SIMULATED ADAPTIVE MANAGEMENT FOR TIMBER AND WILDLIFE UNDER UNCERTAINTY

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ABSTRACT.—A spatially explicit stochastic behavior simulation model for the endangered red-cockaded woodpeckers (*Picoides borealis*) is coupled with a forest management optimization algorithm to simulate adaptive (feedback) management within an uncertain environment. To update the adaptive forest harvest schedule in a timely manner during each management planning period, a genetic algorithm heuristic is employed. This model is used to evaluate management policies for the production of timber and red-cockaded woodpeckers.

Forest management plans are typically based on an "optimal" activity schedule which can be rendered infeasible during implementation due to changes in the resources being managed and management goals. Thus in practice, such an activity schedule is evaluated periodically during implementation, and is often replaced with a newly generated "optimal" schedule. This paper describes an analytical tool for evaluating management strategies that take into account this adaptive implementation of activity schedules.

Computer simulation models offer valuable, and often the only, tools for testing and examining intricate theories concerning the response of wildlife to management activities. This is especially true for species that depend on a variety of resources in specific spatial patterns at the landscape level. In this study a spatially explicit wildlife behavior simulation model is coupled with forest management optimization algorithm to simulate adaptive management (feedback) for timber and wildlife benefits. Uncertainty is introduced into the system through the stochastic simulation of changes in the spatial distribution of red-cockaded woodpecker (*Picoides borealis*) (RCW) groups. The changes in the distribution of the RCW groups influence the decision options for forest management optimization, and forest harvest activities influence the distribution of RCW groups. This results in a feedback loop between simulated wildlife behavior and forest management. To generate near optimal forest harvest schedules in a timely manner, a genetic algorithm (GA) optimization heuristic is applied. The result is a feedback system between RCW groups and forest management actions.

This modeling system (Hughell 1996) is used to evaluate adaptive management policies and optimization strategies over a 200-year planning horizon. The management policies define each stand's minimum rotation age as a function of the stand's proximity to a RCW group. The optimization strategies are volume control and the utilization of explicit 200-year near optimal harvest schedules (generated by a genetic algorithm).

RCW GROUP BEHAVIOR / FOREST MANAGEMENT MODEL

The Red-cockaded woodpecker (*Picoides borealis*) (RCW), an endangered species associated with the coastal pine forests of the southern U.S., is considered a cooperative breeder because of the manner in which it nests and forages in family groups (which consist of a breeding pair and reproductively mature helpers) (Walters et al. 1988). RCW prefer to nest in live longleaf pine (*Pinus palustris*) trees over 95 years of age, or in loblolly pine (*P. taeda*) over 75 years, although they have been found in much younger trees (Hooper 1988).

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The RCW group behavior / forest management model[2] grows even-aged longleaf pine stands, simulates the behavior of RCW groups and harvests stands based on specified management schemes. The forested landscape is modeled as a lattice of 4-hectare hexagon cells. Each stand is grown and RCW foraging suitability (birds / hectare) is calculated accordingly. RCW behavior and stand development are simulated in five-year iterations, nested within 20-year forest management cycles which harvests stands based on their current condition and proximity to RCW nesting groups (Fig. 1).

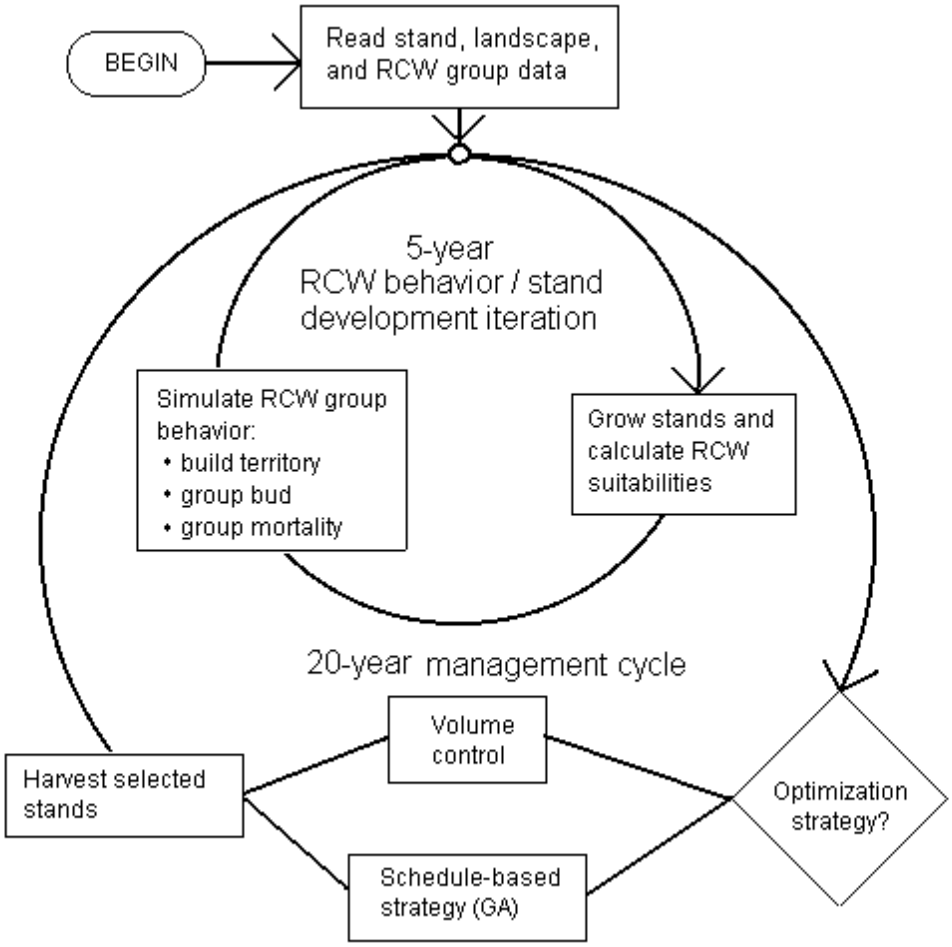

Figure 1.—Flow diagram for the RCW group behavior / forest management model.

RCW group behavior simulation

At the beginning of each five-year RCW behavior iteration, deterministic equations based on stand age and site index project the wood volume and RCW foraging suitability. The equation for estimating the foraging resources is based on a RCW energy-cost territory viability model developed by Smith and Coles (1993). Because creation of RCW foraging habitat is a benefit provided by standing trees (as opposed to a benefit realized only when the trees are harvested), the parameter of interest for the evaluation of different rotation ages is the cumulated flow of foraging resources up to when the stand is harvested (Hartman 1976). Therefore, compatible equations were developed for estimating the current foraging resources (for RCW behavior simulation) and accumulated foraging resources (for management planning).

[2]The source code (*Borland C++*) are available upon request to Dr. Joseph Roise (email: roise@cfr.cfr.ncsu.edu).

The optimal single-stand rotation age based on the culmination of the mean annual increment is 30 years for timber and 110 years for RCW foraging resources. Based on this information, the theoretical tradeoff between timber and RCW is obvious -- harvest as early as possible for timber and harvest at 110 years for RCW. However, the true situation is more complex once the distribution of the stands through time and space is taken into account.

The wildlife simulation model abstracts the behavior of RCW groups down to three activities: (1) build RCW foraging territories; (2) "bud" (create) RCW groups with a specified probability; (3) destroy RCW groups with a specified probability. RCW foraging territories are simultaneously built by sequentially appending adjacent cells to the territory of each RCW group until the group has accumulated sufficient foraging resources. In the event that a RCW group is unable to append sufficient unoccupied foraging cells (within the maximum RCW foraging distance of one km from the group's nesting cell) to accumulate the minimum required foraging resources, then that group is destroyed and its foraging cells are released for other groups. After all the territories are built, each group is sequentially evaluated for a potential bud (split) with a given probability (annual per group bud probability is .1). Once a group has been selected for a potential bud, one of its foraging cells is stochastically selected (weighted by the available foraging resources) to be the nesting site for the new group, and foraging territories are simultaneously built for the existing group and the new group. If the territory build operation is unsuccessful, then only one group remains.

A typical simulation is 200 years (40 five-year RCW iterations and ten 20-year management cycles). The simulation outputs evaluated are the minimum one planning period wood volume harvested and the average number of RCW groups over the last 100 years of simulation. The former corresponds to the maximum even flow volume of timber produced, and the latter to the RCW viability, after a 100 year warming-up period.

Forest Management

The forest management cycle determines the set of stands to be harvested in the current 20-year planning period based on the user specified *management scheme*, made-up of a *RCW management policy* and an *optimization strategy*. These schemes provide the mechanism to produce different mixes of timber and RCW benefits. The *RCW management policy* defines the width of a circular buffer around each RCW group nesting cell, and the minimum harvest ages for the stands inside and outside this buffer. The reasoning here is that RCW groups can be favored by extending the harvest age for those stands nearest to the RCW nesting site. Only if the RCW proximity buffer width is assigned a value of zero can a stand with a RCW nesting group be harvested (labeled a "non-RCW management policy"). Otherwise, stands containing active nesting groups can never be harvested, although they can be scheduled for harvest in future planning periods. Information on where individual RCW groups are foraging is not used for management planning since this information is usually not available for real world management planning.

The *optimization strategy* determines whether a rule-based or a schedule-based algorithm is applied to select the stands to be harvested. The rule-based strategies programmed are volume control with random selection of stands and the selection of the oldest stands first. In either case, stands are selected for harvest until a predefined target volume is met or until there are no more stands available for harvest. The implementation of the volume control strategies requires simulations with different target volumes to determine the harvest level that results in the best combination of timber and RCW outputs.

The schedule-based optimization strategies formulate the scheduling problem as a Model I optimization problem (Johnson and Scheurman 1977) for maximizing a linear combination of the multiple objectives of minimum one-period timber volume and accumulated RCW foraging resources. Included in the description of the optimization strategy are the relative weights assigned to the resource outputs.

These optimization problems can theoretically be solved by integer linear programming (ILP), however for problem sizes of over 450 management prescriptions (decision variables) solutions were rarely obtained within 12

hours of CPU time with *Lindo*[3] on a SUN SPARC UNIX workstation (Hughell 1996). Because scheduling problems generated by the simulation model have up to 8000 management prescriptions, and because each simulation run must solve ten such optimizations (one for each 20-year management cycle), ILP is not a feasible option. Therefore, a genetic algorithm (GA) optimization heuristic is utilized to produce a set of near optimal solutions in a timely manner. A genetic algorithm (GA) is a random search heuristic guided by the principles of natural selection and Darwinian evolution, with it roots in efforts to model biological genetic processes through computer simulation. It is a technique for searching a space of potential solutions in order to locate a superior set of solutions which are superior (Goldberg 1989, Michalewicz 1992).

RESULTS

The RCW group behavior simulation / forest management model is applied to demonstrate the application of stochastic simulation to evaluate adaptive management schemes for the sustained production of timber and wildlife benefits. Three randomly generated landscapes and one landscape representing a 4800 hectare section of the Croatan National Forest (eastern North Carolina) are simulated. Each random landscape is made-up of a systematic mosaic of seven-cell stands randomly assigned an age between 0 and 120 years and a site index between 45 and 105 feet (base age of 50 years). RCW groups are randomly located within the landscape. For the Croatan National Forest landscape, all pine stands are treated as longleaf pine and all non-pine stands are treated as non-forested land.

The management policies evaluated are buffer widths from zero to 800 meters with a minimum rotation age of 100 years inside the buffer and 60 years outside. Hughell (1996) evaluated other minimum harvest ages and found these values were represented in the majority of the management schemes that make-up the joint production possibilities frontier (non-inferior solution set).

The optimization strategies evaluated are:

(i). volume control with random stand selection;
(ii). volume control with age-based stand selection;
(iii). harvest schedule (generated by GA) with weights from 0 to 1.0 assigned to timber and foraging resources.

For each management scheme (combination of management policy and optimization strategy) and landscape, eight simulation runs with identical starting conditions were executed to assess the variability in outcome. Each run covered a 200-year simulation horizon divided between 40 five-year RCW behavior cycles and ten 20 five-year management periods. The statistics collected for each run were the minimum one-period timber volume harvested (corresponding to the MAXMIN timber optimization objective) and the average number of RCW groups over the last 100 years of simulation (the first 100 years was considered a warming-up period and, therefore, ignored). These two output statistics were then averaged over the eight simulation runs for the management scheme and plotted against each other to determine graphically those schemes that define the joint production possibility frontier[4].

Management Schemes

As expected, larger buffer widths and higher weight assigned to the RCW foraging resources resulted in more RCW groups, and smaller buffers and weights produced more timber. With few exceptions, the volume control

[3] Lindo 5.3, Linear Interactive Discrete Optimizer, Lindo Systems, Chicago, IL.

[4] The joint production possibility frontier is the noninferior decision set of solutions, where an improvement in one of the objective is not possible without a loss in the other objective.

strategy with the selection of the oldest stands first was superior to the volume control strategy with the random selection of stands. This is because the older stands are usually already beyond the age where the culmination of timber volume has occurred and, therefore, are the best candidates to be harvested for the production of timber. The selection of the periodic target volume for volume control is critical to the success of the volume control optimization strategy. Here this selection is made through multiple simulation runs with different target volumes.

To evaluate characteristics common to all four landscapes evaluated, the joint production possibility frontier for the simulations carried-out on these landscapes was scaled to a per hectare basis and plotted in Figure 2. For all landscapes except for the largest (R200), the schedule-based optimization strategies (that define the joint production possibility frontier) produced more timber, while the non-schedule based volume control strategies produced more RCW groups. This can be attributed to the uncertainty introduced into the system by the RCW groups. With no uncertainty (i.e. non-RCW management) the GA generates a near optimal harvest schedule which, when implemented, maximizes the production of timber. However, as management objectives favor RCW groups, more uncertainty is introduced into the system and it is more likely the selected harvest schedule will become infeasible. Therefore, at some RCW density the implementation of harvest schedules becomes more of a liability than an advantage toward meeting management objectives.

With the larger landscape (R200), two factors work against the schedule-based optimization strategy. First, with more decision options (a result of the large number of stands), it is more difficult for the GA to obtain harvest schedules with a performance sufficiently near that of the optimal schedule. Therefore, management decisions are consequently based on inferior harvest schedules. The second factor is that with more stands there is more flexibility in the selection of stands to meet the target volume.

The Croatan National Forest landscape (CNF) produced less timber and fewer RCW groups per hectare (Fig. 2) because of its lower overall site index (57 compared with 72 feet) and the irregular shapes of stands, making it more difficult for RCW groups to obtain a contiguous block of foraging resources.

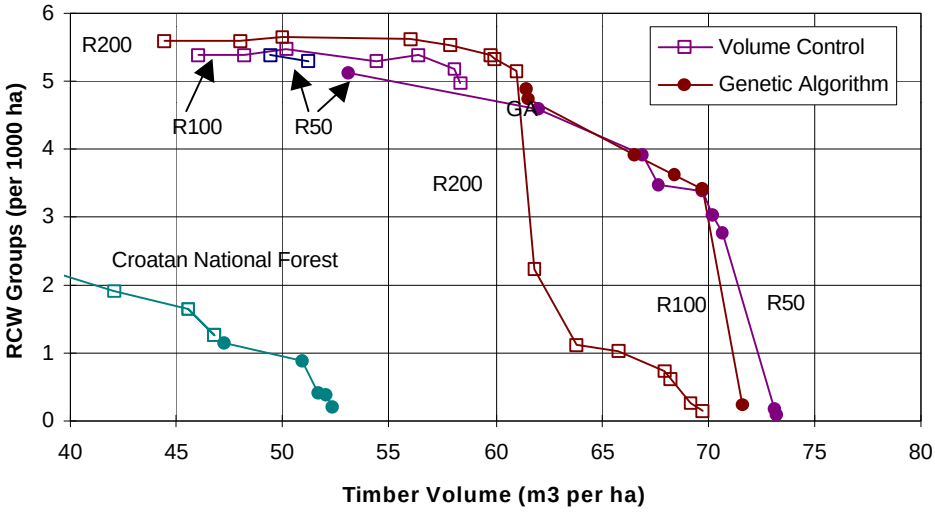

Figure 2.—Comparison of timber and RCW outputs among four landscapes studies (R50, R100, R200 and CNF). Management schemes are identified as volume control (VC) and schedule-based genetic algorithm

CONCLUSIONS

Through example, this study demonstrates how optimization techniques can be coupled with wildlife behavior simulation models to test adaptive management policies and optimization strategies. However, it is important to

recognize that this study is based on a highly simplified representation of reality. The behavior of RCW groups has been abstracted down to three processes: build RCW group foraging territories, split RCW groups and destroy groups. It is assumed that timber on all stands grow along deterministic (age - volume) growth curves based only on site index. It is also assumed that the RCW foraging and nesting suitability is a deterministic function of the stand age and site index. The only stand management decision option considered is in which planning periods should a stand be harvested. As of this writing, no attempts have been made to validate the model.

Despite the simplicity of the models developed, this study demonstrates how different management policies and optimization strategies can be evaluated within the context of adaptive management. It was found that above a certain level of uncertainty, the application of non-schedule based strategies (e.g. simple volume control) are more effective at producing both superior timber and wildlife benefits than the implementation of explicit harvest schedules.

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