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RESPONSES OF PLANT AND ANIMAL HABITAT DIVERSITY TO FOREST MANAGEMENT AND CLIMATE CHANGE: A MODELING APPROACH

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ABSTRACT

We are modifying the gap model, ZELIG, to simulate changes in the diversity of plant and animal species following various silvicultural treatments and climate change scenarios. This report summarizes our progress during the first year of this study. Specifically, model modifications, model verification, and a demonstration project exercising the utility of the model to evaluate tradeoffs of alternative silvicultural prescriptions are documented. Modifications implemented included a reformulation of the height-diameter allometry, consideration of snag and log dynamics, and addition of a forest management module that can simulate any number of silvicultural prescriptions. Results of the verification effort using the most recent version of ZELIG (PNW.OSU.2) indicated the model predicts with some reasonability temporal dynamics of Douglas-fir stands at 500-1100 m elevation. Potential modifications to improve model performance were identified. Although results are preliminary, the demonstration exercise offered insight into the costs and benefits, with respect to timber production and diversity of bird habitat, associated with varying levels of structural retention following timber harvest. Future efforts of this modeling project are outlined.

INTRODUCTION

Interest in preserving biological diversity in the Pacific Northwest (PNW) region has motivated both scientists and land managers to better evaluate the effects of silvicultural prescriptions and anticipated climatic changes on the dynamics of plant and animal communities. Although it is essential that well designed field experiments be conducted to evaluate effects of these disturbances on biodiversity patterns, studies will generally be limited in the size and number of treatments and restricted to a narrow time period. Findings of empirical studies alone will generally be insufficient for understanding patterns of biodiversity over the temporal (50+ yrs) and spatial scales (stand to landscape level) that forest managers must consider.

We are developing a simulation modeling approach to evaluate the influence of natural and anthropogenic disturbance on biodiversity patterns. This approach offers the ease of evaluating a multitude of experiments or hypotheses over varying scales of space and time in a timely and cost-effective manner.

We are modifying the forest succession model, ZELIG (Urban 1990), to simulate changes in the diversity of plant and animal species following various silvicultural treatments and climate change scenarios. ZELIG is a mechanistic distance-independent gap model derived from the FORET model of Shugart & West (1977). ZELIG simulates the establishment, death, and growth of individual trees on a small model plot (e.g., 0.1 ha) corresponding to the zone of influence of a canopy-dominant tree. Processes are constrained by available light, soil moisture, soil fertility, and temperature. Aggregating numerous model plots provides an estimate of average stand dynamics over time.

We chose to use ZELIG because of its versatility. The individual-tree approach of ZELIG offers the ability to manipulate stand structure to emulate a variety of silvicultural prescriptions. By modifying the moisture and temperature values used by the model, trends in woody plant diversity can also be assessed under anticipated changes in climatic conditions. Using field data, statistical models of habitat suitability based on stem density and basal area can be developed for wildlife species. Structural features simulated by ZELIG can be used by these models to evaluate trends in the diversity of wildlife habitat under varying silvicultural prescriptions and climatic regimes.

The specific objectives of this research were to:

1. Modify ZELIG.PNW to model plant forms in addition to trees (namely, shrubs);

2. Assemble data on life history attributes of prevalent shrubs in western Oregon for use in parameterizing the model;

3. Add subroutines to the model to simulate the dynamics of snags and fallen trees;

4. Add a disturbance subroutine to the model to emulate plant mortality associated with natural disturbances and timber management strategies;

5. Assemble quantitative data on microhabitat use by terrestrial vertebrate species in western Oregon;

6. Develop multivariate classification functions that characterize habitat associations for each vertebrate species;

7. Develop a subroutine that uses these functions to classify model output in terms of suitability as habitat for each vertebrate species;

8. Validate the model by comparing simulation results to field data on plant and wildlife habitat diversity patterns across successional and elevational gradients;

9. Use the model to predict changes in plant and wildlife habitat diversity in relation to: (a) stand silvicultural prescriptions involving rotation age, thinning schedule, retention of snags, woody debris, and green trees; (b) landscape-level silvicultural prescriptions involving timing of harvest, stand size, and edge characteristics; (c) altered temperature and precipitation regimes expected under global climate change, and (d) synergistic interactions between climate change and forest management practices.

This study was initiated in July 1990. Much of our effort in this initial phase concentrated on installing the generic version of ZELIG (PNW.1.1) on the Oregon State University mainframe computer, assembling field-data sets for model comparisons, testing and improving model performance, adding snag and log dynamics, developing wildlife-habitat association models, and developing the ability to simulate forest management scenarios.

This four part report summarizes our progress during the first year of this study. Additions and modifications we've made to the model are documented in the MODEL MODIFICATIONS section. Procedures and results of our model verification effort using the most current version of ZELIG (PNW.OSU.2) residing at Oregon State University are reported under MODEL VERIFICATION. To demonstrate the utility of our simulation approach, we performed two suites of silvicultural experiments to evaluate the effects of

alternative prescriptions on forest dynamics and diversity of bird habitat. This exercise also served to evaluate the protocols used to develop wildlife-habitat models and the habitat classification process. Results and analyses of our simulation experiments are presented in the APPLICATIONS chapter. The last section, NEXT STEPS, summarizes our progress and gives an overview of future efforts.

MODEL MODIFICATIONS

INTRODUCTION

Previous testing of an earlier version of ZELIG (PNW.1.1) identified four main features of the model requiring modifications and/or further analysis (Garman and Hansen 1991). In brief, model performance was found to be severely affected by inadequate predictions of tree height from dbh. It was recommended that species parameters used in the dbh-height allometry be modified and/or that the allometric equation be replaced by a different approach. Problems with the leaf area and light extinction calculations appeared to affect the model's ability to simulate realistic densities of larger stems. Further evaluation of these calculations was suggested. A filter for limiting sapling establishment was recommended to eliminate the large pulse of shade-tolerant species in simulations initiated from bare ground. Both natural and suppressed mortality were suspected to be too severe. A comparison of predicted and actual mortality rates was suggested.

Fixes to several of the problems identified from previous model testing are included in the current version of ZELIG (PNW.OSU.2). In addition, modules were added in accordance with the objectives of this project (q.v. page 2). Specifically, enhancements and additions in the current version of ZELIG include a new dbh-height allometry, consideration of snag and log dynamics, the ability to implement silvicultural prescriptions, and process and control features which facilitate the design and control of simulation scenarios and data I/O. Although the addition of these modifications more than doubled the number of lines of code, the current version retains the modularity of its predecessor. Some enhancements, in fact, were implemented to increase modularity. Modifications implemented are documented below in addition to others that were attempted but did not produce satisfactory results.

MODIFICATIONS AND ENHANCEMENTS

Modifications to Existing Algorithms

In the previous version of ZELIG, height of a tree was modeled as a function of diameter using a quadratic function where the coefficients of the function are derived from species' diameter and height maxima (Urban 1990). Because these coefficients are also used to calculate optimal diameter growth, adjusting maximum diameter or height to improve the dbh-height relationship also affected diameter increment. Also, owing to the quadratic property of the function, predicted height actually decreased for large

values of diameter. Although use of this basic approach has been successful in simulating western coniferous forests (q.v. Burton 1990), we felt that it was more appropriate to disassociate the dbh-height relationship from diameter increment and to model predicted height using an asymptotic function.

The dbh-height allometry was replaced with empiricallyderived models based on the Richard's function (Table 1). Data from the Forest Science Data Base (FSBD) and the USDA Forest Service Western Oregon Continuous Forest Inventory (CFI) were used to derive model coefficients. Trees with broken tops, or for which diameter and/or height were estimated or calculated were not used. Data for each species were plotted initially and noticeable outliers were eliminated. The non-linear routine of SPSS-X (SPSS 1988) was used to derive the regression coefficients. Seed values used in the non-linear regressions were varied to determine stability of regression coefficients. Because data were pooled across a variety of site conditions, the models we are currently using represent an average relationship between diameter and height for a species. Future efforts will be made to derive dbh-height models by site class and/or by geographic local (e.g., coastal Oregon, Oregon Cascades). Results will be submitted for publication.

Two additions were incorporated into ZELIG for more realistic comparisons of simulated tree data with actual field measures. The generic biomass equation was

supplemented with species-specific equations obtained from the BIOPAK system (Means et al. 1991) (Table 2). Species' coefficients used in these equations reside in a file that is read in at program initiation. The new biomass function automatically uses the generic equation for those species not included in this file. Calculation of tree volume is a new feature in ZELIG. The tree volume function handles three equation forms obtained from the BIOPAK system (Table 3). Species-specific volume coefficients also reside in a file that is processed at program initiation. Because there is no default equation for tree volume, coefficients for all species included in a simulation must occur in the disk file. A default volume equation will eventually be implemented.

A regeneration filter was implemented but proved not to be successful. The filter works by allowing only species that require mineral soil for seedling establishment, such as Douglas-fir and red alder, to colonize model plots for a specified period of time when initiating a simulation from bare ground. All species all eligible to become established after this time lag. Using this simple time-delay filter with a time lag of 10 years decreased the large influx of shade-tolerant species such as western hemlock during the first 100 years. However, the increased density of Douglasfir early on in the simulation affected the establishment of western hemlock later in the simulation. Comparison of model results with field data revealed that use of the

regeneration filter actually decreased the ability of the model to simulate western hemlock in older stands. If warranted, further efforts will be made to improve on this regeneration filter. Because it must be selected at program initiation to be activated, the filter can remain implemented without being used.

The diameter growth equation used in ZELIG is based on species-specific diameter and height maxima, and a dimensionless growth parameter, G, that is typically estimated by trial and error. As a more objective alternative we attempted to use species-specific empirical models of diameter increment based on the commonly used Weibull function. Evaluation of diameter increment data derived from the reference stand data bases in the FSDB indicated that data were insufficient for developing models that could be used in ZELIG. The basic approach used by ZELIG in modeling tree growth is to begin with a maximum potential and subsequently decrement this potential by constraints such as available light. Thus, data used to derive the Weibull functions had to represent diameter growth under optimal conditions. Calculated diameter increments of dominant individuals probably closely matched maximum potential. Diameter increments of suppressed stems, however, were clearly well below their optima. Fitting Weibull functions using all available diameter data as well as using only maximum values produced very poor models of optimal diameter increment for even the common most species.

Without adequate data for open grown stems, it is of little value to pursue the use of Weibull functions to model diameter increment in ZELIG.

Snag and Log Dynamics

Simulation of both snags and logs is a new feature in ZELIG.PNW.OSU.2. The logic used to model standing and downed-dead wood was derived from Graham (1982). We chose her approach because it provided estimates of transition between decay classes and between snag and log states, and was straight forward. Unlike her simulation model, we do not deal explicitly with fragmentation and mineralization of dead wood. One slight anomaly in Graham's approach is that three instead of the usual five decay classes (q.v. Cline et al. 1980) are used for snags but five classes are used for logs. We had to approximate the log decay class when a snag became a log.

Each snag and log on each plot is tracked instead of the more common cohort approach. Although our approach requires greater computer memory requirements, we felt that it was necessary given the potential requirement in the wildlife-habitat classification process for detailed snag and woody debris data. Also, tracking individual pieces may facilitate linkages with future modeling projects dealing with carbon storage and nutrient cycling. The previous version of ZELIG eliminated a tree from the simulation when it died. The current version treats dead trees ≥ 10 cm dbh as snags. We felt that stems less than this size were of little importance and including them would unnecessarily increase computational time. Data recorded for each new snag includes the current simulation year, the diameter and height of the tree, and a decay class status of I. Additionally, a snag is associated with one of five decay groups based on the tree species and the diameter (Table 4). Transition of a snag between decay classes is deterministic, based on fixed residence times for each decay group (Table 4). A snag is eliminated from the simulation upon reaching the end of the last decay class.

Logs are created from the breakage of snag boles. The bole volume breaking off to form a log varies by decay group and decay class (Table 4). We assumed that the volume lost to breakage ends up as a single log. The time at which breakage of a snag occurs is stochastically determined, but occurs in a decay class where breakage is designated (q.v. Table 4). If a snag has not experienced breakage by the end of this decay class, breakage will occur before transition to the following decay class.

The dimensions of a log resulting from breakage are estimated by determining the actual volume to be removed (volume of the snag X percent breakage), estimating down from the top of the snag the length of a paraboloid that would equate to this volume, then determining the diameter

of the snag at this distance from the top using a rearrangement of the taper equation presented by Kozak et al. (1969). Species-specific regression coefficients are required by the taper equation. Because the species of a snag is not recorded, we used taper coefficients derived for Douglas-fir for slow decaying species (decay groups I-III, Table 4) and coefficients for western hemlock for fast decaying species (decay groups IV-V). Taper coefficients were derived from measures recorded in a dendrometer data base stored in the FSDB (StudyID TV009). The estimated length and large-end diameter of the breakage, and decay group of the snag are stored for each log. We estimated the decay class of the log to be one greater than that of the snag. Transition of logs between decay classes is also deterministic and based on estimates of duration in a decay class (Table 4). Logs are eliminated from the simulation upon reaching the end of the last decay class.

Forest Management Dynamics

A core requirement of our simulation approach is the ability to implement a variety of silvicultural prescriptions. A management module was added to ZELIG that can simulate just about any type of real-world silvicultural prescription at any time during a simulation. The management options included in this module and parameters specific to each option are summarized in Table 5. Each

operation is handled as an individual event, thus any combination of events can be implemented at any given point in time. Events are prioritized, however, with clearcutting with or without green-tree retention and thinning operations having the highest priority, followed by retention of snags then logs, and lastly, establishment of plantations. This scheme insures that retention of live trees occurs first before trees can be converted to snags or logs.

The algorithm used for the retention of trees, snags, and logs attempts to retain equal amounts across all model plots included in the simulation. The algorithm is fairly flexible in that it will aggregate retention if a retention item is unequally distributed across the model plots. Although the current algorithm proved to be more than adequate for our initial applications, we will likely implement the ability to specify the desired dispersion pattern (e.g., uniform or aggregated) of each retention item. This will then give us the means to evaluate not only retention levels but also pattern of retention.

Dynamics of Natural Disturbances

Natural disturbances such as windthrow and wildfire are not explicitly simulated in the current version of ZELIG. To some degree, these disturbances can be emulated using the forest management options. For instance, both windthrow and wildfire can be simulated by specifying the retention of a

few large trees with the remaining stems becoming snags and/or logs. Future efforts may be made to explicitly model natural disturbances.

Data I/O

Data I/O capabilities were expanded to handle the addition of snags and logs, and the processing and output of detailed data for analyses of model runs.

In the previous version of ZELIG, records for each stem on a model plot can be stored to disk and later read in at program initiation to initialize each model plot in a simulation run. This processing was modified to handle the additional records of snags and logs.

The ability to output tallies of selected data types for each model plot in a simulation was added. Data types include density, basal area, and volume of trees by species, density and basal area of snags and logs by decay class, and volume of logs by decay class. Data can be aggregated in up to ten size-classes (based on dbh or diameter at large end for logs) and recorded at regular intervals or at specific times during a simulation. Plot-level tallies are automatically recorded for each plot when a management event occurs. A plot number and a status code is always associated with each output record to indicate if the data represents current or pre-harvest levels, was removed during harvest, was planted, or represents post-harvest levels. Also, codes are used to indicate a tree becoming either a snag or a log. This coding scheme permits recording of all data to just one file for each structural feature. Recording these data for each model run enables a copious amount of analyses of stand dynamics under varying silvicultural prescriptions. Stand-alone analysis packages were developed for processing of these data.

Diameter increment and mortality rate of trees by species can be output by user-specified size classes. An option to average across a specified number of years is provided. These data are useful in comparing model results among runs as well as in model testing with field data.

User Interface

An interactive queue-oriented interface was added to facilitate dynamic control of program execution and to provide dynamic feedback of simulation results. Using the primary queue which is displayed at program initiation, the operator can build silvicultural prescriptions by selecting specific management options (q.v. Table 5), and select to output plot-level tallies, diameter increment, and mortality data. Two to four queues follow a selection from the primary queue, prompting the operator for all necessary parameters; e.g., year in which to implement a clearcut, minimum dbh of a retained green-tree, minimum length of a

retained log, data types included in plot-level tallies, and size classes to use for grouping plot-level tallies.

Additional features include the ability to review queue selections, allowing the operator to review all choices prior to initiating the simulation. The operator can choose to display current simulation results such as stand-level summaries of tree composition and structure, density and basal area of snags, and density and volume of logs by decay class. The operator can also designate the simulation year in which the program will 'pause'; that is, processing is directed to the function handling the queuing sequence at the beginning of the designated simulation year. During a pause, the primary queue is displayed on the screen allowing the operator to modify previous selections or to review the current simulation results. The ability to temporarily halt the simulation and review results is especially useful in providing timely feedback when testing model modifications. The queuing process can be terminated and program execution continued. The program can be 'paused' any number of times during a simulation run.

Anticipated Model Enhancements

In addition to the minor enhancements mentioned above, we will include the consideration of shrub dynamics in the next version of ZELIG. We plan to use routines similar to those in ZELIG.BC (Burton 1990). Shrubs are an important

feature in most forested communities in the PNW region. They provide both food and cover for wildlife species and can impact stand development through intense competition with saplings. With the shrub component in the model we will be better suited to simulate stand dynamics in shrubdominated systems such as coastal Douglas-fir forests. We will also expand our abilities to evaluate alternative prescriptions to include simulating effects of varying levels of brush control on timber production and diversity of plant and animal habitat.

Modified versions of the leaf area allometry, the growth equation, and the regeneration routine have recently become available (D. Urban pers. comm.) and will be implemented and tested prior to all other modifications.

MODEL VERIFICATION

INTRODUCTION

An important part in the development of any model designed to deal with a specific, applied problem is testing its ability to predict real-world conditions. A limited amount of model testing using actual stand data was performed in the initial phase of adapting ZELIG to the PNW region (Garman and Hansen 1991). Although useful, this testing only evaluated the model's ability to simulate oldgrowth stands.

As a comprehensive test of model performance, we used our current version of ZELIG (PNW.OSU.2) to simulate the dynamics of Douglas-fir stands over a 500 year period for three elevations in the Oregon Cascades and compared model results at specific time points with field data. We limited the analysis to a 500 year period owing to limitations of field data. We chose to test across elevations as a means to evaluate the generality of the model. Results of this verification effort will provide insight into not only how well the model performs, but will elucidate where and possibly why the model fails. Of equal importance, results will serve as a benchmark for evaluating the improvement in model performance of future enhancements.

METHODS

Field Data

From the plethora of data sets available to us in the OSU Forest Science Data Base (FSDB) and other sources, we selected for model comparisons only those data that primarily characterized Douglas-fir stands and for which topographic and stand-age data were readily available. Data sets used were the H. J. Andrews Experimental Forest reference stands, a Douglas-fir old-growth chronosequence study, and the USDA Forest Service Western Oregon Continuous Forest Inventory (CFI). Collectively, these data sets provided measures of Douglas-fir stands over a wide range of site conditions, ages, and elevations. Each data set contained measurements of individual trees on a number of plots. Plot size varied among data sets, ranging from ca. 0.06 to 0.1 ha. Measures of both snags and logs were available only in the old-growth data set. Snags were also available in the CFI data base. Plot-level attributes such as geographic location, elevation, disturbance history, and age of dominant trees were either included as records in the data bases or were obtained from field records. Only those plots that represented natural stands and were located on the western side of the Oregon Cascades were considered for this analysis.

The three elevations selected for our analysis were based on the availability of field data. We grouped plots into 200 m elevation-classes and 10 year age-classes and determined the number of plots for each age-elevation combination. Excluding age-elevation combinations with less than 5 plots, elevation classes with midpoints 500, 900, and 1100 m were deemed to give the best possible range of stand ages and sample sizes (Table 6).

Stand tallies were derived by averaging plot-level tallies (units/ha) of tree, snag, and log measures over plots of similar age for each of the three elevation Only trees ≥ 5 cm dbh were included because several classes. of the data sets did not record trees smaller than this diameter. Means and 95% confidence intervals for each measure were calculated. It was our original intent to divide the available plot data for the three elevations selected for use in this study into a verification and validation data base, where the latter would be used as an independent test of the final version of the model. Owing to data limitations, we included all available plots in the verification data base except for 450 year-old plots which were numerous enough to be partitioned. Additions to this limited validation data base will occur as other regional data sets become available.

Simulation Parameters

Site and species parameters used in each simulation run are presented in Table 7. Mean monthly temperatures for each elevation were calculated using the regression models presented by Urban et al (1990). Precipitation values also vary by elevation and were estimated using the model developed by R. Neilson (EPA, Corvallis). Tree species included in the simulations were those typically associated with Douglas-fir forests across the three elevations used in this analysis. All seven species were included in each simulation.

Simulation Runs

Simulation runs were initiated from bare ground and included 30 0.07-ha model plots. Data for each model plot were recorded every ten years during a simulation. Data included basal area and density of live trees ≥5 cm dbh by 10-cm size classes and species, basal area and density of snags and logs, and volume of logs. Stand-level means and 95% confidence intervals of measures were obtained from averaging across model plots.

Analyses

Model results were compared with field data for each elevation by plotting means and 95% confidence intervals of

measures over time and visually assessing similarity. We used the 95% confidence intervals to assess degree of overlap in the distributions about the actual and simulated means. Statistical tests were not performed, however. Measures included total density and basal area of trees and snags, density and basal area by tree species, and total density and volume of logs. We limited our analysis of tree species to Douglas-fir and western hemlock because they are the primary species regulating stand dynamics at the elevations used in our analysis.

Diameter distributions of tree stems were compared between actual and simulated stands at each elevation to evaluate the model's ability to predict stand structure. Distributions for total stems, and for Douglas-fir and western hemlock were compared.

RESULTS

Plots of means and 95% confidence intervals of the selected measures for the three elevations are shown in Figures 1-3. For each elevation, simulated values of total basal area and density of trees showed a high degree of overlap with field values especially for stands >100 yearsold. Although the model tended to predict an over abundance of trees within the first century, the trend in both density and basal over time were similar between actual and

simulated data. This is best illustrated in the simulations at 900 m and 1100 m (Figures 2 and 3, respectively). Predicted basal area and density of Douglas-fir at all elevations agreed well with actual values. Similarity in successional trends of measures was also evident. There were noticeable discrepancies between means of simulated and actual values at year 200 at 500 m (Figure 1), year 300 at 900 m (Figure 2), and year 320 at 1100 m (Figure 3). The actual values corresponding to these time points are suspect given the wide confidence intervals around most and that they were derived from a limited number of field plots (≤ 6 , q.v. Table 6). Also, each of these points tended to deviate from the temporal pattern produced from interpolating between the other respective data points. This was especially true for basal area at 1100 m (Figure 3).

Results for western hemlock in all three simulations revealed problems with the model's ability to handle this species. Predicted values of density and basal area exceeded actual values for most stands less than 100 yearsold. So many were established in this time period that the peak values of simulated density and basal over the 500 year period occurred at ca. 75-125 yrs. This initial influx of copious amounts of western hemlock accounts for the model's tendency to over predict total tree densities in the first 100 years. Prediction of the western hemlock component improved considerably with stand age at all elevations. Confidence intervals for actual and simulated values in

stands \geq 300 years-old overlapped considerably. The exception was in the simulation at 500 m (Figure 1) where basal area of 450 year-old stands was much less than that of actual stands.

The model's ability to realistically simulate snags was marginal at all three elevations. Predicted densities deviated considerably from actual values for stands <100 years-old. Densities were ca. two to ten times greater than actual values. Agreement between predicted and actual values of density improved in older stands. Although there was some overlap of confidence intervals for basal area values, predicted values tended to be lower than actual values in stands <100 years-old but higher in older stands. Results indicate a tendency for the model to predict too many small snags over the first 100 years, but too many large snags in older stands.

Log measures were poorly predicted by the model at all elevations. Predicted log densities exceeded actual values over the first 100 years reflecting the over abundance of snags. Prediction of log densities improved in older stands. There was very poor agreement between predicted and actual values of log volume. Actual values of log volume in stands >100 years-old were similar or exhibited moderate increases with stand age. Predicted log volume exhibited a steady rise with stand age. Because predicted and actual log densities were not grossly different in older stands, we suspect that parameters used to derive the dimensions of a newly formed log are the primary source of error.

Stand Structure

Diameter distributions for total stems for the three elevations are shown in Figures 4-6. Trends in the distributions of Douglas-fir and western hemlock stems were similar to that of total stems and are not shown.

Diameter distributions appreciably differed between simulated and actual stands for <150 year-old stands at all elevations. Simulated stands in the first 10-20 years had more than twice the number of stems <20 cm dbh compared to actual stands. Actual stands 40-140 years-old tended to have size classes distributed as an inverse "J" (taking into account that stems <5 cm dbh were not included) which is commonly associated with self-replacing stands. Simulated stands of similar age tended to have most stems in two to four adjacent size classes resulting in an inverted "U" distribution which is indicative of even-aged stands. The model essentially simulated single-layered stands over the first 140 years. The distribution of stems in simulated stands 300-500 years-old took on the form of an inverse "J" and closely matched that of actual stands.

Further analysis of simulation results suggests that the influx of the large number of stems in the initial years of a run sets the stage for the development of single-

layered stands. Stems tend to be aggregated into a few size-classes early in a simulation with each size class containing a large number of stems. Owing to the high density of stems, only the larger similarly-sized stems can successfully compete for light and grow. Over time, this cohort of stems forms a relatively even and dense canopy that retards the establishment and growth of smaller size classes. Only canopy stems of similar height can successfully compete. Stem distributions of simulated stands do not become dispersed until later in succession when gap dynamics open up the canopy.

DISCUSSION

Results of model verification indicate that ZELIG performs reasonably well in predicting the temporal dynamics of stand-level characteristics of Douglas-fir stands over a range of elevations. The model appears to be fairly robust in that both the good and the not so good results occurred equally across elevations.

The close agreement between predicted values of density and basal area of Douglas-fir stems and actual values across varying stand ages demonstrates a significant improvement over the previous version of ZELIG (PNW.1.1). Use of the empirically-based height-dbh models is largely responsible for this improvement. Parameters used to model height from

diameter in the previous version tended to produce large but short Douglas-fir which were quickly overtopped by species such as western hemlock (q.v. Garman and Hansen 1991). The empirically-based height-dbh allometry more accurately models height growth of Douglas-fir and its potential competitors. With the current species' parameters for the height-dbh allometry, the faster growing Douglas-fir quickly reaches the canopy of a model plot. The height growth of slower growing shade-tolerant species lags behind that of Douglas-fir. Only after large Douglas-fir begin to drop out of the canopy does western hemlock begin to increase in importance. This is best illustrated in the simulation results at 900 m (Figure 2). Basal area of Douglas-fir steadily climbs over the first 300 years then gradually declines owing to simulated natural mortality. This gradual decline is accompanied by a gradual increase in both basal area and density of western hemlock. Simulation runs extended out to 900 years indicate that western hemlock will eventually dominate a simulated stand at years 600-850.

The simulated transition of uniform stands to more structurally diverse old-growth stands is evidence of the model's ability to simulate gap dynamics in the coniferous forests of the PNW. Although the model possibly fails to adequately simulate structure of younger stands, its success in predicting with some precision both the structure and composition of old-growth stands is encouraging.

The establishment of an unreasonable number of stems of slow-growing shade-tolerant species such as western hemlock in the first century of a simulation initiated from bare ground has been an ongoing problem with the model. Use of the new dbh-height models which ensures that the faster growing Douglas-fir quickly controls the overstory did little to ameliorate this problem. Currently, ZELIG determines the availability of saplings for establishment using species-specific relative rates in addition to environmental constraints. Altering these relative rates will favor a species over another. We have 'experimented' with different combinations of these rates to reduce initial densities of western hemlock. Typically, when we reduced western hemlock stems the model overestimated Douglas-fir. The primary aim of the modifications in the new regeneration routine developed by D. Urban is to better control the establishment of saplings. Implementation of this mod into our version of ZELIG is underway. When completed, model results will be compared with field data to determine the need for further analysis.

The large number of similarly-sized stems colonizing a model plot appears to affect the models ability to realistically predict the structure of actual stands over at least the first 140 years. Other factors may also be involved, however. For instance, over estimating leaf area or the rate of light extinction will restrict available light to the upper portions of a canopy and also lead to the

development of a single-layered stand. Establishing too many stems as well as over estimating the rate of light extinction could produce the same result. The non-linearity of the model makes it difficult to analytically determine where the model fails. Detailed comparisons of simulation results with the dynamics of naturally regenerating plots over the first ten years would greatly aid in pinpointing problems with the model. Regional data sets are available for this comparison (e.g., Watershed 10, H. J. Andrews Experimental Forest). The need to pursue this analysis will be determined after testing the new regeneration routine.

The accumulation of too many snags in the first 100 yrs is likely a result of the overstocking of live stems. Eliminating this overstocking will likely improve the prediction of snags. How this will affect predictions of snags in older stands will have to be evaluated.

Reducing the number of snags will likely improve the prediction of log densities. Problems with the prediction of log volume will have to be isolated. Findings suggest that simulated logs are too large and/or the rate of log decay is too slow. Parameters used to model snag breakage may need to be modified to produce fewer large logs. Also, use of a stochastic function to model log decay may be more appropriate than the current method of using fixed time intervals for each decay class.

FUTURE TESTING EFFORTS

The recent modifications to the leaf area calculations, growth equations, and regeneration routine developed by D. Urban (pers. comm.) will be implemented into ZELIG.PNW.OSU.2. Model results using these mods will be compared with the benchmark measures obtained in this study. Fixes to problems encountered with these new routines as well as to those revealed in the present study will be implemented. As a final test of model performance, we will compare model results with an independent data set in a manner similar to that used in this study. If data permits, we will perform model validation at the three elevations used in this study. Otherwise, tests will be performed at elevations for which data are most available. Data sets will be added to the existing validation data base as they become available. Test results will be documented and submitted for publication.

To date, we've concentrated mostly on testing the ability of the model to simulate natural stands. A large thrust of this project, however, is to simulate stand dynamics in response to novel silvicultural prescriptions. The ability of ZELIG to realistically simulate managed stands over time has not been tested. Testing model behavior under all possible management scenarios is impossible owing to data limitations. However, we will acquire remeasurement data from as many different silvicultural studies as possible to compare with model results. Acquiring confidence in the model's ability to simulate responses of stands to commonly used silvicultural practices will increase the model's credibility to realistically predict consequences of as yet untested management techniques such as those proposed under the concept of "New Forestry".

We are in the process of obtaining data from the Black Rock Alternative Prescription study. Model testing will be performed by first initializing ZELIG with initial stand conditions of the study, manipulating structure and composition of model plots as performed on the ground, and comparing simulated and actual stand dynamics. Results of this and other testing performed along these lines will be documented and presented in a future report. The availability of data will determine if validation testing of this aspect of model performance will be possible.
APPLICATIONS: SIMULATING FOREST AND BIRD HABITAT DYNAMICS UNDER ALTERNATIVE SILVICULTURAL PRESCRIPTIONS

INTRODUCTION

Forest managers are under intense pressure to increase the output of multiple resources. Traditional silvicultural techniques in the Pacific Northwest (PNW) were primarily designed to maximize wood production and habitats for game animals. Evidence is building that these techniques negatively effect some other important forest resources. Consequently, innovative new silvicultural methods are under development (Gillis 1990). There is considerable need to quantify the effects of traditional and new management techniques on wood production, habitat diversity, water quality, economics, and other factors. Several field experiments have been initiated to provide this information. Simulation modeling is also needed to deal with the longer time scales (decades to centuries) and larger spatial scales (stands to landscapes) relevant to forest management.

Some of the new forestry approaches are designed to maintain or increase structural heterogeneity in stands for the benefit of plant and animal diversity. Many species are associated with fine-scale habitat configurations involving canopy layering, tree size, and presence of snags and fallen logs (Ruggerio et al. 1991). Hence, plant and animal community diversity is correlated with the number of such "microhabitats" present in a stand. Natural forests in the PNW support relatively high levels of structural heterogeneity and species diversity (Hansen et al. 1991). Clearcutting and other traditional forest management practices in the region create evenly aged, sized, and spaced forest plantations. Such practices appear to be very effective at increasing growth rates of Douglas fir, the primary commercial species in the region. They also, however, reduce habitat heterogeneity and species diversity relative to that found in natural forests (Hansen et al. 1991). The new forestry approaches endeavor to remedy this outcome by retaining in harvest units various levels of live trees, snags, fallen trees, and shrubs.

The costs and benefits of such structural retention are poorly know. Shade cast by retained trees is likely to reduce growth rates of regenerating trees, but the shape of the relationship is yet to be determined. On the other hand, the additional growth of the retained canopy trees may compensate for the shading effects on seedlings and saplings.

The responses of forest wildlife to structural retention are also open to question. Several studies have demonstrated positive associations between cavity-nesting birds and snag levels and between some small mammal and amphibian species and fallen trees abundance (Ruggerio et

al. 1991). These species will undoubtedly benefit from increased retention of coarse woody debris (cwd).

Retention of canopy trees may elicit a more complex response from the animal community. Species associated with open-canopy habitats are likely to fare poorly under increasing levels of canopy closure. Even relative low levels of tree and snag retention may jeopardize such species by providing perches for predators and increasing rates of nest predation. At the same time, it is not clear what levels of forest closure are sufficient for forestdwelling species. Our field studies indicate that the abundance of some forest bird species is linearly related to level of live tree retention. Other species show threshold responses where bird density is very low at levels of canopy closure below about 70%. Clearly, predicting bird community response to forest management requires consideration of both microhabitat dynamics and the habitat requirements of individual bird species.

In this chapter we demonstrate the utility of ZELIG for quantifying the responses of wood production and bird habitat diversity to alternative forest management practices. Complex silvicultural prescriptions are implemented involving harvesting, planting, thinning, and retention of canopy trees, snags, and fallen trees. Stand dynamics are simulated over several harvest rotations. And output is quantified in terms of forest structure, wood production, and bird habitat diversity.

METHODS

Prescriptions

Two types of applications were done. The first was designed to examine the effects over several rotations of differing levels of structural retention in harvest units (Figure 7). The three runs retained in harvest units, respectively, 0, low, and moderate levels of live trees, snags, and fallen trees. The regime of planting, thinning and harvest rotation regime was held constant among the runs. Harvest units were planted with 988 Douglas fir (PSME) seedlings per hectare, thinned to 543 PSME per ha at years 15 and 30, and harvested at year 100. The model was initialized with a simulated 300 year-old natural forest, and run for a 500-year period. The retention levels and management regime are within the range of those used on federal forest lands in the PNW today.

The second application involved four sets of comprehensive management treatments for lands poor in structural diversity due to past logging or other disturbance. Each differed in management objective, desired forest structure, and silvicultural manipulations (Figure 8). The wood production run emulates practices typical on private forest lands. The multiple use run is representative of many National Forest lands. Some federal forest managers are interested in hastening the development

of structural complexity in young managed stands for the benefit of late successional species like spotted owl. The habitat diversity run is designed for this purpose and gives no consideration to wood production. Finally, the natural fire run serves as a control. These projections were initiated with a simulated 70 year-old stand that regenerated naturally after deforestation. The runs continued for a 500-year period.

For all simulations, ZELIG was initialized to environmental conditions, tree species, and tree lifehistory attributes appropriate for 900 m elevation in the west-central Cascades or Oregon. Forty 0.07 ha plots were modeled for each run.

Habitat Classification

Our basic approach for classifying the habitat suitability of model results was to first obtain field data on bird abundance and vegetation characteristics in small sample plots. Discriminant Analysis was then used to develop multivariate functions distinguishing the habitat characteristics of plots occupied by a bird species from those of unoccupied plots. These functions were used to classify ZELIG plots as suitable or unsuitable for each bird species. For these classifications, the forty 0.07 ha model plots were aggregated into 10 0.28 ha plots to achieve a grain size comparable with that at which the bird data were

analyzed. Habitat suitability of a modeled stand was expressed and the percent of plots that were classified as suitable.

Field Data

Our goal was to use for the habitat analyses data from as many stand configurations as possible, in order to increase the generality of the habitat functions. We were particularly interested in including samples from managed stands with various levels of structural retention. After evaluating numerous data sets collected by various scientists, we settled on those listed in Table 8. Other data sets were not included because of incompatibility in sample design, plot size, or tree size classes. The stands included in the analysis included a nice range of age classes of natural and managed forest. The range of structural retention in managed forest was restricted to just two levels (none and ca. 30 trees per ha). [Additional data from two studies of green tree and snag retention will be available for future ZELIG applications.]

The results of all three studies were combined. Birds were sampled over two breeding seasons in each study. Habitat variables described the species and size classes of trees; size and decay classes of snags; and size and decay classes of downed logs. These data were reduced to four

diameter classes (1:2.5-10 cm; 2:10-50 cm; 3:50-90 cm; 4:>90 cm), five snag decay classes, and three log decay classes.

Habitat Functions

The assumptions of Discriminant Analysis (DFA) are that: data that are normally distributed, samples are independent, and groups are similar in covariance (Affi and Clark 1984). Our habitat data break at least the first two of these assumptions. Tests for normality revealed that the distributions of the habitat variables were heavily skewed toward 0 values. Data transformations did not help much. We reduced the skewedness by including variables that had >=30 nonzero values and by aggregated neighboring sample plots to increase the scale of analysis to 3200 m^2 . Logistic Regression (LR) does not assume normality (Affi and Clark 1984). Our comparisons of the two methods revealed little difference in the results of the habitat analyses. We decided to use Discriminant Analysis for this application, despite the skewedness of the data, and to use Logistic Regression for applications to be submitted for publication.

Both DFA and LR assume independence among plots. Our sample plots are unlikely to be independent because they were contiguous along transects and because they were small relative to the territory sizes of most of the bird species sampled. Aggregating the plots to the 3200 m² scale should reduce, but not remove, the sample dependency. We will attempt to deal more rigorously with the problem in future applications.

The selection of habitat variables strongly influences the results of DFA and the ability to satisfactorily classify the habitat suitability of ZELIG output. Stronger DFA models result when more, rather than fewer, variables that are good discriminators are considered. The generality of the classification functions is reduced, however, as variable number increases, as does the likelihood that ZELIG results will lie outside the domain of the classification functions. Consequently we chose to include the subset of all habitat variables that were the best discriminators between groups. Variables initially included in the models: had >=30 nonnegative values; significantly (P<0.10) differed between occupied and unoccupied sample plots; and were likely to have a causal (rather that correlational) effect of habitat suitability. The variable set was reduced further using stepwise DFA with F-to-enter of P=0.15 and Fto-remove of P=0.30.

A sensitivity analysis was performed to determine which of the following types of variable sets produced the strongest discriminant models: (1) tree species by size class, snag and log size by decay class; (2) tree species by size class, snag and log size class; (3) tree species by size class; and (4) tree type (hardwood and conifer) by size class. We found that the strength of the models decreased

slightly as fewer variables were included (Table 9). We choose to use variable set 4 to maximize the compatibility between the habitat classification functions and the output of the ZELIG model. The bird species reported here include the 14 species which had which significant habitat classification functions.

Analysis of Model Results

We chose to report a subset of the simulation response variables that is simple yet informative. These involve harvest level (total basal area or BA cut, cumulative harvest plus current BA of live trees), stand structure (total BA live trees, mean dbh live trees, density of snags (>10 cm dbh), volume of logs (>10 cm diameter), and bird habitat (richness, shannon index, and habitat suitability for bird guilds and selected species). The guilds were defined as follows: bark gleaners - brown creeper; closedforest understory - Swainson's thrush, winter wren; canopy gleaners - chestnut-backed chickadee, golden-crowned kinglet, hermit/Townsend's warbler, Wilson's warbler. Hammond's flycatcher, western flycatcher; open-canopy understory - orange-crowned warbler, rufus-sided towhee, rufus hummingbird, song sparrow, white-crowned sparrow. Differences among model runs were not analyzed statistically. Standard error is reported as a measure of the within sample variability.

RESULTS AND DISCUSSION

Structural Retention Runs

Forest Structure

Forest structure differed substantially among the three runs. Shading by canopy trees inhibited the growth rates of regenerating trees sufficiently that BA of live trees under no retention surpassed that under low retention by year 60 and that under moderate retention by year 100 of each rotation cycle (Figure 9). At the end of each cycle, tree BA was still increasing rapidly under no retention but had reached an asymptote for the moderate retention run. This suggests that the differences in basal area would be even more pronounced under longer rotations. Interestingly, BA of the open-grown plantation at year 100 was nearly as great as in the 300 year-old natural stand used to initiate the runs.

Mean tree dbh was inversely related to retention level during most of each harvest cycle (Figure 10). This was due to the retained canopy trees suppressing the growth of regenerating trees. Hence, variation in dbh was positively related to retention level (not shown in Figure 10).

Density of snags (>10 cm dbh) was relatively low without retention, probably due to the absence of much mortality induced by suppression (Figure 11). Snag levels were generally higher under low retention than moderate retention. The higher shading under moderate retention limited the number of trees that exceeded 10 cm dbh.

Volume of downed logs (>10 cm dbh) was generally positively related to retention level (Figure 12). The larger number of big trees (>90 cm dbh) on moderate retention plots allowed greater recruitment into the cwd population. In all cases except for low retention in the first harvest cycle, however, there were insufficient large trees at harvest time to meet the specified levels of tree, snag, and fallen log retention. More logs were retained under low than under moderate retention during the initial harvest because fewer of the large trees were required for tree and snag retention in the former run than the latter.

These findings suggest that shading by even low densities of overstory trees can substantially reduce the size structure and growth rates of regenerating PSME. At the same time, retention of large trees, snags, and fallen logs at harvest time clearly increases the abundance of snags and logs throughout the harvest cycle.

Harvest Rates

Harvest levels were, as expected, inversely related to retention levels (Figure 13). Basal area logged was nearly eight times higher under no retention than under moderate

retention. The total wood production (cumulative amount harvested plus basal area of live trees) was dramatically greater under no retention than for the other two scenarios (Figure 14). The level under no rotation exceeded that for moderate retention by 75 percent at year 100 and by almost 400 percent at year 500. These findings suggest that alternative silvicultural approaches that emphasize structural retention may have a substantial cost in terms of lost wood production.

Habitat Suitability

The guild of canopy gleaners included six species with habitat functions heavily weighted toward larger conifers (dbh classes 3 and 4). Conifers of dbh class 2 (CON2) were also included in the models for four species, though this variable contributed relatively little to the discriminatory power of the classification functions models. Simulated habitat suitability for this guild was highest during the first 20 years of each harvest rotation under the no retention run (Figure 15). Thereafter, it was generally highest under low retention.

Interestingly, these results were strongly influenced by the density of CON2. This variable was very dense under no retention during the decades following harvest, causing these plots to be scored as suitable habitat. Suitability was relatively low under moderate retention because the

shading substantially reduced the density of CON2. The density of CON4 in this run was sufficiently high to just offset the lower density of CON2 and maintain habitat suitability at a level similar to the no retention run during years 40-80 of each cycle. The low retention run had the highest suitability during these years because CON2 was only slightly lower than under no retention and because the low levels of CON4 were sufficient to more that offset this difference.

Brown Creeper, the only species in the bark-gleaners guild, was associated exclusively with CON3 and CON4. Only at the end of each harvest cycle under no retention were these variables sufficient to allow habitat to be rated as suitable (Figure 16)

The closed-forest understory guild included Swainson's thrush (associated with CON1 and CON2) and winter wren (associated with CON4). Swainson's thrush generally had suitable habitat under no and low levels of retention (Figure 17). Winter wren had habitat only after harvest under no retention, a result that conflicts with field data.

The five open-canopy species were all associated with CON1. Habitat suitability was high for the first 30 years following harvest under all three scenarios (Figure 18). Thereafter, it dropped to low levels. Differences between the three runs are not obvious.

Across the entire bird community, habitat richness and diversity were relatively high but variable during the first

few decades following harvest for all three runs (Figures 19 and 20). Both of these measures decreased by the end of each harvest cycle. This trend was due to the loss of opencanopy species and the gradual decline of habitats for canopy-gleaners (because of a decrease of CON2). Interestingly, habitat diversity during this time was positively associated with level of structural retention.

This effort to classify model output in term of suitability as bird habitat had mixed success. The results for open-canopy species were generally as expected. This provides support for the value of our basic approach. Results for the guild of canopy gleaners were less satisfactory. The effects of CON2 were too strongly expressed and resulted in patterns of habitat suitability that differ from those observed in nature. The situation could likely be remedied by using finer dbh classes. Many species react very differently to 10 cm dbh trees than to 50 cm dbh trees. It is also important for this type of analysis to obtain calibration data for more sites that have varying retention levels.

Comprehensive Prescriptions

Forest Structure

Total BA accelerated most rapidly during the first few decades in the habitat diversity and natural succession runs (Figure 21). An asymptote was reached in both by year 40 but BA continued to increase slowly for the remainder of the runs. The wood production reached relatively high levels of basal area by the end of each harvest cycle. Under multiple use, BA at the end of each harvest cycle increased with successive harvest cycles and surpassed that of wood production by year 400.

Mean dbh was greater during the latter part of each harvest cycle under wood production than for any of the other runs (Figure 22). However, virtually no trees >50 cm dbh were produced under wood production and variation in tree size was relatively low. All four dbh classes were well represented in the other three scenarios. The largest number of CON3 and CON4 in any runs occurred in years 15-100 of the habitat diversity run. This outcome suggests that silvicultural techniques are available to rapidly increase the size of canopy trees and increase variation in tree size for the benefit of late successional species or for other purposes.

PSME dominated total BA under all the runs (Figures 23 and 24). Western hemlock (TSHE) was best represented under natural succession and habitat diversity, gradually increasing in BA over the course of the runs. Some plants and animals are associated with TSHE and the dark understories they produce and would seem to benefit by the habitat diversity and multiple use prescriptions.

Snags (>10 cm dbh) were relatively sparse under wood production and somewhat higher under the three other runs (Figure 25). Volume of fallen trees (>10 cm dbh) was particularily high under the habitat diversity and natural succession runs (Figure 26). Large snags and logs are of the greatest benefit to wildlife. It would be informative to examine the size class distribution of cwd under the different scenarios. Unfortunately, we did not plot these data for this analysis.

Harvest Levels

As was found in the first application, harvest levels were substantially higher in the wood production run than in the multiple use run (Figure 27). This was also true relative to total wood production (Figure 28). Again, this illustrates the cost of structural retention in terms of reduced harvest output.

Habitat Suitability

The dynamics of the canopy-gleaner guild were controlled, as in the first application, primarily by the abundance of CON2 (Figure 29). In every case where habitat suitability exceeded 40% for this guild, CON2 was relatively high. Although CON4, the variable with which these species are most associated in nature, reached as high as 35 trees/ha, this was not sufficient to outweigh the effects of CON2. For this reason, this guild did not have increasing habitat abundance in forest with larger trees, as would be expected.

The closed forest understory guild maintained 50% habitat suitability under wood production due to the affinity of Swainson's thrush for CON1 (Figure 30). Winter wren was rare under all runs. CON4 was never sufficient for habitat to be rated suitable. This result is suspect. The problem may be that conifer species were not considered in the habitat analysis; winter wren is positively associated with large TSHE and large PSME (Table 9).

The open canopy guild had high habitat suitability during the first few decades under wood production (Figure 31). The peaks in habitat suitability for this guild were not as large following harvest under multiple use. The guild persisted at very low levels during the other two simulations. The bark gleaner, brown creeper, had no suitable habitat in any of the runs. The reasons for this are not clear.

Habitat richness and diversity for the entire community differed relatively little among the four prescriptions (Figures 32 and 33). These variables were more variable under wood production but mean values were similar to the other runs. It is important to tend to some of the above mentioned problems in habitat classification before putting much stock in these results.

CONCLUSIONS

This exercise demonstrated the utility of ZELIG for implementing complex silvicultural prescriptions and for quantifying several forest responses over long time periods. The results are useful for evaluating many of the hypotheses raised in the Introduction on the consequences of alternative silvicultural practices. Please recall, however, that this version of the model has not been validated. Until it is, model results should considered as hypothetical.

The ZELIG simulations confirm that traditional practices for wood production do result in PSME growth rates well in excess of those under natural succession. The

structural diversity of such managed stands is substantially lower than natural forests, however.

Further, the model projected that retaining structural elements at harvest has substantial consequences for stand characteristics. Even relatively low densities of canopy trees strongly inhibited growth rates of regenerating conifers and influenced forest structure throughout the rotation cycle. Consequently, simulated harvest rates and total wood production were dramatically higher under clearcutting than under retention cuts. This finding suggests that efforts to increase structural complexity and habitat diversity will have a substantial cost in wood production. It is important to note here that the present version of the model does not consider key factors influencing long-term site productivity (e.g., nutrient cycling, soil dynamics), factors that may be degraded and reduce wood production in successive cycles of traditional silviculture.

The prescriptions designed to maintain or increase structural complexity in managed forests were rather successful. Density of large trees, variation in tree size, abundance of snags, and volume of fallen trees all were relatively high under the various retention runs. Moreover, the prescription of thinning of relatively old plantations (70 years) substantially hasten the development of large trees and complex tree size structures. These findings give

hope that managed forests that are now simple in structure can be rehabilitated and be manipulated to have structural patterns more similar to natural forests.

The modeling effort was less informative about the responses of bird habitats to the different prescriptions. Our data sets adequately sampled relatively few cavitynesting species, thus we did not even include snags in the habitat functions. The habitats of open-canopy species showed expected patterns. They were abundant after clearcutting and sparse otherwise. Interestingly, the retention of canopy trees did result in less habitat for this guild than occurred without retention.

Unfortunately, results for the canopy-gleaner guild appeared anomalous. Most of these species are associated with older forests and were expected to have increasing levels of suitable habitat as forests aged. The variable set used for developing the habitat classification functions is the likely culprit. We have successfully modeled this guild in the past using data the considered both trees species and a greater number of tree diameter classes. In any case, the problems with this group of late-successional species rendered rather meaningless the comparison of overall bird habitat richness and diversity among the different prescriptions.

Several things can be done to improve the results of habitat classification for these types of ZELIG applications. Calibration data is required from a greater

range of sites. This will allow us to build significant classification functions for more species and produce functions more applicable for simulation of alternative silvicultural techniques. Additional sensitivity analyses are also needed to determine the habitat variable sets that are most useful for classifying PNW bird habitats. It is also desirable to develop habitat classifications for other taxonomic groups such as small mammals and amphibians.

It is important to keep in mind that reasonable results were obtained for over half of the bird species considered. The results for these species emphasize the utility of the general approach for projecting animal habitats under various disturbance and management regimes.

In total, these applications demonstrate the value of using gap models to examine the long-term ecological consequences of alternative stand management practices. The simulations reported here are, perhaps, the most rigorous done to date in the PNW for questions of forest structure, harvest rates, and bird habitat dynamics under alternative management practices.

NEXT STEPS

The purpose of this report was to: document the modifications made to ZELIG for PNW forests; evaluate model performance relative to field data; and to demonstrate the utility of the model for simulating forest and habitat dynamics under differing management practices.

Overall, the development of ZELIG.PNW appears to be progressing nicely. All of the new subroutines we proposed to add to the model have now been incorporated. Changes in the formulation and calibration of the height/diameter functions have substantially improved the model's ability to simulate tree growth. A large collection of empirical data sets have been assembled for model testing (probably the most complete collection ever compiled for testing a gap model). The verification effort reported here shows that, while some modifications are still needed, the model is performing rather well for PNW forests. Finally, the demonstration runs clearly show the value of the model for simulating forest and animal habitat dynamics under alternative silvicultural practices.

Several additional steps are envisioned to bring this phase of the project to its conclusion by March 1992. A new formulation of the growth equation developed by Dean Urban will be incorporated into the model. Scientists involved with ZELIG.PNW will meet in early November to evaluate this

report and decide on any additional modifications that may improve model performance. The collection of field data for validating the model will be expanded to include more plots from managed plantations. A rigorous validation will be conducted and prepared for publication. Additional data on bird habitat relations in stands with variation in structural complexity have now been collected and will be used to develop better habitat classification functions. Additional sensitivity analyses on the variable sets used for habitat classification will also be performed. Finally, applications of the model for questions of alternative silvicultural practices will be performed and submitted for publication.

5

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FIGURE LEGENDS

Figure 1. Means and 95% confidence intervals for simulated and field measures of total trees, Douglas-fir (PSME), western hemlock (TSHE), snags, and logs at 500 m elevation. Simulated means and 95% confidence intervals are based on 30 model plots. See Table 6 for sample sizes of field data. (A) densities, (B) basal area for trees and snags; volume for logs.

Figure 2. Means and 95% confidence intervals for simulated and field measures of total trees, Douglas-fir (PSME), western hemlock (TSHE), snags, and logs at 900 m elevation. Simulated means and 95% confidence intervals are based on 30 model plots. See Table 6 for sample sizes of field data. (A) densities, (B) basal area for trees and snags; volume for logs.

Figure 3. Means and 95% confidence intervals for simulated and field measures of total trees, Douglas-fir (PSME), western hemlock (TSHE), snags, and logs at 1100 m elevation. Simulated means and 95% confidence intervals are based on 30 model plots. See Table 6 for sample sizes of field data. (A) densities, (B) basal area for trees and snags; volume for logs.

Figure 4. Diameter distributions of simulated and actual stands at 500 m elevation. Stand age is noted in upper right in each graph. Simulated values are means of 30 model plots. See Table 6 for sample sizes of actual stands.

Figure 5. Diameter distributions of simulated and actual stands at 900 m elevation. Stand age is noted in upper right in each graph. Simulated values are means of 30 model plots. See Table 6 for sample sizes of actual stands.

Figure 6. Diameter distributions of simulated and actual stands at 1100 m elevation. Stand age is noted in upper right in each graph. Simulated values are means of 30 model plots. See Table 6 for sample sizes of actual stands.

Figure 7. Silvicultural prescriptions simulated in the analysis or structural retention in timber harvest units.

Figure 8. Four comprehensive sets of silvicultural prescriptions simulated with ZELIG.

Figure 9. Basal area (and SE) of live trees under three levels of structural retention as simulated with ZELIG.

Figure 10. Mean diameter at breast height (dbh) of live trees under three levels of structural retention as simulated with ZELIG.

Figure 11. Density (and SE) of snags (>10 cm dbh) under three levels of structural retention as simulated with ZELIG.

Figure 12. Volume (and SE) of fallen trees (>10 cm dbh) under three levels of structural retention as simulated with ZELIG.

Figure 13. Basal area (and SE) of live trees harvested under three levels of structural retention as simulated with ZELIG.

Figure 14. Total wood production (as determined by summing cumulative basal area of live trees harvested up until the time step with standing basal area at the time step) under three levels of structural retention as simulated with ZELIG.

Figure 15. Mean proportion of ZELIG plots classified as suitable for bird species in the canopy gleaners guild under three levels of structural retention as simulated with ZELIG.

Figure 16. Mean proportion of ZELIG plots classified as suitable for bird species in the bark gleaners gleaners

guild under three levels of structural retention as simulated with ZELIG.

Figure 17. Mean proportion of ZELIG plots classified as suitable for bird species in the closed-forest understory guild under three levels of structural retention as simulated with ZELIG.

Figure 18. Mean proportion of ZELIG plots classified as suitable for bird species in the open-canopy understory guild under three levels of structural retention as simulated with ZELIG.

Figure 19. Number of bird species classified as having some suitable habitat under three levels of structural retention as simulated with ZELIG.

Figure 20. Diversity of bird habitats as calculated with the Shannon index under three levels of structural retention as simulated with ZELIG.

Figure 21. Basal area (and SE) of live trees under four silvicultural prescriptions as simulated with ZELIG.

Figure 22. Mean diameter at breast height (dbh) of live trees under four silvicultural prescriptions as simulated with ZELIG. Figure 23. Basal area (and SE) of Douglas fir (PSME) under four silvicultural prescriptions as simulated with ZELIG.

Figure 24. Basal area (and SE) of western hemlock (TSHE) under four silvicultural prescriptions as simulated with ZELIG.

Figure 25. Density (and SE) of snags (>10 cm dbh) under four silvicultural prescriptions as simulated with ZELIG.

Figure 26. Volume (and SE) of fallen trees (>10 cm dbh) under four silvicultural prescriptions as simulated with ZELIG.

Figure 27. Basal area (and SE) of live trees harvested under four silvicultural prescriptions as simulated with ZELIG.

Figure 28. Total wood production (as determined by summing cumulative basal area of live trees harvested up until the time step with standing basal area at the time step) under four silvicultural prescriptions as simulated with ZELIG.

Figure 29. Mean proportion of ZELIG plots classified as suitable for bird species in the canopy gleaners guild under four silvicultural prescriptions as simulated with ZELIG. Figure 30. Mean proportion of ZELIG plots classified as suitable for bird species in the closed-forest understory guild under four silvicultural prescriptions as simulated with ZELIG.

Figure 31. Mean proportion of ZELIG plots classified as suitable for bird species in the open-canopy understory guild under four silvicultural prescriptions as simulated with ZELIG.

Figure 32. Number of bird species classified as having some suitable habitat under four silvicultural prescriptions as simulated with ZELIG.

Figure 33. Diversity of bird habitats as calculated with the Shannon index under four silvicultural prescriptions as simulated with ZELIG.







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Figure 5





RETENTION LEVEL

Initial condition: 300 yr old, natural regen Planted 988 PSME/ha, thinned yrs 15, 30 543 PSME/ha Duration: 500 yrs Rotation cycle: 100 yrs

	None	Low	Med	
Green Trees	0	7.4 PSME/ha canopy 7.4 TSHE/ha subcan	24.7 PSME/ha canopy 24.7 TSHE/ha subcan	
Snags	0	5/ha, >50 cm dbh random selection	12.4/ha, >50 cm dbh random selection	
Logs	0	45.6 linear m >3 m in length > 50 cm large dbh random selection	91 linear m >3 m in length > 50 cm large dbh random selection	

COMPREHENSIVE PRESCRIPTIONS

Initial condition: 70 yr old, natural regen, no legacy

Duration: 500 yrs

	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Objectives	Maximum wood production	Balance wood production, early and late habitat diversity	Maximize late seral habitat diversity	Control: Natural succession after severe fire
Target Structure	Even tree size, spacing age; single canopy layer; no snags or logs	2-3 tree size classes and canopy layers, moderate retention of trees, snags, logs;	Multiple tree sizes, ages and canopy layers; canopy heterogeneity; high retention of CWD and snags	Low canopy tree, moderate snag and log retention; natural regeneration
Prescription	Clearcut (70 yr cycle), remove all CWD plant 988 PSME/ha thin yr 15&30 to 543 trees/ha 70% PSME 30% TSHE	Clearcut (100 yr cycle), retain: 19.8 trees/ha can 19.8 trees/ha subcan 50% PSME 50% TSHE 10 snags/ha >38 cm dbh 225 m/ha logs >3 m len >38 cm dbh thin as in sim 1	Retain 124 trees/ha can 50% PSME 50% TSHE convert others to snags all trees >10 cm dbh plant PSME TSHE THPL 82/ha each yr 80, kill canopy trees to 74/ha 50% PSME 50% TSHE retain others as snags	Retain 19.8 PSME/ha can 19.8 PSME/ha subcan 25 snags/ha >38 cm dbh 527 m/ha logs >3 m len >38 cm dbh random selection natural regeneration

LIVE TREES



LIVE TREES





SNAGS

Year



LIVE TREES HARVESTED



Standing Basal Area and Cumulative Harvested











BIRD HABITAT RICHNESS









Year

Figure 21





Figure 22



Figure 23

WESTERN HEMLOCK







SNAGS

Figure 25

FALLEN TREES



Year

Figure 26





Year



Standing Basal Area and Cumulative Harvested

Figure 28





Figure 30



Figure 31



Habitat Richness





Figure 33

·	Coefficients			
Species	A	E	С	R ²
ABAM	62.4651	-0.0195	1.4244	0.91
ABPR	85.3823	-0.0077	0.8947	0.83
ACMA	28.9092	-0.0257	0.5598	0.38
ALRU	32.7916	-0.0276	0.7382	0.57
ARME	23.3639	-0.0244	0.6826	0.52
LBDE	34.9528	-0.0196	1.0781	0.76
PIJE	45.5568	-0.0213	1.3293	0.68
PIPO	52.4950	-0.0151	0.9411	0.80
PISI	100.0395	-0.0028	0.7052	0.82
PSME	84.1202	-0.0085	0.9262	0.84
QUGA	19.8971	-0.0430	1.2711	0.52
TABR	20.0000	-0.0700	1.1000	_2
THPL	60.1341	-0.0082	0.7839	0.82
TSHE	63.6254	-0.0139	1.0149	0.87
TSME	34.5450	-0.0382	1.6489	0.83

Table 1.	Regression coefficients used to predict tr	:ee
	height from diameter at breast height. ¹	

¹ Height[m]-1.37 = $A*(1 - \exp(B*dbh[cm]))^{C}$

² estimated

	BFT ²		BBL		BBD		BSB		BSW	
Species	во	B1	во	B1	во	B1	во	B1	во	B1
ABAM	2.3591	2.1926	1.6708	2.6261	-0.17724	2.8050	2.965718	2.3179	4.124354	2.4970
ABCO	2.3591	2.1926	1.6708	2.6261	-0.17724	2.8050	2.106921	2.7271	2.551192	2.7856
ABGR	2.3591	2.1926	1.6708	2.6261	-0.17724	2.8050	2.106921	2.7271	2.551192	2.7856
ABLA	2.3591	2.1926	1.6708	2.6261	-0.17724	2.8050	2.253295	2.3149	4.018261	2.3891
ABPR	2.0349	2.1683	2.7261	2.3324	3.37880	1.7500	2.791887	2.4313	3.600994	2.6043
ACMA	3.1427	1.6170	2.6717	2.4300	4.79180	1.0920	2.338000	2.5740	3.414800	2.7230
ALRU	2.4473	2.3149	-0.9119	3.4886	-0.70784	2.6240	2.265353	2.4617	4.238755	2.4618
PSME	4.0616	1.7009	3.2137	2.1382	3.37880	1.7500	2.902625	2.4818	4.841987	2.3323
TABR	2.7778	2.1280	1.7588	2.7780	-0.17724	2.8050	2.766209	2.3474	4.176308	2.5353
THPL	4.2908	1.7824	3.6417	2.0877	3.37880	1.7500	2.385440	2.1987	3.862652	2.4454
TSHE	2.7780	2.1280	1.7588	2.7780	-0.17724	2.8050	2.766209	2.3474	4.176308	2.5353

Table 2. Regression coefficients used to predict above ground total biomass of trees¹ (obtained from the BIOPAK system [Means et al. 1991]).

 $\ln[g] = B0 + B1 + \ln(dbh[cm])$

² BFT = live foliage mass, BBL = live branch mass, BBD = dead branch mass, BSB = stem bark mass, BSW = stem wood mass. Total above ground biomass = BFT+BBL+BBD+BSB+BSW

	Coefficients			
Species	BO	B1	B2	Equation Form ¹
ABAM	0.291600	-	-	1
ABCO	0.222300	-		1
ABGR	0.222300	-	-	1
ABLA	0.271900	-	-	1
ABMA	0.246700	-	-	1
ABPR	0.273400	-	-	ī
ACMA	1.623161	2.224620	0.575610	2
ALRU	4.988311	2.499900		3
PICO	0.378200	— 1	-	1
PIEN	0.310700	-	-	ī
PIJE	0.273900	-	-	1
PILA	0.250900	-	-	1
PIPO	0.293400	-	-	1
PISI	0.228600	-	-	1
PSME	0.234600	-	-	1
TABR	0.254200	-	-	1
THPL	0.218000	-	-	1
TSHE	0.254200	-	-	1
TSME	0.292100		-	1

Table 3. Regression coefficients used to predict tree volume (obtained from the BIOPAK system [Means et al. 1991]).

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1 1-> m³= B0 * dbh[m]² * height[m] 2-> cm³= B0 + B1 * ln(dbh[cm])² + B2 * ln(height[m]) 3-> cm³= B0 + B1 * ln(dbh[cm])

<u></u>		Snags		-	Logs
Decay group ¹	Decay class	Duration in decay class ² (yrs)	Breakage (% vol.)	Decay class	Duration in decay class ² (yrs)
I	I II III	20 40 60	10.0 67.0 0	I II III IV V	15 35 77 130 219
II	I II III	15 25 40	0 46.0 0	I II III IV V	10 26 53 116 194
III	I II III	8 10 22	0 59.0 0	I II III IV V	5 17 39 102 174
IV	I II III	5 13 22	0 62.0 0	I II IV V	7 15 25 51 -
v	I II III	5 10 15	0 54.0 0	I II IV V	5 13 19 39 -
1 slow ince I II III	v-decayi ense-ced ≥ 65 cm > 40 < ≤ 40 cm	ng species (De ar) dbh 65 cm dbh dbh	ouglas-fir,	western	redcedar,
fast IV <u>></u> V <	-decayi 25 cm 25 cm	ng species (a dbh dbh	ll others)		

Table 4. Parameters used to model snag and log dynamics in ZELIG, version PNW.OSU.2. (from Graham 1982).

² years since death

Forest management options included in ZELIG.PNW.OSU.2. Associated with each option are user-specified parameters that control the specifics of the management action. Table 5.

	Option	Parameters
1)	Clearcut without green- tree retention	simlulation year
2)	Clearcut with green- tree retention	simulation year; retention level, min. size, canopy status, and species(s) of retained trees.
3)	Thinning	simulation year; thinning level [based on basal area or density], min. size, canopy status, and species(s) of trees retained.
4)	Retention of snags	simulation year; min. size and density of snags retained, and method used to retain snags - select from existing snag pool, select from live trees, randomly select from live trees and snag pool, fixed proportion from live trees and existing snags, or all snags become trees (species id of trees may be selected, but not required).
5)	Retention of logs	as in 4, but for logs. Additionally, min. length of a retained log and total linear length of logs instead of density can be specified.
6)	Establish a plantation	simulation year, stocking density by species.

	Stand Age	# of plot	.S	
Elevation	(yrs)	Trees & Snags	Logs	
500 m	20	8		
(400-600 m)	40	28	22	
	50	5	-	
	60	6	5	
	80	7	5	
	90	19	13	
	200	6	6	
	450	23	23	
900 m	10	7	7	
(800-1000 m)	20	. 7	7	
•	40	5	-	
	70	17	17	
	130	14	14	
	140	6	6	
	300	6	6	
	450	40	40	
	500	15	15	
1100 m	20	5	-	
(1001-1200 m)	60	9	8	
•	80	8	8	
	150	9	5	
	320	5	5	
	450	21	5	

Table 6. Number of plots by elevation and age included in the verification data base.

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Table 7. Site and species parameters used in ZELIG simulations for each elevation.

Site: Oregon Cascades

Lat: 44.0 Long: 122.4

Soil parameters:

Field Capacity (cm): 30.00 Wilting point: 15.00 Fertility (max annual productivity): 25.00 Mg/ha

500 m Elevation

Month	ly ter	mperat	tures	(^o c)	and :	standa	ard de	eviat	ions		
J	F	M	A	М	J	J	A	S	0	N	D
2.4	4.8	6.9	9.6	11.4	11.8	16.8	13.6	15.8	12.1	6.4	2.3
2.0	1.7	1.8	1.9	1.3	1.2	1.0	1.6	1.1	0.9	1.7	1.8
Month	ly pre	ecipit	tation	n (cm)	and	stand	dard d	deviat	tions	:	
J	F	M	Α	M	J	J	Α	S	0	N	D
21.9	13.8	15.1	10.8	6.7	5.7	1.4	2.3	6.1	10.1	22.5	25.5
14.8	11.1	10.1	5.4	5.2	5.2	1.6	3.6	5.6	10.7	17.7	18.1

<u>900 m Elevation</u>

Monthly	y tem	perat	ures	(°c)	and s	standa	ard de	eviati	ions		
J	F	М	Α	M	J	J	Α	S	0	N	D
1.0	2.9	.4.9	8.6	10.6	12.3	16.5	14.9	14.9	11.1	8.1	0.9
2.0	1.7	1.8	1.9	1.3	1.2	1.0	1.6	1.1	.9	1.7	1.8

Monthly precipitation (cm) and standard deviations: J F M A M J J A S O N D 26.3 17.0 17.5 12.8 7.5 6.5 1.8 2.8 7.3 11.3 25.3 30.8 14.8 11.1 10.1 5.4 5.2 5.2 1.6 3.6 5.6 10.7 17.7 18.1

<u>1100 m Elevation</u>

Monthly temperatures				(°c)	and s	standard deviations					
J	F	М	A	M	J	J	Α	S	0	N	D
0.2	1.8	3.8	7.8	9.8	11.8	15.9	14.7	14.1	10.1	8.0	0.2
2.0	1.7	1.8	1.9	1.3	1.2	1.0	1.6	1.1	. 9	1.7	1.8

Month]	ly pre	ecipit	tation	(CM)	and	stand	ard	deviat	tions:		
J	F	M	Α	M	J	J	Α	S	0	N	D
28.5	18.6	18.7	13.8	7.9	6.9	2.0	3.0	7.8	11.9	26.6	33.3
14.8	11.1	10.1	5.4	5.2	5.2	1.6	3.6	5.6	10.7	17.7	18.1

Continued, next page

Table 7.,	Cont'd.	Species	parameters	used	in	ZELIG,	version
		PNW.OSU.	2.				

Species	Age	DBH	Height	G	GDD	S	D	N	Seed
TSHE	500	225	8000	190	311 2480	ī	3	$\overline{2}$	5
PSME	1100	300	8500	215	604 2461	4	4	2	5
THPL	1500	300	6000	150	292 2481	2	3	2	÷ 5
ABAM	600	200	7500	180	118 1815	1	2	2	5
ALRU	100	150	4000	225	400 3080	4	2	2	5
TABR	400	50	2000	40	311 2030	2	3	2	3
ACMA	300	250	4000	100	478 2361	2	2	2	5

Age (yrs), DBH (cm), and Height (m) are maximum values; G is the growth parameter; GDD is the degree day limits (minimum, maximum); S, D and N are coded values for tolerance to shade, drought, and nutrient stress, respectively; Seed is relative rate of sapling establishment. Table 8. Bird habitat data set used to generate habitat classification `functions.

Stand Sampling Plot Size Sample P.I.s LocationElev. Name Size² Type¹ (m²) (用) Hethod ------------....... 200-500 MOC, MY Transect 800 1200 Coast Hansen West-NM Range Peterson Central OR Coast Horvath Range 900-1100 NM, OG Transect 800 400 West-Roswell Hansen Ridge Central Noon Purcell OR Waters Cascades 700-1300 MOC, SW Transect 800 580 Blue Hansen West-River Spies Central OG OR Cascades ¹ MOC (managed open canopy)-Clearcuts (2-8 years), no structural retention.

' MOC (managed open canopy)-Clearcuts (2-8 years), no structural retention. MY (managed young)-Douglas-fir plantation (25-30 years), no structural retention.

NM (natural mature)- natural forest (80-190 years).

OG (old growth)-natural forest (>=200 years).

SW (shelter wood)-Douglas-fir plantation (3-6 years) with retention of ca. 30 canopy trees per ha.

² Number of plots.

Table 9. Attributes of Discriminant Analysis habitat classification functions for two bird species across different sets habitat variables.

Data Variable Kappa³ R⁴ Variables⁵ Set¹ Set² Winter Wren PSME4+PSME5+TSHE5 CR 1 .55 .36 -TJPL2-PSME1 TSHE5+PSME5+PSME4 CR 2 .43 .29 -PSME1 . .29 PSME5+TSHE5-PSME1 .42 CR 3 .26 CON5+CON4-CON1 CR 4 .58 .31 .14 CON4+HWD2 ALL 4 Song Sparrow CR .81 .60 PSME1+LOG22-PSME3 1

CR	2	.72	.56	PSME1+LOG2-PSME3
CR	3	.69	.51	PSME1-PSME3
CR	4	.66	.51	CON1
ALL	4	.60	.35	CON1-CON2

¹ CR-Coast Range, ALL-all data sets in Table 1.

- ² 1-trees by species and 5 size classes, snags and logs by size and decay classes; 2-trees by species ad 5 size classes, snags and logs by size classes; 3-trees by species and 5 size classes; 4-trees by type (conifer or hardwood) and 4 size classes.
- ³ Cohen's Kappa Statistic (Titus et al. 1987), a measure to the percent better than chance of classification success of the calibration data.
- ⁴ Coefficient of determination.

⁵ PSME1,3,4,5-density of Douglas-fir trees of in size classes 1,3,4,5; TSHE5-density of western hemolock in size class 5; TJPL1-density of western redcedar in size class 1; CON1,4,5-density of conifer trees in size classes 1,4,5; HWD2-density of hardwood trees in size class 2; LOG22-density of fallen logs in size class 2 and decay class 2; LOG2-density of fallen logs in size class 2.