Coarse Filter Ecosystem Management in a Nonequilibrating Forest

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ABSTRACT. The natural disturbance model of forest management is the basis of many of the sustainable forest management systems being proposed for the boreal forest of Canada. Wildfire is the dominant natural agent of disturbance in the boreal mixed-wood forest. The natural disturbance model assumes that timber harvesting systems emulating the annual area burned by natural fire, its spatial distribution, and the amount of residual material can be developed. It is further assumed that natural processes can be emulated closely enough to maintain forest biota at natural or near-natural population levels. This is a coarse filter approach to ecosystem management.

In order to emulate the natural rate of disturbance, one needs to quantify it. The annual area burned in the study area, under natural conditions, is characterized as a random draw from a lognormal distribution. A modeling system comprised of an aspatial Monte Carlo simulation model and a linear programming based forest activity scheduling model was developed. The simulation model is used to develop 200 yr forecasts of probability distributions for habitat area of five vertebrate species under a stochastic wildfire regime. These probability distributions are used to construct habitat area constraints for use in an optimization model to help quantify the trade-offs between timber values and maintenance of the range of natural variability in the forest.

The model is used to identify the trade-offs between forest harvesting, wildlife habitat, and the degree of similarity between the managed forest structure and the distribution of structures that could be generated by natural disturbance. FOR. SCI. 49(2):209–223.

Key Words: Timber supply, wildlife habitat, forest fire, natural disturbance, simulation, optimization.

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SCIENTIFIC AND PUBLIC CONCERNS about biodiversity, the sustainability of wildlife habitat, and other difficult-to-value services of forested ecosystems are leading governments and forest products companies in Canada to move away from sustained yield timber management towards sustainable forest management. The goal of management is changing from the production of an optimum mix of commodities and services from the forest (e.g., timber, range, water, wildlife, and recreation) to the maintenance of the ecological integrity of the forest: the production of the commodities and services is taken to be a byproduct of a healthy ecosystem. The Alberta Forest Legacy (Alberta Environmental Protection, undated) and the Canadian Council of Forest Ministers' (1997) Criteria and Indicators of Sustainable Forest Management are evidence of a political commitment to sustainable forest management in Canada.

Ecosystem health and ecological integrity are difficult concepts to define and measure. Partly as a result of this difficulty, the natural disturbance model (NDM) of sustainable forest management has been developed (Hunter 1993). By mimicking the results of natural processes as closely as possible, it is hypothesized that NDM management will minimize the negative impacts of timber harvest on forest biota. Hunter (1993) identifies three ways in which timber harvesting practices could be used to emulate natural disturbance:

1. the rate of harvest could be matched to the rate of natural disturbance,
2. the size and spatial organization of harvest blocks could be matched to the size and spatial organization of openings created by natural disturbance, and
3. the amount of residual organic material left on-site after harvest could be matched to that which would be left after a natural disturbance.

Hunter's approach is a coarse filter approach to ecosystem management in the context of the coarse filter/fine filter system proposed by the Nature Conservancy (1982). The underlying hypothesis is that maintenance of the distribution of habitat types that would occur under natural conditions (the coarse filter) will satisfy the habitat requirements for most species while recognizing that more specific management prescriptions (the fine filter) are needed for species of special concern. Hunter (1990, p. 238–239) provides a good summary of the coarse and fine filter approaches. Much of the discussion of NDM management for the boreal mixedwood forest section (Rowe 1972) of western Canada has focused on emulating the effects of stand-replacing wildfire, because it is the most important, or at least the most dramatic, natural agent of change in this part of the boreal forest.

Of the three ways in which harvesting can emulate wildfire, the harvest rate decision is likely to have the greatest direct impact on the costs and benefits of timber production. A change in the annual harvest area will obviously have an impact on the annual harvest volume. The harvest rate decision will also have important ecological impacts as it will directly affect the future age class distributions of the forest. Because of successional pathways, the species composition of the forest may also be affected by changes in the harvest rate.

The magnitude of annual fluctuations in natural disturbance rates may make emulation of the rate of natural disturbance unacceptable to the forest products companies managing much of Canada's boreal forest. Nearly constant rates of disturbance are not natural, and the variation associated with natural rates of disturbance may not be acceptable from a timber production standpoint. How can the natural disturbance model be reconciled with the desire for a relatively stable stream of outputs from the forest? The solution may be to change the focus of the natural disturbance model from emulating the rate of disturbance to emulating the outcomes of the natural disturbance regime.

In this article, we will use the term *forest structure* to refer to the composition of the forest as described by the area in each cover type by age class combination. The goal of natural disturbance management is to manage the forest in a way that maintains the naturalness of the forest, while capturing some of the economic benefits of timber production. In a highly stochastic ecosystem with no equilibrium structure, judging the degree of naturalness to be achieved in the managed forest is difficult: there is no naturally occurring equilibrium structure against which to compare structures resulting from management.

We use a Monte Carlo simulation model to project the natural development of forest structure over a 200 yr time period using an annual time step. The forest is subject to disturbance by fire, but no harvesting is permitted in the simulation model. The output of the simulation model can be used to produce an empirical probability density function (EDF) of the area in each cover type by age class combination, for each year of the simulation period.

Five vertebrate species with very different habitat requirements were chosen to provide an aggregated representation of the forest structure. In this representation, forest structure is described in terms of the area of habitat (of at least a specified quality index) for each of the five species. Projections of the EDF of habitat area for each of the species over the 200 yr simulation period are used a shorthand representation of the distribution of forest structure outcomes that could occur if the forest was left unmanaged and was subject to natural disturbance.

Quantiles from these projected EDFs of habitat area were used to set minimum habitat area constraints in a forest activity scheduling model, with the goal of examining tradeoffs between financial objectives and the "naturalness" of the managed forest.

Background

Fire Regime

In order to emulate natural disturbance through timber harvest, the rate of natural disturbance must be quantified. Conceptually, the simplest way to quantify the rate of disturbance is to use a single number such as the average annual rate of burn. Van Wagner (1978) used this representation of

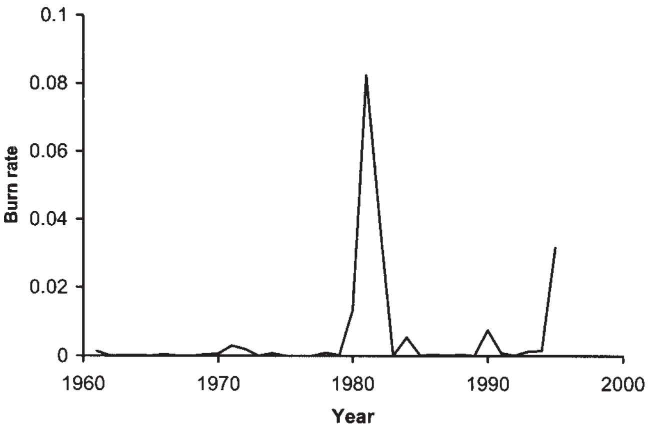

Figure 1. Historical rate of burn for study area (corrected for fire suppression effects).

disturbance by wildfire to develop the negative exponential model of the equilibrium age class structure for a forest subject to a constant annual burn rate. If the annual rate of disturbance can be treated as constant, the rate of harvest under the natural disturbance model would be set to the natural rate, assuming that wildfire is replaced by harvesting in the managed system. Armstrong et al. (1999) examine the timber supply implications of this management regime with different characterizations of this natural rate for an area in northeastern Alberta, Canada. Harvey et al. (2002) propose an NDM management regime for a forest in northwestern Quebec. They specify a target age-class structure based on the negative exponential model, and a fire cycle of 140 yr.

Figure 1 shows the annual rate of burn compiled by Armstrong (1999a) for an 8.6 million ha study area in the boreal mixedwood forest of northeastern Alberta, Canada. Clearly, this time series does not show a constant annual rate of burn. Armstrong (1999a) characterizes the area burned in each year of this time series as a serially independent random draw from a lognormal distribution. This characterization has two very important implications for the natural disturbance model: the "true" mean rate of natural disturbance for this area is not practically quantifiable because of the extreme variability of the observed rates, and there is no equilibrium age class distribution for a forest with this natural disturbance regime. For this part of the boreal mixedwood forest, management strategies based on a fixed annual rate of disturbance (e.g., Armstrong et al. 1999), or designed to produce a specific age class structure (e.g., Harvey et al. 2002) clearly do not emulate the natural system. See Armstrong (1999a) for a more complete discussion of these issues. Armstrong's lognormal model of the disturbance regime for this area provides the disturbance component of the simulation model used in the current study.

Habitat Models

Cumming et al. (1994) used a deterministic aspatial simulation framework to examine potential conflicts between wildlife habitat and timber supply. Their representation of habitat quality is used for the current study. The forest is described in terms of area in cover type by habitat stage combinations. The recognized cover types were pine, white spruce, aspen, mixed, and black spruce. The white spruce, aspen, and mixed cover types represent stands that occur on mesic sites. They are differentiated based on crown closure by species group. The white spruce cover type comprises mesic stands with 80% or more of the crown area occupied by softwood species; the aspen cover type comprises mesic stands with 80% or more of the crown area occupied by hardwood species; and the mixed cover type represents all other mesic stands. Six habitat stages were recognized: establishment, the interval to maximum stem density, the interval to maximum crown closure, the interval to maximum basal area, a mature stage, and an overmature stage. These habitat stages were related by to stand age and cover type as shown in Table 1.

Cumming et al. (1994) relate cover type and habitat stage to habitat quality for five vertebrate species: American marten (*Martes americana* Turton), meadow vole (*Microtus pennsylvanicus* Ord), broad-winged hawk (*Buteo platypterus* Vieillot), black-throated green warbler (*Dendroica virens* Gmelin), and northern three-toed woodpecker (*Picoides tridactylus* Linnaeus). These species are not special in the sense that they are endangered or at risk in Alberta. The

Table 1. Habitat quality index by vertebrate species, cover type, and habitat stage. Blank entries represent a habitat quality index of 1. After Cumming et al. (1994).

		Habitat stage					
Species	Cover type	1	2	3	4	5	6
American marten	Pine			2	2	2	2
	White spruce			2	3	4	6
	Mixed				2	3	4
Meadow vole	Pine	3	2				
	White spruce	6	3				
	Aspen	6	3				
	Mixed	6	3				
	Black spruce	3	2				
Broad-winged hawk	Aspen					4	6
	Mixed				4	5	4
Three-toed woodpecker	Pine	4			2	4	5
	White spruce				3	4	6
	Mixed				2	3	4
	Black spruce	3			2	4	6
Black-throated green warbler	White spruce			2	4	5	4
	Mixed			2	4	6	6

Table 2. Habitat stage definition by cover type and age range. After Cumming et al. (1994).

Habitat stage		Age range (yr)	
ID	Description	Aspen cover type	Other cover types
1	Establishment	0–5	0–5
2	To maximum stem density	6–15	6–25
3	To maximum crown closure	16–30	26–60
4	To maximum basal area	31–60	61–100
5	Maturity	61–80	101–150
6	Overmaturity	81+	151+

marten, vole, and woodpecker are listed as secure; the hawk and warbler are listed as sensitive in Alberta (Alberta Sustainable Resource Development 2002). These species were chosen because they have very different habitat requirements, allowing for a convenient shorthand representation of the structure of the forest. They also have relatively small home ranges, which may allow for their habitat requirements to be represented with an aspatial model.

Cumming et al. (1994) justify their choice of species as follows:

> The pine (sic) marten was chosen for its preference for mature stands containing white spruce, and because it and other large mustelids face habitat losses throughout the circumpolar boreal forests... . The meadow vole illustrates a species dependent upon open, recently disturbed habitat. The three-toed woodpecker is characteristic of old coniferous stands, whereas the black-throated green warbler is associated with mature and older mixed and coniferous stands. The broad-winged hawk nests and forages almost exclusively in mature deciduous stands.

The habitat quality indices developed by Cumming et al. (1994) and presented in Table 2 were based on a review of available literature—see their article for a thorough discussion of the habitat models used here. Habitat quality index is coded as an integer between one and six inclusive, where one represents unsuitable habitat and six represents ideal habitat. This numeric scale follows that used by McNichol et al. (1981) to indicate avian abundance in different habitats. It proves to be convenient for the modeling presented here.

Study Area and Starting Forest Structure

The initial forest structure and yield relationships used in this study are based on data provided by Daishowa-Marubeni International Ltd. (DMI) for part of their Forest Management Agreement (FMA) area in north-central Alberta, Canada. The FMA area is an important timber supply area for a pulp mill and several sawmills. The study area is approximately bounded by 56°N and 57°40′N lat. and 115°W and 117°W long. The starting age-class distribution by cover type is shown in Table 3. This represents the current condition of the 888,713 ha of net merchantable land base for the study area. The net merchantable land base is the part of the total forest area considered suitable and available for timber harvest activities. The area is net of stands which are considered never merchantable due to low projected volume, muskegs and other wetlands, and areas deleted for stream and lake buffers, and other operational considerations. Harvestable volumes are assumed to change with stand age according to the yield tables presented in Figure 2. The most striking feature of the initial forest structure presented in Table 3

Table 3. Initial forest structure for study area. Area (ha) by age and cover type.

Age (yr)	White spruce	Aspen	Mixed	Pine	Black spruce	Total
10	2	5			18	25
20	70	636	2,483	6,210	521	9,920
30	5	3,400	710	231	3	4,349
40	1,050	1,304	1,049	663	128	4,194
50	4,552	61,422	7,196	2,402	2,068	77,640
60	18,970	224,645	33,004	31,950	15,674	324,243
70	8,420	82,523	11,718	10,675	11,164	124,500
80	7,307	39,726	8,289	3,743	6,805	65,870
90	6,531	11,763	6,203	2,364	11,545	38,406
100	14,407	30,753	12,688	3,844	12,275	73,967
110	8,310	11,674	5,386	2,425	4,686	32,481
120	11,015	12,301	9,348	1,144	2,534	36,342
130	17,193	7,554	8,802	330	4,516	38,395
140	17,398	8,052	6,309	426	4,027	36,212
150	6,779	1,590	3,005	695	2,498	14,567
160	1,614	198	243	912	1,781	4,48
170	443	25	12		73	553
180	23				20	43
190	384		134	6	289	813
200			26		22	48
210	90				265	355
260					42	42
Total	124,563	497,571	116,605	68,020	80,954	887,713

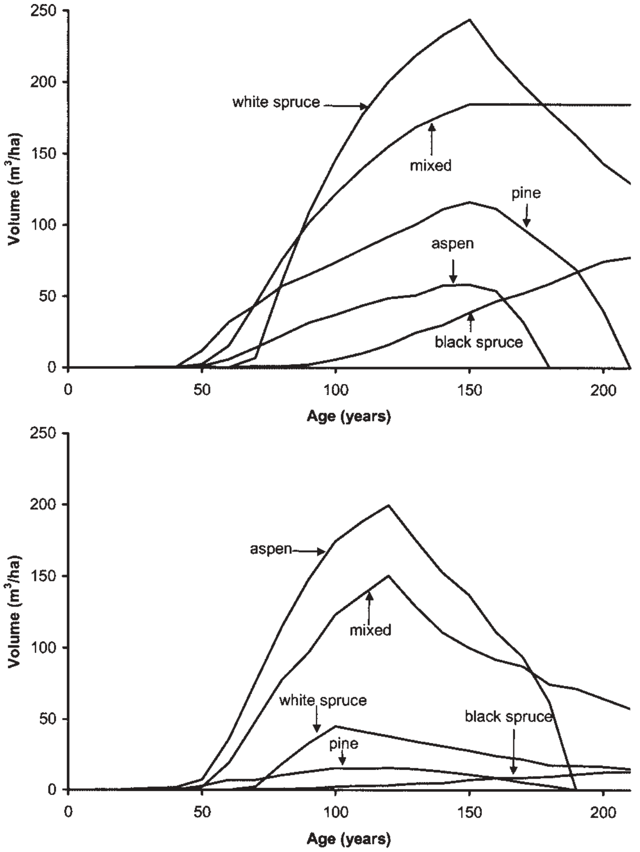

Figure 2. Softwood (top) and hardwood (bottom) merchantable volume yields (m^{3}ha^{-1}) by cover type and age (yr).

is the large area of forest in the 60 yr age class (324,243 ha or 36.5% of the land base). Spikes in the age class distribution are characteristic of forests subject to the lognormal disturbance regime (Armstrong 1999a). Most of the yield curves presented in Figure 2 show declining volumes somewhere between 100 and 150 yr of age. These declines reflect stand breakup.

Literature Review

The research reported here is related to two major streams in the literature: the relationship between timber supply and catastrophic events, and the relationship between timber supply and wildlife habitat. Some of the earliest literature relating timber production to the risk of fire was related to the effect of incorporating fire risk on the optimal forest rotation (Routledge 1980, Martell 1980, Reed 1984). The major result from this work was that recognition of the risk of a stand-killing fire reduces the optimal rotation age of an even-aged stand. Van Wagner (1978) showed that the equilibrium age class distribution of a forest subject to a constant annual rate of burn follows a negative exponential distribution. Using a simulation model, he later examined the joint effects of harvesting and fire on the long-term sustainability of timber supply levels (Van Wagner 1983). Reed and Errico (1986) develop a model similar to Van Wagner's in a linear programming framework. A major assumption of these models is a constant annual rate of burn. Boychuk and Martell (1996) improve on the representation of the annual burn rate by incorporating the probabilities of high and low burn rate years in an optimization framework.

In the landscape ecology literature, spatially explicit models incorporating human and natural disturbance are becoming increasingly common [e.g., LANDIS (Mladenoff and He 1999) and DISPATCH (Baker 1999)]. Hof and Bevers (1998) present several optimization models capturing many important spatial relationships for wildlife habitat including edge and area dependencies, habitat size thresholds, habitat connectivity, and population growth and dispersal. They also present models which include measures of species richness and equity in the objective function, with the intent of sustaining biodiversity. The spatially explicit dynamic models presented by Hof and Bevers (1998) are typically quite small in terms of the number of distinct spatial units recognized (they commonly use 25 cells arranged in a grid). This is at least partly due to the computational difficulties of solving large spatially explicit mathematical programming problems.

Montgomery et al. (1994) present an interesting study linking a spatially explicit population viability analysis of the northern spotted owl (*Strix occidentalis* caurina [Merriam]) to habitat protection efforts and to markets for timber. In this way, the authors were able to develop estimates of the marginal cost for the probability of preservation of a species. This is a fine filter approach to ecosystem management in that the habitat requirements and population dynamics of one species is modeled in great detail. The fine filter approach is particularly relevant to endangered species.

Spatially explicit models are enjoying a great deal of popularity in the landscape ecology and conservation biology literature. This is partly due to the assumption that habitat fragmentation and other metrics of landscape pattern are important factors related to the probability of population extinction. However, there is some evidence that habitat loss (reduction in area) may have a greater impact on the probability of extinction than fragmentation (i.e., total habitat area is more important than its spatial arrangement). Fahrig (1997, 2001) uses an individual based, spatially explicit simulation model to show that the effects of habitat loss can greatly outweigh the effects of fragmentation. Trzcinski et al. (1999) examined the effects of forest cover and fragmentation on the presence of 31 forest breeding bird species (as determined from Breeding Bird Atlas data) on ninety-four 100 km^2 landscapes. The results of this study indicate that habitat area is a better predictor of species presence than the degree of fragmentation of the landscape. Schmiegelow and Mönkkönen (2002) argue that the relative importance of habitat area and fragmentation is ecosystem- and species-specific.

Cumming et al. (1994) develop an aspatial simulation model to explore potential conflicts between timber production and wildlife habitat. The habitat models developed by Cumming et al. (1994) are used directly in this study. The study uses a highly aggregated aspatial representation of the forest. This is a departure from the current trend toward very detailed spatially explicit representations of forests in planning models, but is adequate for the problem modeled here, given that the main objective of this study is to demonstrate how projected variability in habitat area over time could be used to set criteria for judging the success of coarse filter ecosystem management. If spatially explicit habitat models for these species in this study area were available, they could be used in a similar manner, at the cost of additional computing time.

By our use of an aspatial habitat model here, we are not suggesting that aspatial models can capture all important habitat elements for all animals. This is clearly not the case. Many animals use different vegetation types to satisfy different needs (e.g., food and cover). These vegetation types need to be close enough to each other to allow the animals to move between them. The ability of animals to disperse through an area often requires a travel corridor with specific characteristics. The spatial configuration of vegetation types may be an important determinant of the suitability of an area as habitat for some species.

The focus of this article is not on the survival of a particular species such as presented in Montgomery et al. (1994). Nor is it the development of optimal forest harvesting plans under the risk of catastrophic disturbances as presented in Reed and Errico (1996) and Boychuk and Martell (1996). This article is about the development of a set of constraints that can be used to capture the intent of coarse filter ecosystem management objectives (as expressed in Hunter's natural disturbance model, and the concept of the range of natural variability) in a nonequilibrating system such as the boreal forest. We view this study as a small step toward a system incorporating ecosystem management goals and timber production, in an optimization model applied to a dynamically variable ecosystem. We believe that the representation of the goals of coarse filter ecosystem management as formulated here provides a useful starting point for discussion and further research.

Monte Carlo Habitat Projection

Monte Carlo simulation is a technique that can be used when one or more of the variables in the simulated system is a random variable. The value that such a variable takes on in a simulation is determined by a random draw from the variable's assumed probability density function. By repeating the simulation procedure several times, one can develop an understanding of the probability density functions for outputs of the modeled system.

Monte Carlo simulations were used to project the probability distribution of habitat areas for each of the five vertebrate species. One thousand simulated projections of forest structure were run, each of which projected the development of the forest for 200 yr. The starting point of each projection was taken to be the initial forest structure (Table 3). In each year of each simulation, the annual burn rate (λ_t) was drawn from the lognormal distribution estimated by Armstrong (1999a).

$$\lambda_t = \min(0.20, \exp x),\ \ x \sim N(\mu, \sigma^2),\ \ t = 1, 2, \ldots, 200 \qquad (1)$$

These simulations use $\mu = -8.097$ and $\sigma = 2.853$. These parameters are easily interpretable: μ is the mean of the natural logarithm of the annual proportion of the area burned under a natural disturbance regime; σ is the standard deviation. The annual proportion of area burned for this study was truncated at 0.20 in order to prevent burn proportions much greater than evident from the historical record.

The simulation model takes the following steps:

1. For each of the 1,000 simulation runs
    (a) Retrieve the initial forest structure as area in cover type by age combinations.
    (b) For each of the 200 yr in the simulation
        i. Randomly draw the annual disturbance rate from the distribution described by Equation 1.
        ii. Determine the area burned in each cover type by age cell by multiplying the area of the cell by λ_t. Set the age of the burned proportion to zero. Increment the age of all cells by one year.
        iii. Use Table 1 to assign a habitat stage to each new cover type by age cell.
        iv. Use Table 2 to assign a habitat quality index to each cover type by age cell for each species.
        v. For each of the habitat quality indices from 2 through 6
            A. Calculate the total area of habitat of at least the habitat quality index being processed.
            B. Store the results for processing in Step 2, below.
2. For each of the 200 years in the simulation
    (a) For each of the five vertebrate species
        i. For each of the habitat quality indices from 2 through 6
            A. Sort the stored results by ascending total area.
            B. Create an EDF by assigning a quantile to each item in the sorted list (position in the list divided by 1,000).
            C. Store the results.

These simulations represent the development of the forest in the study area over a 200 yr period in response to the natural fire regime. No timber harvest or fire protection activities are modeled in the simulations. The simulations took approximately 5 hr to run on a 500 MHz dual Pentium III processor running Microsoft Windows NT 4.0.

The most important outputs of the simulations are the EDFs of habitat area. Figure 3 shows the EDF for black-

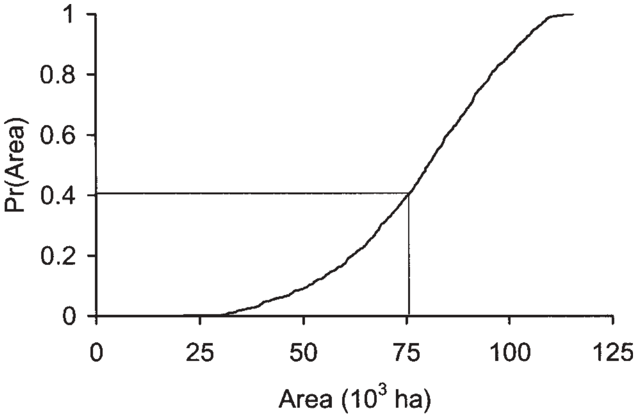

Figure 3. Empirical cumulative probability density function for black-throated green warbler habitat of habitat quality 5 or 6, in year 50.

throated green warbler habitat with a quality index of five or better, in year 50 of the simulations. The simulation output contains the information to produce EDFs like this one for each of the species, each of the habitat quality indices, and each year in the simulations. There are 1,000 points that make up the curve, each one corresponding to a Monte Carlo run. The habitat quantiles can be read from this curve by drawing a horizontal line from the desired quantile on the vertical axis to the curve, and from the intersection dropping a vertical line to the horizontal axis from which the habitat area associated with the quantile can be read. In this case the habitat area associated with quantile 0.40 is approximately 75,000 ha.

In this article, the focus is on good habitat, that is, habitat with a quality index of five or greater. Simulation results for the other quality indices are presented in Armstrong (1999b). Figure 4 presents 200 yr projections of the empirical distribution functions of good quality habitat used to set constraints for the optimization part of this study. The probability distributions of the area of good habitat are projected for each of the five species. The panels of the figure show the 95% confidence limits and the quartiles for each of the projections. The main conclusions to draw from this figure are that, under natural conditions, one would expect the median habitat areas for each of the species to change substantially over the projection period, and that variation in projected habitat areas become extremely large in a relatively short period of time (say, 20–40 yr). The large changes in projected median habitat areas indicate that the system is not currently in an equilibrium with respect to area of habitat for the five species examined, and the large variation around the median reflects the nonequilibrating nature of the system.

The habitat area projections for broad-winged hawk and for black-throated green warbler show a large increase at 20 and 40 yr, respectively. This reflects the transition of a large area of aspen from habitat stage 5 to habitat stage 6 (ideal habitat for broad-winged hawk) at 20 yr from present, and the transition of a large area of mixed from habitat stage 4 mixed to habitat stage 5 at 40 yr from present. Both transitions reflect the spike in the age class distribution at 60 yr. In both cases, the habitat quality index changes from 4 to 6 at the time of the transition.

This presents an interesting planning problem. Under the natural disturbance model of management, the goal is to maintain the characteristics of a natural ecosystem. However, the simulations conducted show that there is no single "ecologically correct" mix of habitats for the forest and that the realized mix of habitat areas is likely to change dramatically over time. Another consideration is that there are trade-offs between areas of habitat for the different wildlife species. For example, with the models used here, overmature white spruce is good habitat for American marten and three-toed woodpecker, but less than ideal for meadow vole, broad-winged hawk, and black-throated green warbler. Allowing white spruce stands to reach overmaturity delays the creation of new good habitat for meadow vole, broad-winged hawk, and black-throated green warbler.

The values for μ and σ used in these simulations are statistical estimates of the true values for these parameters. It is useful to examine the sensitivity of the simulation results to the parameters used to characterize the disturbance regime. The 95% confidence limits ($\mu \pm 1.96\sigma/\sqrt{n}$) for the mean were calculated to be –9.042 and –7.151. The simulations were rerun with these confidence limits serving as the value for μ. Figures 5 and 6 summarize the simulation results for the lower and upper confidence limits, respectively. The results for the estimate and the lower limit of μ are very similar. The results when μ is set to the upper confidence limit are quite different from the base case. The median values of habitat area for the black-throated green warbler, broad-winged hawk, American marten, and three-toed woodpecker are at considerably lower levels than under the base case. This is a reflection of substantially higher burn rates, resulting in smaller areas of older forest at the end of the simulation period. Any characterization of the natural disturbance rate for an area will be an estimate. Sensitivity analyses of results to variations in these estimates will usually improve the understanding of the problem.

Constrained Optimization

For the purposes of the optimization model, it is assumed that the objective of the forest manager is to maximize the net present value of timber harvest. Because of concerns for wildlife habitat, minimum habitat areas will be expressed as constraints. Fire suppression occurs and is assumed to be 100% effective. Thus we ignore the effects of fire in the optimization model.

The forest management problem is framed as a straightforward implementation of the Model II timber harvest scheduling formulation [Johnson and Scheurman (1977)] with additional constraints on the minimum level of habitat area for each species of interest in each time period. The notation used here closely follows that used by Dykstra (1984, p. 130–136). The model was developed using the Woodstock modeling system (Remsoft Inc. 1998). Following the convention used in the Woodstock documentation, we will use the term *development type* to refer to areas of forest that follow a particular yield curve. We assign yield curves based on the cover types identified in Table 3, so in this case, development types correspond to cover types. A timber type

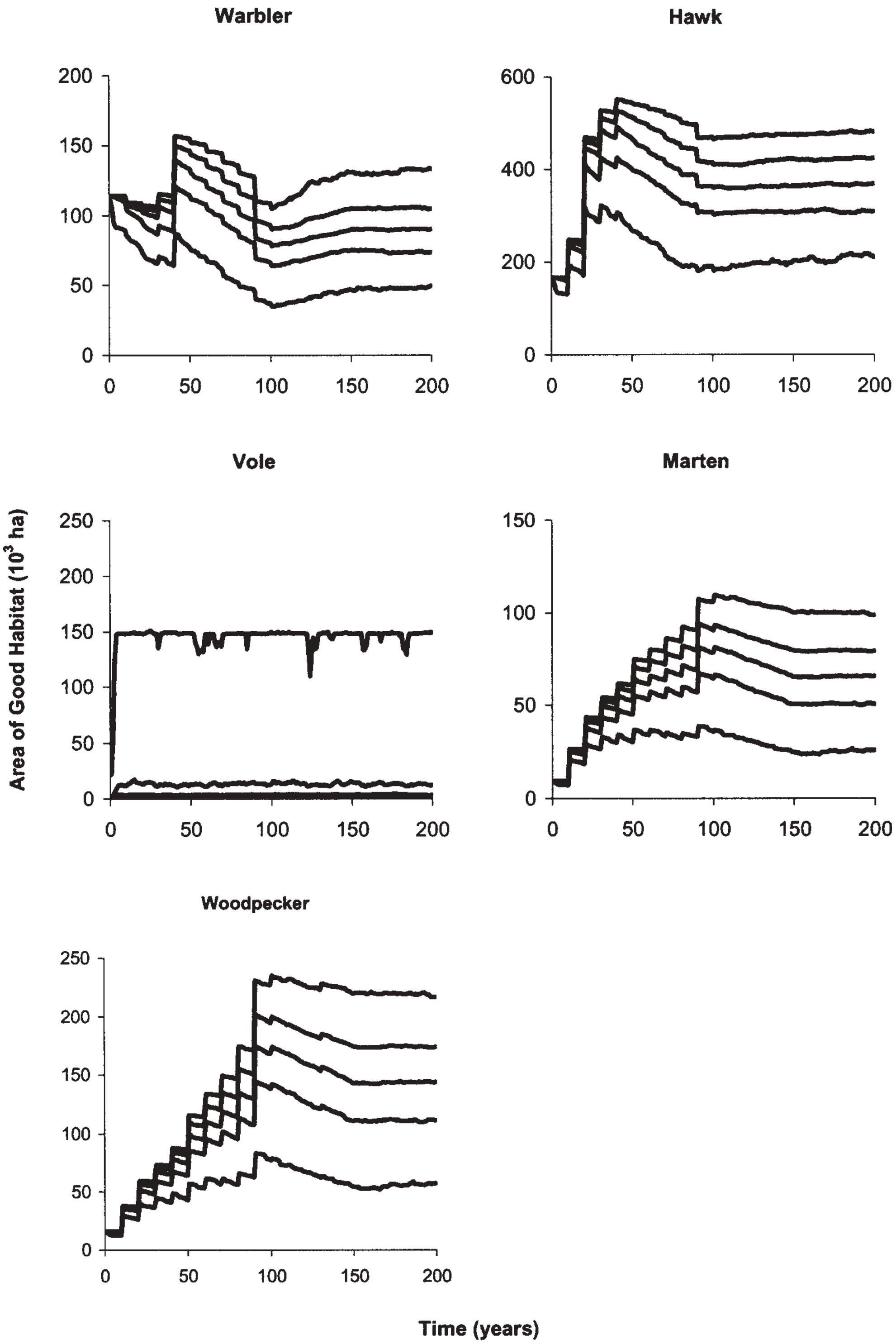

Figure 4. Projected habitat area quantiles for habitat quality indices of five or greater for five vertebrates. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. μ as estimated (–8.097).

refers to a particular age class within a development type.

The objective function used here is

$$\max Z = \sum_{i=1}^{D} \sum_{k=1}^{H} \sum_{j=-M+1}^{k-N} c_{ijk} x_{ijk} \tag{2}$$

where

Z = net present value ($)

D = the number of timber development types,

H = the number of periods in the planning horizon,

x_{ij} = area (ha) of forest in development type i, born in period j, and harvested in period k,

M = age of oldest existing timber type, in periods,

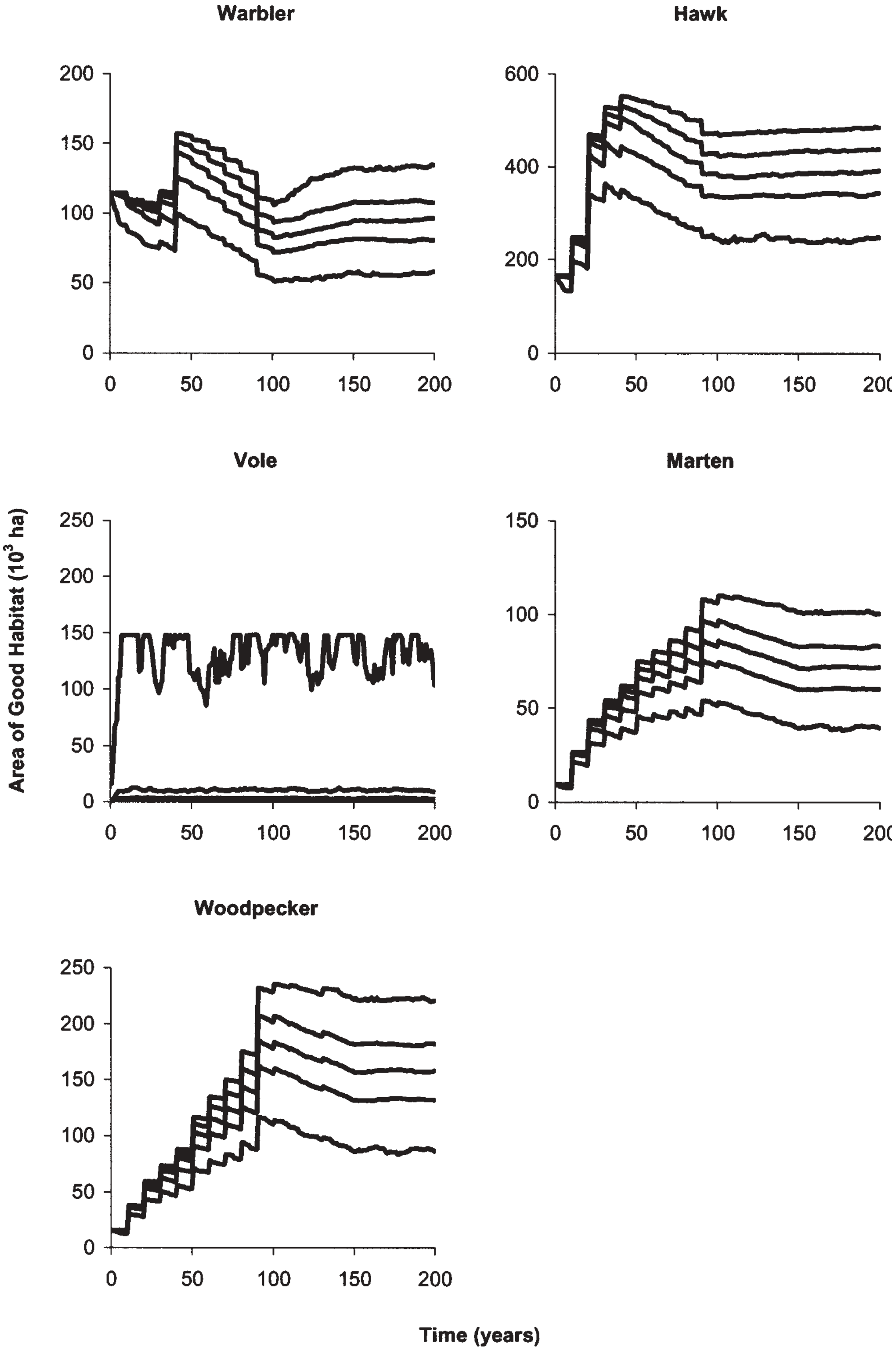

Figure 5. Projected habitat area quantiles for habitat quality indices of five or greater for five vertebrates. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. μ at lower confidence limit (–9.042).

N = minimum number of periods between birth and harvest, and

c_{ijk} = discounted net revenue ($/ha) associated with harvesting in period k, forest in development type i that was born in period j.

Area constraints are incorporated to ensure that all of the area of the forest is explicitly assigned to a harvest or no-harvest activity.

$$\sum_{k=1}^{H} x_{ijk} + u_{ij} = A_{ij} \qquad i = 1, 2, \dots, D; \quad j = -M+1, -M+2, \dots, 0 \qquad (3)$$

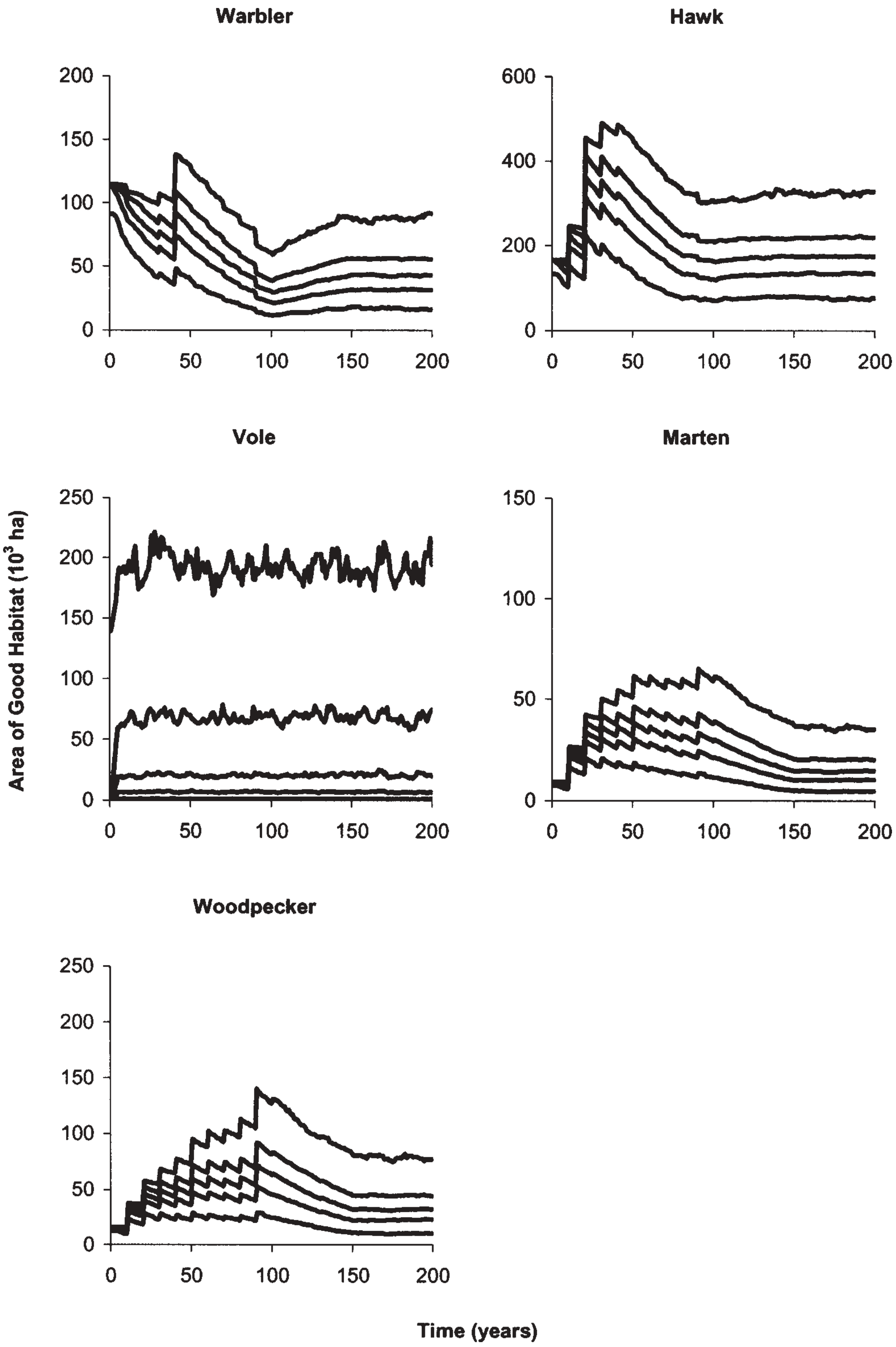

Figure 6. Projected habitat area quantiles for habitat quality indices of five or greater for five vertebrates. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. μ at upper confidence limit (–7.151).

$$\sum_{l=k}^{H} x_{ikl} + u_{ik} = \sum_{j=-M+1}^{k} x_{ijk} \quad i=1,2,...,D; k=1,2,...,H \quad (4)$$

where

A_{ij} = initial area (ha) of development type *i* born in period *j*, and

u_{ij} = area(ha) of forest in development type *i* born in period *j* that is never harvested in the planning horizon.

Volume flow constraints are used to control the variation in the harvest of timber volume from one period to the next.

$$(1-\alpha)F_k - F_{k+1} \leq 0 \qquad k=1,2,...,H-1 \qquad (5)$$

$$(1-\beta)F_k - F_{k+1} \ge 0 \qquad k = 1,2,\ldots,H-1 \tag{6}$$

$$F_k = \sum_{i=1}^{D} \sum_{j=-M+1}^{k} v_{ijk} x_{ijk} \qquad k = 1,2,\ldots,H-1 \tag{7}$$

$$(1-\alpha)G_k - G_{k+1} \le 0 \qquad k = 1,2,\ldots,H-1 \tag{8}$$

$$(1-\beta)G_k - G_{k+1} \ge 0 \qquad k = 1,2,\ldots,H-1 \tag{9}$$

$$G_k = \sum_{i=1}^{D} \sum_{j=-M+1}^{k} w_{ijk} x_{ijk} \qquad k = 1,2,\ldots,H-1 \tag{10}$$

where

F_k = softwood volume (m^3) harvested in period *k*,

α = maximum proportional decrease in harvest volume from one period to the next,

β = maximum proportional increase in harvest volume from one period to the next,

v_{ijk} = softwood harvest volume (m^3ha^{-1}) associated with development type *i*, birth period *j*, and harvest period *k*,

G_k = hardwood volume (m^3) harvested in period *k*, and

w_{ijk} = hardwood harvest volume (m^3ha^{-1}) associated with development type *i*, birth period *j*, and harvest period *k*.

Inventory accounting rows are used to track the area of forest in each timber type at the beginning of each period.

$$R_{ij1} = A_{ij} \qquad i = 1,2,\ldots,D;\ j = -M+1, -M+2,\ldots,0 \tag{11}$$

$$\begin{aligned} R_{ijk} = R_{ijl} - x_{ijl} \qquad & i = 1,2,\ldots,D; \\ & j = -M+1, -M+2,\ldots,0; \\ & k = 2,3,\ldots,H;\ l = k-1 \end{aligned} \tag{12}$$

$$\begin{aligned} R_{ijk} = \sum_{l=k}^{H} x_{ijl} + u_{ij} \qquad & i = 1,2,\ldots,D;\ j = 1,2,\ldots,H-1; \\ & k = j+1, j+2,\ldots,H \end{aligned} \tag{13}$$

where

R_{ij} = area (ha) of development type *i*, born in period *j*, standing at the beginning of period *k*, and

h_{ijkl} = habitat coefficient for development type *i*, birth period *j*, time period *k*, for species *l*.

Equation (11) accounts for the standing inventory at the beginning of the first period. Equation (12) accounts for the area of forest born before the period that is standing at the beginning of the second and subsequent periods. Equation (13) accounts for the area of forest born during the planning horizon.

The habitat area constraints for each species are

$$\begin{aligned} \sum_{i=1}^{D} \sum_{j=-M+1}^{k} h_{ijkl} R_{ijk} \ge Q_{kl} \qquad & k = 1,2,\ldots,H; \\ & l = 1,2,\ldots,C \end{aligned} \tag{14}$$

Nonnegativity constraints apply to each activity in the linear programming formulation.

$$x_{ijk} \ge 0; u_{ij} \ge 0; F_k \ge 0; G_k \ge 0; R_{ijk} \ge 0 \qquad \forall i,j,k \tag{15}$$

For this study, h_{ijkl} was set to one for each combination of development type, birth period, time period, and animal species that has a habitat index of five or greater according to Table 2. For every other combination, h_{ijkl} was set to zero. The intent of this formulation was to allow for constraints on area meeting a particular habitat quality. An alternative formulation would be to model habitat quality using a continuous scale such as used in a habitat suitability index (HSI) approach. In the usual presentation of HSI models, ideal habitat has an HSI of 1, unsuitable habitat has an HSI of 0, and intermediate habitats have values somewhere between these extremes. If available, HSI models of this form could be used directly in the model formulation presented here: h_{ijkl} would simply be set to the HSI appropriate for the combination of development type, birth period, time period, and animal of interest.

The annual discount rate is assumed to be 5%. The conversion surplus value is assumed to be 60 \$ m^{-3} for softwood timber and 50 \$ m^{-3} for hardwood timber at the mill gate. As used here, conversion surplus is a measure of the value of logs delivered to the mill. It represents the selling price of the final products (e.g., lumber and pulp chips) less all the variable costs of milling and marketing the product, expressed on a per cubic meter of roundwood basis (Davis et al. 2001, p. 407). Every harvested stand is assumed to be clearcut. However, the yield curves could easily be modified to reflect a volume reduction due to an increase in residual organic material if desired. Stands are assumed to regenerate immediately to the same cover type after harvest. Regeneration costs are assumed to be incorporated into harvest costs. Timber harvest costs are assumed to be 5000 \$ ha^{-1}. Nondeclining yield (NDY) constraints are applied simultaneously to softwood and hardwood volumes: the harvest volume in any one period is constrained to be at least the harvest volume in the previous period. This is consistent with timber harvest scheduling policy on public lands in Alberta. A set of runs was conducted without the NDY constraints to allow for costing of the NDY constraints.

The EDFs for wildlife habitat developed through Monte Carlo simulation are used to set constraints on habitat levels for each of the wildlife species. Runs are made where the habitat area for all species are simultaneously constrained to be at least a specified quantile of the probability distribution of the area of good habitat in each of the periods of the planning horizon. The quantile constraints used are 0.0, 0.025, 0.05, 0.10, 0.125, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.45. The 0.0 quantile represents no habitat constraints (i.e., a pure timber emphasis). The optimization problem is infeasible for all habitat constraint levels of 0.45 or greater. This means that it is not possible for the forest to simultaneously provide good habitat at or above this level for all five vertebrate species over all periods in the planning horizon. Beyond this level, the habitat area for any species can only be increased at the expense of another species.

As implemented in this study, the habitat constraints are variable over the planning horizon, and essentially follow the development of the system under natural conditions, given the forest's present state. An alternative option would be to fix the constraints to a level based on the "steady state" probability distributions. For all five species examined here, the probability distributions of good habitat area stabilize after 100 to 150 yr of simulation. In some cases, it may make more sense to constrain habitat levels based on the terminal distribution. A case in point in this study is the black-throated green warbler. The current area of good habitat for this species is greater than the median area of projected habitat 200 yr in the future. Constraining habitat in early years to levels greater than this median level may be very costly and may be unnecessary if the end point is more important to the decision maker than the path taken to get to it.

The system was modeled using the Woodstock forest modeling package (Remsoft Inc. 1998) and solved using the C-WHIZ linear programming (LP) software (Ketron Management Science 1998). Woodstock provides a convenient way of specifying a forest management problem using a flexible syntax. It can generate an LP matrix as input to solution software such as C-WHIZ and translate the LP solution into easily understandable summary tables and graphs. Five-year periods and a 25 period (125 yr) planning horizon were used for all the Woodstock models. Each of the LP models created took about 2 seconds to solve on a computer with dual 500 MHz Pentium III processors running Microsoft Windows NT 4.0.

Habitat projections under management, relative to the projected 95% confidence interval for natural conditions, are summarized in Figure 7 for habitat quantile constraints of 0, 0.025, and 0.25. In the timber emphasis run (quantile constraint level 0) good American marten habitat is eliminated fairly quickly. This occurs because ideal American marten habitat occurs in older white spruce stands. Because of the value and volume of timber in these stands, they are also prime candidates for logging. The areas of good habitat for broad-winged hawk, three-toed woodpecker, and black-throated green warbler also fall below the 0.025 quantile when the forest is managed without consideration of habitat.

The trade-offs between timber production and habitat considerations is summarized in Table 4 for runs incorporating NDY constraints. The tables shows the net present value, first period annual allowable cut (AAC), and the average AAC over the planning horizon for each of the habitat constraint levels. The NPV of forest management activities with NDY constraints is $1.363 billion with no habitat constraints. This declines to $0.622 billion at the 0.40 habitat constraint level, less than half of the NPV for the unconstrained run. AACs also decline with increasing habitat constraint levels.

Table 5 shows the same information for runs without NDY constraints. The net present value of the no habitat constraint, non-NDY plan is more that 1.5 times that of the no habitat constraint, NDY plan. However, this proportional difference becomes much smaller when the habitat constraints are implemented. For example, the NPV at the 0.025 quantile constraint without NDY is only 1.16 times the NPV with NDY.

A useful output of most LP solvers is a listing of the shadow prices of each of the constraints in the model. The shadow price of a constraint represents the improvement in the objective function value that could be achieved if the constraint was relaxed by one unit, all other things being equal. Figure 8 presents the shadow prices by period for habitat constraints set to the quantiles 0.025, 0.250, and 0.400. In all cases, the shadow prices are expressed on a per hectare basis. In all cases, the shadow price for meadow vole habitat is zero and is not presented in the figure.

For the quantile 0.025 constraint, the largest shadow prices are associated with American marten and black-throated green warbler in the early periods of the planning horizon. This is not surprising, as ideal American marten habitat is overmature white spruce, and ideal black-throated green warbler habitat is overmature mixed stands. The yield curves in Figure 2 show that total volume declines with increasing age for overmature timber. Net present value maximizers

Table 4. Run output summary by habitat constraint level with NDY timber constraints.

		Annual allowable cut (10^6 m^3/yr)					
		Period 1			Average		
Habitat quantile	NPV ($\$ \times 10^6$)	Softwood	Hardwood	Total	Softwood	Hardwood	Total
0.000	1,363	0.829	1.239	2.068	0.829	1.239	2.068
0.025	1,164	0.707	1.045	1.752	0.768	1.134	1.902
0.050	1,100	0.682	1.006	1.688	0.763	1.115	1.879
0.100	1,008	0.640	0.783	1.423	0.754	1.069	1.822
0.125	968	0.625	0.662	1.287	0.752	1.047	1.799
0.150	927	0.507	0.542	1.050	0.749	1.035	1.783
0.200	857	0.364	0.403	0.767	0.739	1.006	1.744
0.250	788	0.250	0.290	0.540	0.733	0.981	1.713
0.300	727	0.203	0.236	0.439	0.726	0.966	1.692
0.350	670	0.168	0.184	0.352	0.715	0.942	1.657
0.400	622	0.143	0.129	0.272	0.704	0.913	1.618

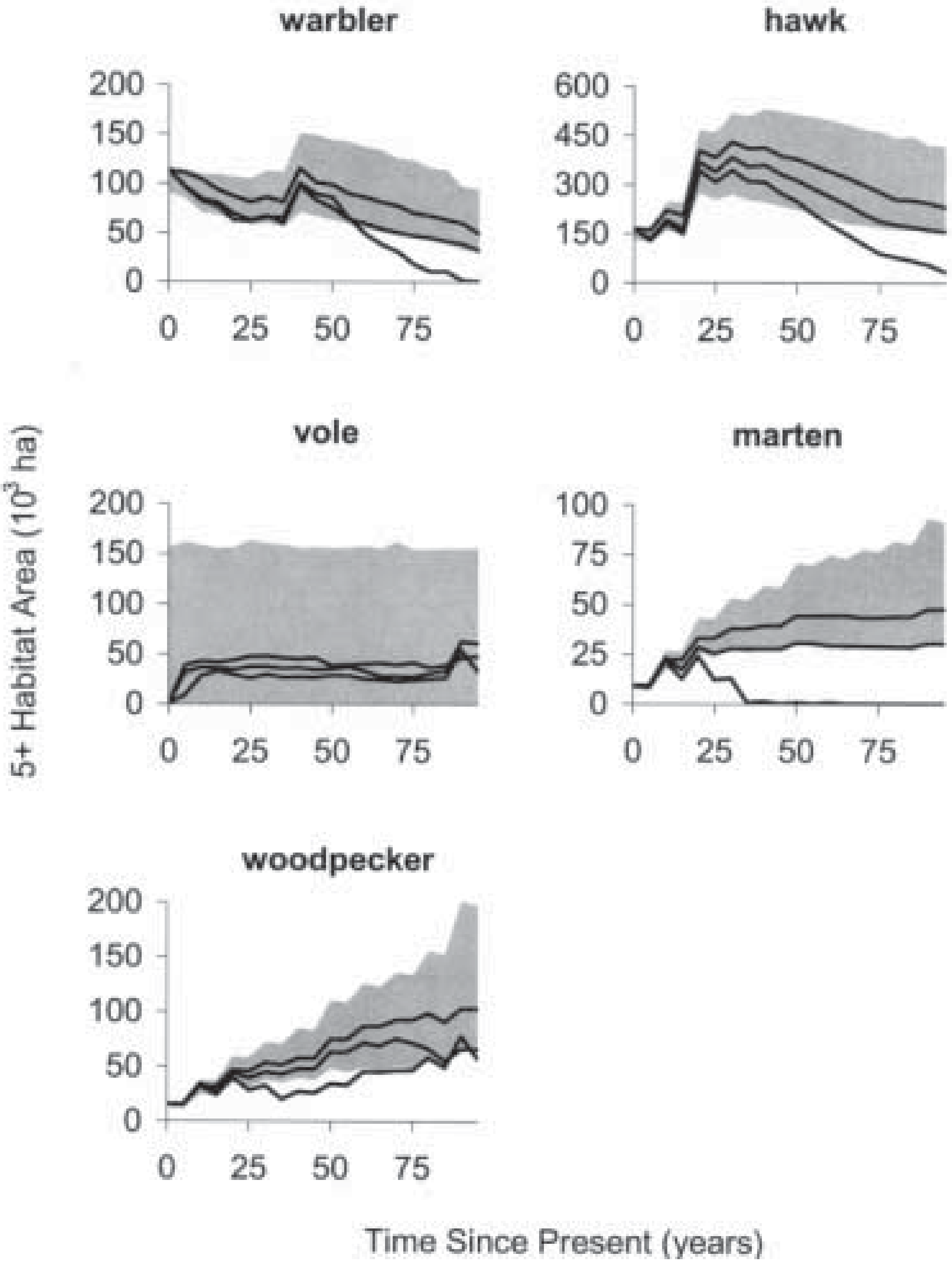

Figure 7. Habitat projections under habitat quantile constraints of 0, 0.025, and 0.25. The 95% confidence limits from the simulations are shaded gray.

Table 5. Run output summary by habitat constraint level without NDY timber constraints.

		Annual allowable cut (10^6 m^3/yr)					
		Period 1			Average		
Habitat quantile	NPV ($\$ \times 10^6$)	Softwood	Hardwood	Total	Softwood	Hardwood	Total
0.000	2,129	5.475	4.778	10.253	0.821	1.438	2.259
0.025	1,351	1.496	1.427	2.922	0.796	1.250	2.046
0.050	1,260	1.417	1.358	2.774	0.788	1.217	2.005
0.100	1,131	0.791	0.792	1.583	0.784	1.170	1.954
0.125	1,089	0.636	0.651	1.287	0.783	1.153	1.936
0.150	1,051	0.506	0.544	1.049	0.780	1.138	1.918
0.200	985	0.339	0.377	0.716	0.776	1.119	1.895
0.250	918	0.250	0.290	0.540	0.776	1.088	1.864
0.300	856	0.203	0.236	0.439	0.772	1.063	1.835
0.350	798	0.168	0.184	0.352	0.769	1.042	1.810
0.400	748	0.143	0.129	0.272	0.764	1.020	1.784

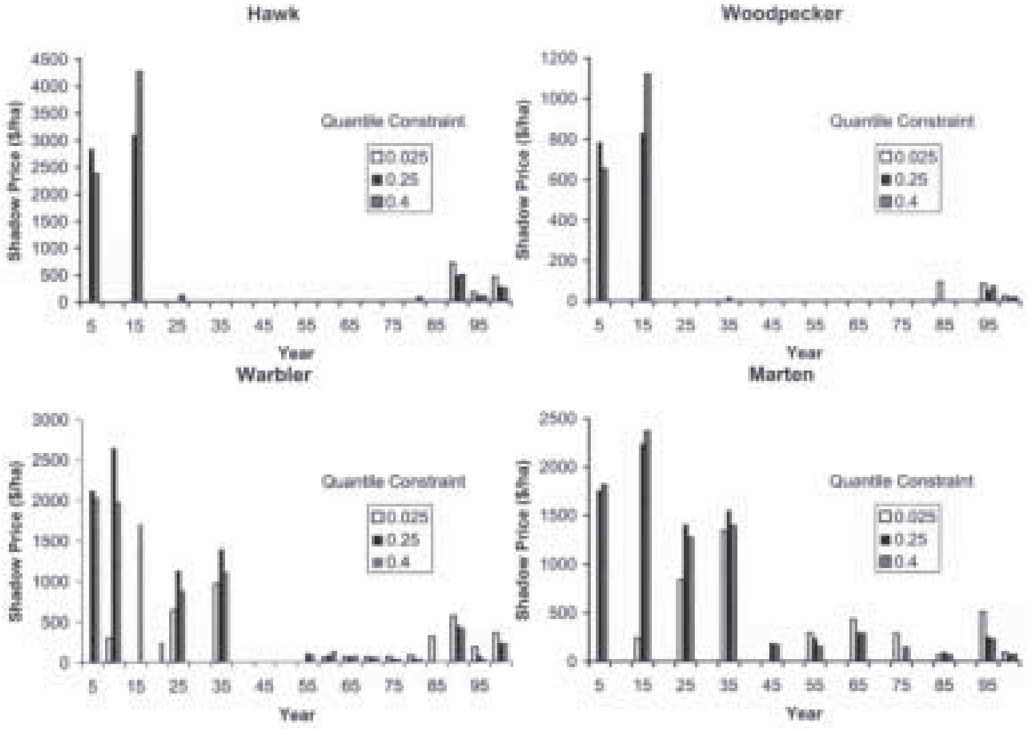

Figure 8. Shadow prices for good habitat area constraints by species and period.

would prefer not to let this timber fall down and rot: there is a financial incentive to log and regenerate these stands. Not harvesting the stands in order to provide American marten and black-throated green warbler habitat therefore has an opportunity cost.

The shadow prices increase dramatically in the earlier periods when the habitats are constrained to the 0.250 quantile. The constraints on American marten and black-throated green warbler are still costly, but constraints on broad-winged hawk habitat are extremely costly in periods 1 and 3. The broad-winged hawk prefers overmature aspen and mature mixed stands. These stands are also prime candidates for logging. Essentially the same story can be told for the quantile 0.40 constraints except that the broad-winged hawk constraints in period 3 are noticeably more expensive.

The shadow prices provide important information on the costs of constraints. They may help identify areas for considering alternative management strategies. For example, if broad-winged hawk habitat is particularly costly in a period, it may be possible to enhance broad-winged hawk habitat through means other than maintaining a particular age class of forest.

Concluding Comments

This article presented a set of models that could be used to help forest managers determine the appropriate harvest level for a forest managed under the natural disturbance model. We argue that the natural rate of disturbance and equilibrium age class structures are inappropriate characterizations of the natural disturbance regime of the boreal mixedwood and should not be used directly as management objectives. As an alternative, we use Monte Carlo simulation to project the variability in habitat for five species of vertebrates for a forest subject to a natural fire regime. The quantiles from these projected distributions are used to set constraint levels for a linear-programming based optimization model. This model is used to develop a table representing the trade-off between financial objectives and habitat quantiles. One of the most important decisions that the forest manager will have to make is which point on the trade-off curve represents the appropriate goal for management.

The main advantage of the modeling system presented here is that it explicitly recognizes that outcomes in this highly variable ecosystem are not certain. The system is used to help identify the trade-offs between competing goals in the context of natural disturbance management. There is substantial room for improvement and development of the modeling system used here. The optimization runs used here were all deterministic. Because it is unlikely that fire suppression efforts will ever eliminate the risk of forest fire, it would be useful to incorporate a stochastic optimization procedure into the system. Both the simulation and optimization components of this study were aspatial. Wildfire behavior and wildlife habitat have important spatial components. Addition of some level of spatial detail to the modeling system may be worth considering. However, we believe that many of the important trade-offs can be captured using an aspatial modeling system such as the one presented here.

In the models used here, each of the vertebrate species used as indicators is given equal weight in the sense that habitat quantile constraints are applied to all species at the same level in all runs. This is consistent with the ideas behind the coarse filter approach to ecosystem management in that no species is assigned a greater weight than any other. However, this system could potentially be used in a public participation context to develop alternatives to help elicit the preferences of the public for different alternative future forests. The alternative future forests could be described in terms of stocks and flows of financial values, recreation opportunities, abundance of habitat for different wildlife species, and other forest values.

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