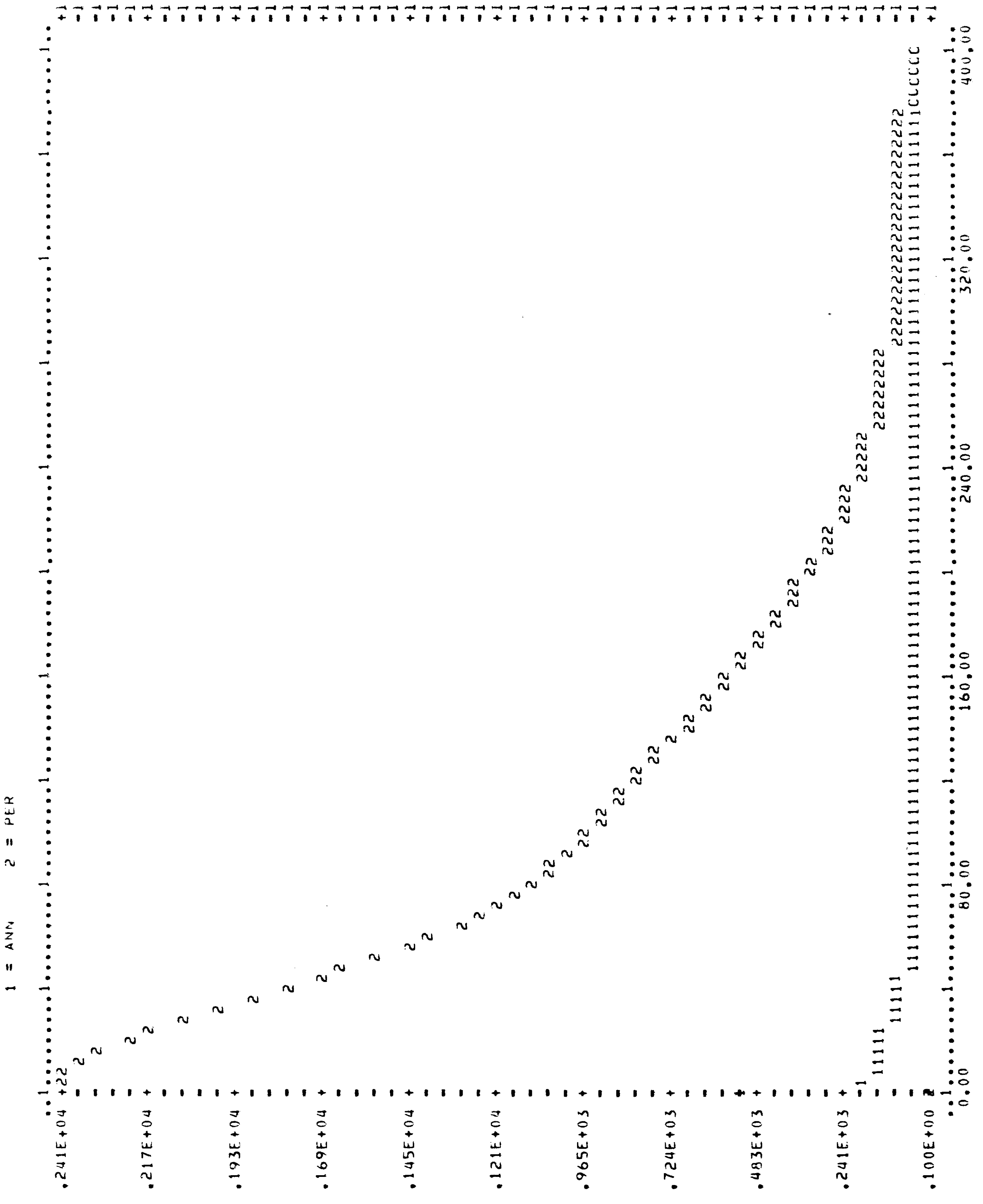
80.00
160.00
240.00
320.00
400.00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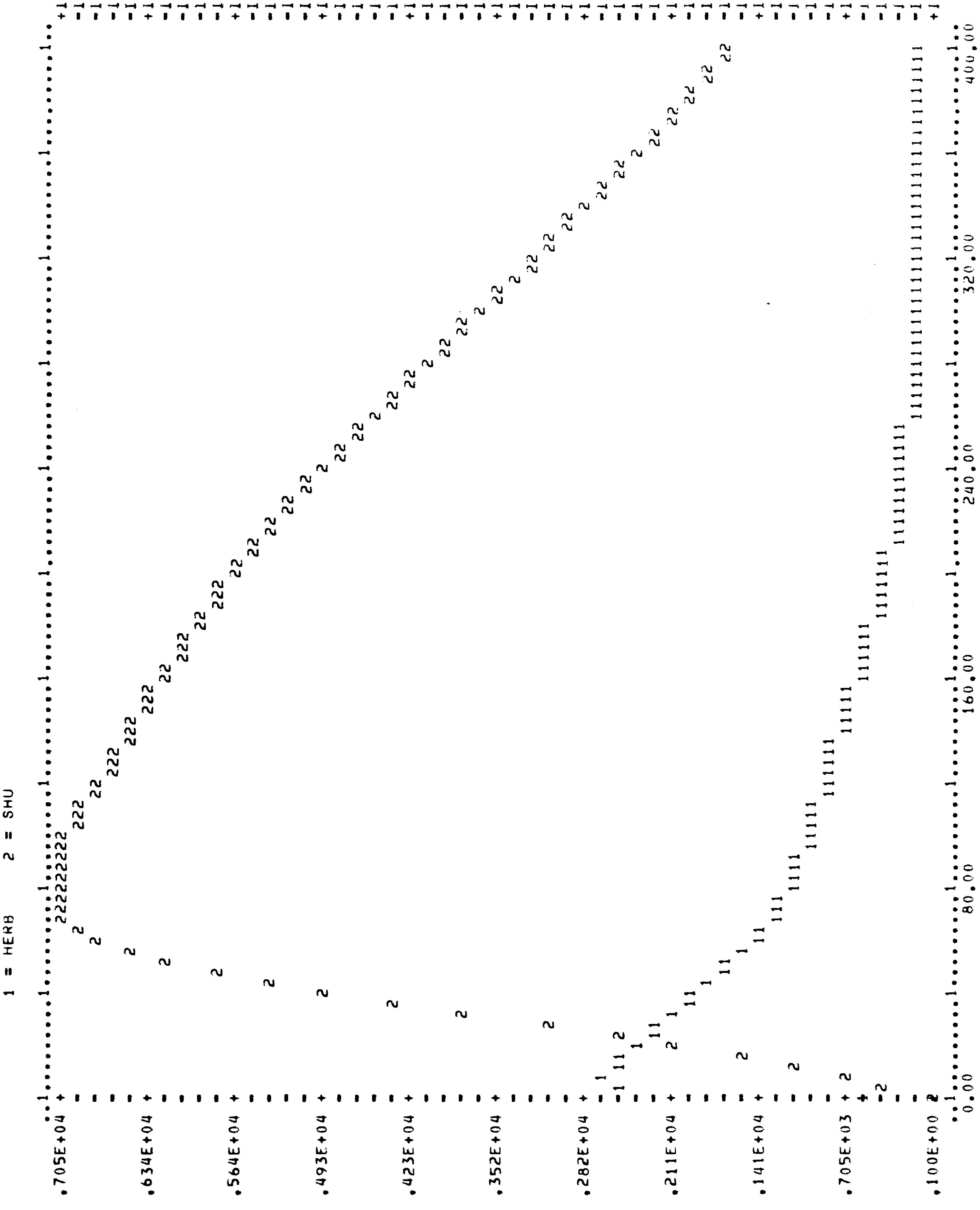
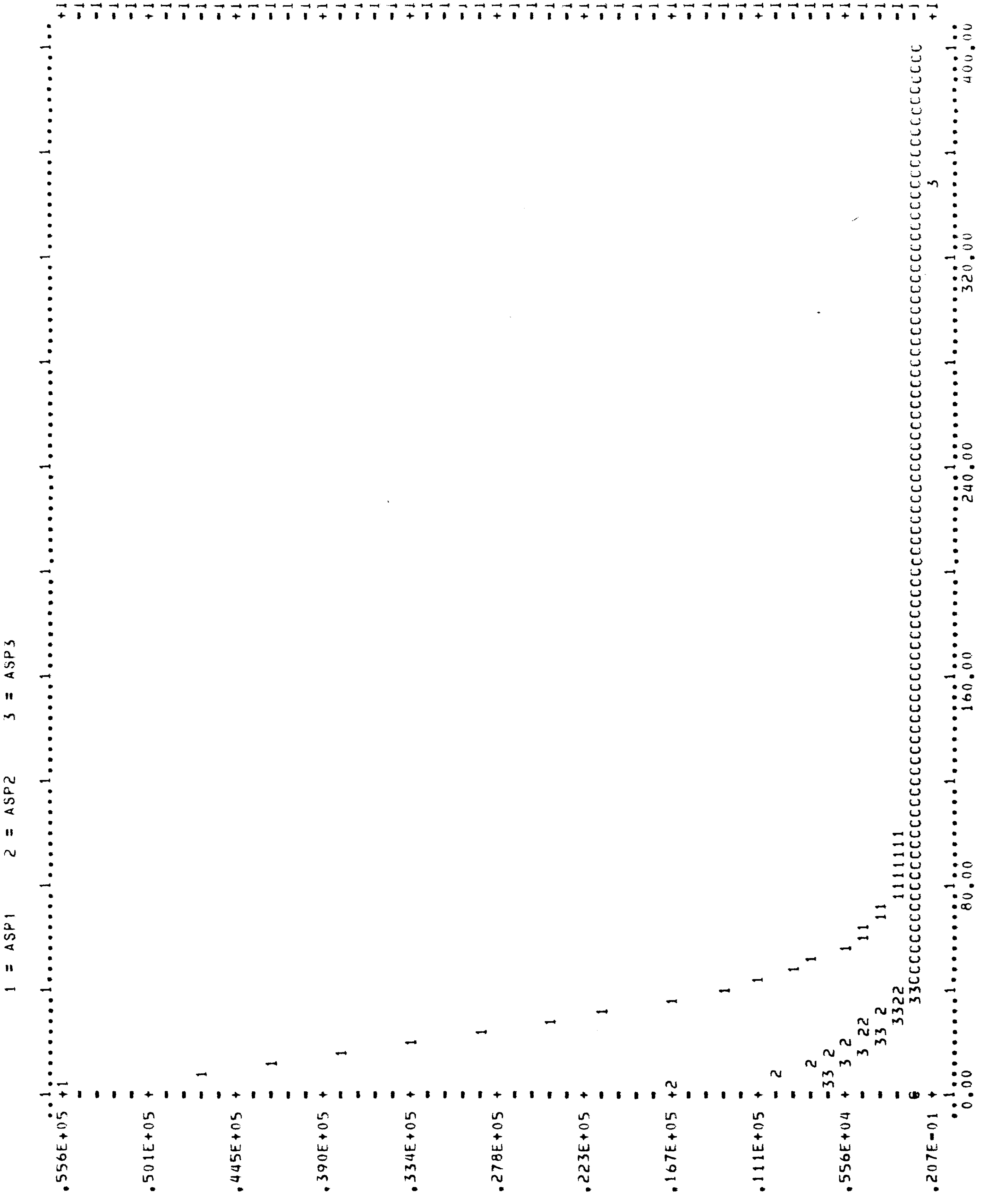
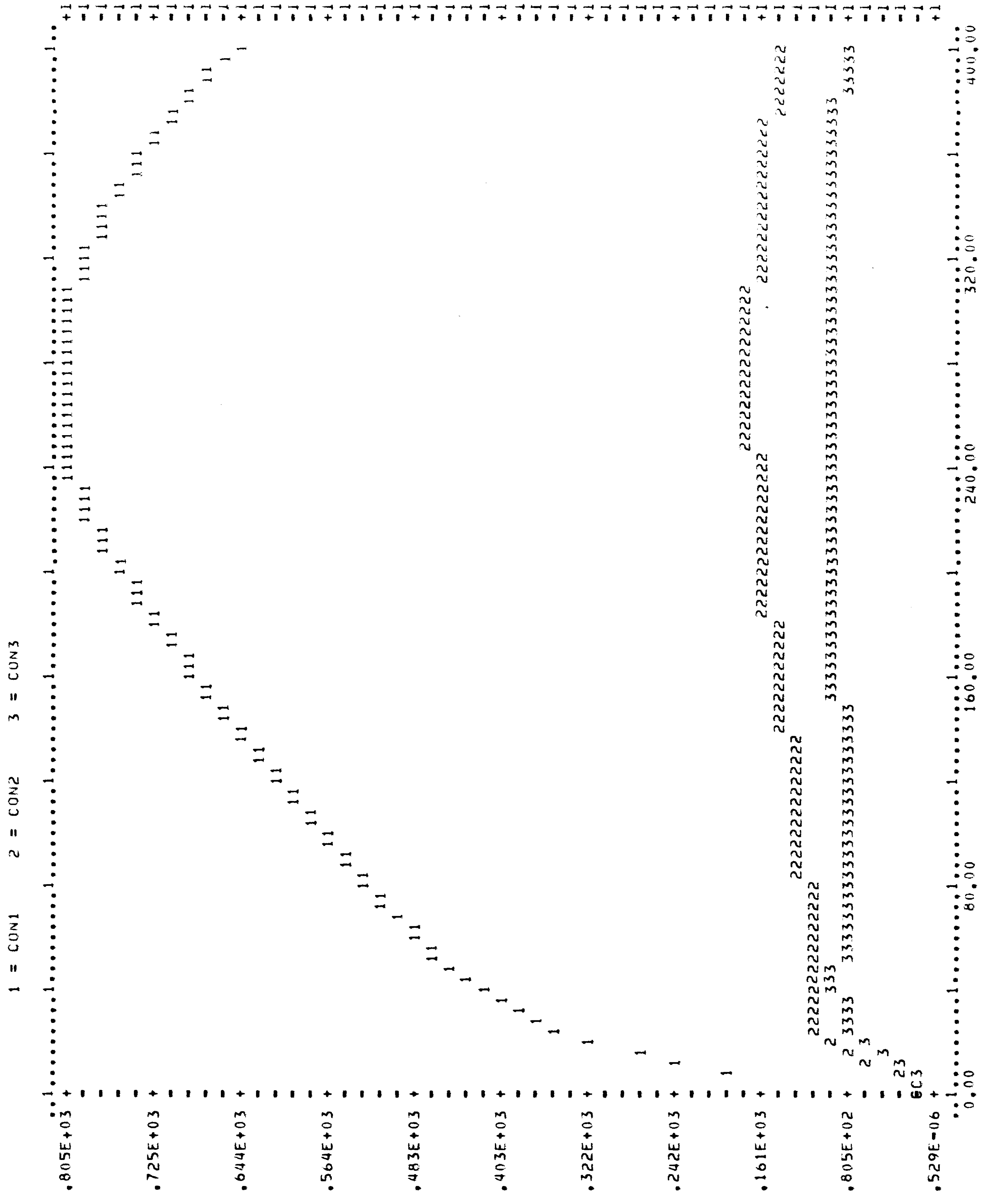
APPENDIX B (cont.)



APPENDIX B (cont.)



APPENDIX B (cont.)



APPENDIX C

Parameter Names, Definitions, Values, Range of Values, and Units for the ASPEN Program.

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
1	MASP	Maximum value for aspen biomass	200,000		kg/ha	Zimmermann 1979 Rodin and Bazilevich 1967
2	MCON	Maximum value for conifer biomass	250,000		kg/ha	Zimmermann 1979
3	MSHU	Maximum value for shrub biomass	10,000		kg/ha	Unpublished data (Bartos, files)
4	MPER	Maximum value for perennial biomass	3,500		kg/ha	Youngblood and Mueggler 1981
5	MANN	Maximum value for annual biomass	500		kg/ha	Youngblood and Mueggler 1981
6	MASP1	Maximum value for ASP1 reproduction class	100,000	80,000-120,000	Numbers/ha	Baker 1925 and unpublished data (Bartos, files)
7	MASP2	Maximum value for ASP2 reproduction class	50,000	40,000-60,000	Numbers/ha	Unpublished data (Bartos, files)
8	MASP3	Maximum value for ASP3 reproduction class	15,000	10,000-20,000	Numbers/ha	Mueggler and Bartos 1977
9	MCON1	Maximum value for CON1 reproduction class	100,000	80,000-120,000	Numbers/ha	Noble and Ronco 1978
10	MCON2	Maximum value for CON2 reproduction class	10,000	5,000-15,000	Numbers/ha	INT-1751 estimate
11	MCON3	Maximum value for CON3 reproduction class	2,500	1,000-5,000	Numbers/ha	INT-1751 estimate
12	MASPS	Maximum biomass value for the sum of all aspen suckers	15,000	10,000-20,000	kg/ha	INT-1751 estimate
13	MSHUH	Maximum biomass value for the sum of all aspen suckers and shrub biomass	15,000	10,000-20,000	kg/ha	INT-1751 estimate
14	MCONN	Maximum biomass value for the sum of all conifer seedlings	15,000	10,000-20,000	kg/ha	INT-1751 estimate
15	ASP	Initial value for state variable aspen	0.1	0-1.	kg/ha	— —
16	CON	Initial value for state variable conifer	.1	0-1.	kg/ha	— —
17	SHU	Initial value for state variable shrubs	.1	0-1.	kg/ha	— —
18	PER	Initial value for state variable perennials	.1	0-1.	kg/ha	— —

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
19	ANN	Initial value for state variable annuals	500	250-500	kg/ha	Bartos and Mueggler 1981
20	ASP1	Initial value for state variable ASP1	0.1	0-1.	Numbers/ha	— —
21	ASP2	Initial value for state variable ASP2	.1	0-1.	Numbers/ha	— —
22	ASP3	Initial value for state variable ASP3	.1	0-1.	Numbers/ha	— —
23	CON1	Initial value for state variable CON1	.1	0-1.	Numbers/ha	— —
24	CON2	Initial value for state variable CON2	.1	0-1.	Numbers/ha	— —
25	CON3	Initial value for state variable CON3	.1	0-1.	Numbers/ha	— —
26	NOCON	Initial value for conifer trees on site	0		Trees/ha	— —
27		Factor to convert sucker numbers (ASP1) to biomass	.006	.004-.006	kg/sucker	Bartos and Johnston 1978
28		Factor to convert sucker numbers (ASP2) to biomass	.1	.04-.11	kg/sucker	Bartos and Johnston 1978
29		Factor to convert sucker numbers (ASP3) to biomass	.8	.6-1.	kg/sucker	Bartos and Johnston 1978
30		Factor to convert seedling numbers (CON1) to biomass	.02	.01-.03	kg/seedling	Unpublished data (Bartos, files)
31		Factor to convert seedling numbers (CON2) to biomass	.4	.2-.6	kg/seedling	Unpublished data (Bartos, files)
32		Factor to convert seedling numbers (CON3) to biomass	2.4	2.-3.	kg/seedling	Unpublished data (Bartos, files)
33		Aspen restriction on ASP1 regeneration	5.	3.-7.	Dimensionless	INT-1751 Estimate
34		Conifer restriction on ASP1 regeneration	6.	4.-8.	Dimensionless	INT-1751 Estimate
35		Shrub restriction on ASP1 regeneration	0.8	.6-.9	Dimensionless	INT-1751 Estimate
36		ASP1 restriction on ASP1 regeneration	.3	.1-.5	Dimensionless	INT-1751 Estimate
37		ASP2 restriction on ASP1 regeneration	.1	0-.3	Dimensionless	INT-1751 Estimate

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
38		ASP3 restriction on ASP1 regeneration	.001	0-.2	Dimensionless	INT-1751 Estimate
39		CONN restriction on ASP1 regeneration	6.	4.-8.	Dimensionless	INT-1751 estimate
40		Unrestricted ASP1 regeneration rate	100,000	80,000-120,000	Suckers/ha/yr	Baker 1925 and unpublished data (Bartos, files)
41		ASP1 mortality	0.45	.3-.6	Yr^{-1}	Unpublished data (Bartos, files)
42		Aspen restriction on ASP1 graduation	.1	0-.2	Dimensionless	INT-1751 estimate
43		Aspen restriction on ASP1 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
44		Conifer restriction on ASP1 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
45		Shrub restriction on ASP1 graduation	.5	.3-.7	Dimensionless	INT-1751 estimate
46		ASP2 restriction on ASP1 graduation	.001	0-.2	Dimensionless	INT-1751 estimate
47		ASP3 restriction on ASP1 graduation	.001	0-.2	Dimensionless	INT-1751 estimate
48		ASP3 restriction on ASP1 graduation	.67	.33-1.	Dimensionless	INT-1751 estimate
49		CONN restriction on ASP1 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
50		Herb restriction on ASP1 graduation	.8	.7-.9	Dimensionless	INT-1751 estimate
51		Unrestricted ASP1 graduation rate	.25	.15-.35	Yr^{-1}	INT-1751 estimate
52		ASP2 mortality	.25	.15-.35	Yr^{-1}	Unpublished data (Bartos, files)
53		Aspen restriction on ASP2 graduation	.1	0-.2	Dimensionless	INT-1751 estimate
54		Aspen restriction on ASP2 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
55		Conifer restriction on ASP2 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
56		Shrub restriction on ASP2 graduation	.7	.5-.9	Dimensionless	INT-1751 estimate
57		ASP3 restriction on ASP2 graduation	.001	0-.2	Dimensionless	INT-1751 estimate

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
58		CONN restriction on ASP2 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
59		Unrestricted ASP2 graduation rate	.2	.1-.3	Yr^{-1}	INT-1751 estimate
60		ASP3 mortality	.1	.05-.15	Yr^{-1}	Unpublished data (Bartos, files)
61		Aspen restriction on ASP3 graduation	.1	0-.2	Dimensionless	INT-1751 estimate
62		Aspen restriction on ASP3 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
63		Conifer restriction on ASP3 graduation	5.	3.-7.	Dimensionless	INT-1751 estimate
64		Shrub restriction on ASP3 graduation	.8	.6-.9	Dimensionless	INT-1751 estimate
65		Unrestricted ASP3 graduation rate	.15	.1-.2	Yr^{-1}	INT-1751 estimate
66		ASP3 graduation conversion to biomass	4.	3.-5.	kg/tree	Bartos and Johnston 1978
67		Aspen mortality	.03	.02-.04	Yr^{-1}	INT-1751 estimate
68		Unrestricted aspen growth rate	.08	.06-1.	Yr^{-1}	INT-1751 estimate
69		Conifer restriction on aspen growth	.001	0-.02	Dimensionless	INT-1751 estimate
70		Conifer restriction on aspen growth	1.2	1.-1.4	Dimensionless	INT-1751 estimate
71		Aspen restriction on CON1 regeneration	.6	.4-.8	Dimensionless	INT-1751 estimate
72		Aspen restriction on CON1 regeneration	.25	.15-.35	Dimensionless	INT-1751 estimate
73		Conifer restriction on CON1 regeneration	.1	0-.2	Dimensionless	INT-1751 estimate
74		Conifer restriction on CON1 regeneration	3.	1.5-5.	Dimensionless	INT-1751 estimate
75		CON2 restriction on CON1 regeneration	.2	0-.4	Dimensionless	INT-1751 estimate
76		CON3 restriction on CON1 regeneration	.2	0-.4	Dimensionless	INT-1751 estimate
77		Shrub and aspen sucker restriction on CON1 regeneration	.2	0-.4	Dimensionless	INT-1751 estimate
78		Perennial and annual restriction on CON1 regeneration	.001	0-.2	Dimensionless	INT-1751 estimate

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
79		Unrestricted CON1 regeneration rate	1,000	750-1,250	Seedlings/ha/yr	Noble and Ronco 1978
80		Time delay in years for conifer reproduction	5.	3.-10.	Yr	INT-1751 estimate
81		CON1 mortality	.7	.5-.9	Yr^{-1}	Noble and Ronco 1978
82		Aspen restriction on CON1 graduation	.5	.3-.7	Dimensionless	INT-1751 estimate
83		Conifer restriction on CON1 graduation	.3	.1-.5	Dimensionless	INT-1751 estimate
84		CON2 restriction on CON1 graduation	.5	.3-.7	Dimensionless	INT-1751 estimate
85		CON2 restriction on CON1 graduation	3.	1.-4.	Dimensionless	INT-1751 estimate
86		CON3 restriction on CON1 graduation	.2	0-.4	Dimensionless	INT-1751 estimate
87		Shrub and aspen sucker restriction on CON1 graduation	.7	.5-.9	Dimensionless	INT-1751 estimate
88		Perennial and annual restriction on CON1 graduation	.7	.5-.9	Dimensionless	INT-1751 estimate
89		Unrestricted CON1 graduation rate	.3	.1-.4	Yr^{-1}	INT-1751 estimate
90		CON2 mortality	.45	.3-.6	Yr^{-1}	Noble and Ronco 1978
91		Aspen restriction on CON2 graduation	.5	.3-.7	Dimensionless	INT-1751 estimate
92		Conifer restriction on CON2 graduation	.3	.1-.5	Dimensionless	INT-1751 estimate
93		CON2 restriction on CON2 graduation	.7	.5-.9	Dimensionless	INT-1751 estimate
94		CON2 restriction on CON2 graduation	3.	1.-4.	Dimensionless	INT-1751 estimate
95		CON3 restriction on CON2 graduation	.5	.3-.7	Dimensionless	INT-1751 estimate
96		CON3 restriction on CON2 graduation	3.	1.-4.	Dimensionless	INT-1751 estimate
97		Unrestricted CON2 graduation rate	.25	.2-.4	Yr^{-1}	INT-1751 estimate
98		CON3 mortality	.1	.05-.15	Yr^{-1}	Noble and Ronco 1978
99		Aspen restriction on CON3 graduation	.5	.3-.7	Dimensionless	INT-1751 estimate
100		Conifer restriction on CON3 graduation	.3	.1-.5	Dimensionless	INT-1751 estimate

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
101		Unrestricted CON3 graduation rate	.2	.1-.3	Yr^{-1}	INT-1751 estimate
102		CON3 graduation conversion to biomass	6.	5.-7.	Kg/tree	Long and Turner 1975
103		Aspen restriction on conifer growth	.5	.3-.7	Dimensionless	INT-1751 estimate
104		Aspen restriction on conifer growth	3.	2.-4.	Dimensionless	INT-1751 estimate
105		Conifer restriction on conifer growth, mortality of conifer trees (#'s) on site, and conifer biomass mortality	.02	.01-.03	Yr^{-1}	INT-1751 estimate
106		Conifer restriction on conifer growth and unrestricted conifer growth rate	.07	.05-.09	Yr^{-1}	INT-1751 estimate
107		Aspen restriction on production of annuals	2.	1.-3.	Dimensionless	INT-1751 estimate
108		Conifer restriction on production of annuals	.005	.001-.01	Dimensionless	INT-1751 estimate
109		Conifer restriction on production of annuals	6.	4.-8.	Dimensionless	INT-1751 estimate
110		Perennial restriction on production of annuals	.6	.4-.8	Dimensionless	INT-1751 estimate
111		Shrub and aspen sucker restrictions on production of annuals	2.	1.-3.	Dimensionless	INT-1751 estimate
112		Conifer seedling restriction on production of annuals	.005	.001-.01	Dimensionless	INT-1751 estimate
113		Conifer seedling restriction on production of annuals	6.	4.-8.	Dimensionless	INT-1751 estimate
114		Unrestricted production rate of annuals	500		kg/ha/yr	Bartos and Mueggler 1981
115		Aspen restriction on perennial production	.5	.3-.7	Dimensionless	INT-1751 estimate
116		Conifer restriction on perennial production	.007	.001-.01	Dimensionless	INT-1751 estimate
117		Conifer restriction on perennial production	6.	4.-8.	Dimensionless	INT-1751 estimate
118		Annual restriction on perennial production	.7	.5-.9	Dimensionless	INT-1751 estimate
119		Shrub and aspen sucker restriction on perennial production	.5	.3-.7	Dimensionless	INT-1751 estimate

Parameter number	FORTRAN name	Definition	Value	Range	Units	Source
120		Conifer seedling restriction on perennial production	.007	.001-.01	Dimensionless	INT-1751 estimate
121		Conifer seedling restriction on perennial production	6.	4.-8.	Dimensionless	INT-1751 estimate
122		Unrestricted production rate of perennials	3,500		kg/ha/yr	Bartos and Mueggler 1981
123		Aspen restriction on shrub regeneration	4.	2.-6.	Dimensionless	INT-1751 estimate
124		Conifer restriction on shrub regeneration	6.	4.-8.	Dimensionless	INT-1751 estimate
125		Shrub restriction on shrub regeneration	.1	0-.2	Dimensionless	INT-1751 estimate
126		Shrub restriction on shrub regeneration	3.5	2.-5.	Dimensionless	INT-1751 estimate
127		Total of aspen sucker restriction on shrub regeneration	.4	.2-.6	Dimensionless	INT-1751 estimate
128		Total of conifer seedling restriction on shrub regeneration	6.	4.-8.	Dimensionless	INT-1751 estimate
129		Annual and perennial restriction on shrub regeneration	.8	.6-.9	Dimensionless	INT-1751 estimate
130		Unrestricted regeneration rate of shrub regeneration	100	75-125	kg/yr	INT-1751 estimate
131		Aspen restriction on shrub growth	.5	.4-.6	Dimensionless	INT-1751 estimate
132		Conifer restriction on shrub growth	.001	0-.01	Dimensionless	INT-1751 estimate
133		Conifer restriction on shrub growth	.5	.25-1.	Dimensionless	INT-1751 estimate
134		Shrub restriction on shrub growth and shrub mortality	.03	.02-.04	Yr^{-1}	INT-1751 estimate
135		Shrub restriction on shrub growth and unrestricted shrub growth rate	.2	.15-.25	Yr^{-1}	INT-1751 estimate
136		Total of aspen sucker restriction on shrub growth	.5	.3-.7	Dimensionless	INT-1751 estimate
137		Total of conifer seedling restriction on shrub growth	.01	0-.1	Dimensionless	INT-1751 estimate
138		Annual and perennial restriction on shrub growth	.4	.2-.6	Dimensionless	INT-1751 estimate

Bartos, Dale L.; Ward, Frederick R.; Innis, George S. Aspen succession in the Intermountain West: A deterministic model. Gen. Tech. Rep. INT-153. Ogden, UT: U.S. Department of Agriculture, Forest Service; 1982. 60 p.

A deterministic model of succession in aspen forests was developed using existing data and intuition. The degree of uncertainty, which was determined by allowing the parameter values to vary at random within limits, was larger than desired. This report presents results of an analysis of model sensitivity to changes in parameter values. These results have indicated areas of needed research. The model responds realistically to various management techniques and could be an aid to resource managers in their decisionmaking process.

KEYWORDS: simulation model, model sensitivity, FORTRAN, Forester diagrams, (fractional) factorial design, *Populus tremuloides*

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