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Integrated Resource Management in the Context of the Range of Natural Variability

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Abstract

The natural disturbance model of forest management is the basis of many of the sustainable forestry systems being proposed for the boreal forest of Canada. Wildfire is the dominant natural agent of disturbance in the boreal mixedwood forest. The natural disturbance model assumes that timber harvesting systems emulating the annual area burned by natural fire (i.e. the fire rate), 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 the forest biota in a natural or near-natural population levels.

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 100-year 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 which will allow for quantification of the trade-offs between timber values and the “degree of naturalness” maintained 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.

Keywords: timber supply; wildlife habitat; forest fire; natural disturbance; simulation; optimization

Introduction

Forest management in much of Canada is in transition from multiple use, sustained yield management to sustainable forest management or, as some call it, ecosystem management. The goal of management is changing from the production of an optimum (or, at least, desirable) 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' Criteria and Indicators of Sustainable Forest Management (Canadian Council of Forest Ministers 1997) 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, NDM management is hypothesized to minimize the negative impacts of timber harvest on forest biota. Hunter (1993) identifies three ways in which timber harvesting practices could emulate natural disturbance:

1. the frequency of harvest could be matched to the frequency 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.

The focus of this paper is the use of an understanding to the natural disturbance regime to help set timber harvest rates. Most of the discussion of NDM management for the boreal mixedwood section (Rowe 1972) of Canada has focused on emulating the effects of stand-replacing wildfire. Wildfire is the most important, or at least the most dramatic natural agent of change in the boreal mixedwood. For the remainder of this paper, natural disturbance is treated as synonymous with wildfire. Armstrong (1999) characterizes the annual area burned in an 8.6×10^6 ha study area in the boreal mixedwood forest of northeastern Alberta as a serially independent random draw from a lognormal distribution. Armstrong uses this characterization of the natural disturbance regime (NDR) to drive Monte Carlo simulations of the development of the forest disturbed by wildfire.

The characterization of the natural disturbance regime (NDR) presented by Armstrong (1999) has implications for natural disturbance based approaches for forest management. The interannual variability in disturbance rates is an important characteristic of the NDR. The relatively infrequent occurrence of extreme fire years largely determines the age class structure of the forest. The mean rate of natural disturbance is not precisely quantifiable. Therefore, attempting to approximate the natural rate of disturbance through management practices is untenable. This also means that other single parameter characterizations of the NDR for the study area (*e.g.* fire cycle or fire return interval) are not meaningful. There is no equilibrium age class distribution for a forest subject to this NDR: management regimes designed to lead to a particular “natural” forest age class distribution are misguided. For example, the negative exponential age class distribution model proposed by Van Wagner (1978) almost never holds for a forest subject to the lognormal disturbance regime with the parameters estimated by Armstrong (1999). The negative exponential age class distribution is not necessarily an invalid goal for the future age class structure of a forest. However, rationalizing this goal on the basis that it is the equilibrium structure for the forest appears to be incorrect.

This is not to say that the natural disturbance model of forest management is inappropriate for the boreal mixedwood forest. The single rate approach to NDM is invalid, as is a target age class distribution. There are, however, alternative interpretations. This chapter presents an approach to the determination of appropriate harvest levels using the natural variability in forest structure as a guide.

A highly aggregated aspatial representation of the forest is used in the models presented here. This is a departure from the current trend towards very detailed spatially explicit representations of forests in planning models, but is appropriate for the problem modeled here[1].

Monte Carlo simulation is used to project the distribution of the structure of a forest (defined in terms of area in age class by cover type combinations) subject to the lognormal NDR. The age class structure is summarized as the empirical probability density function (EDF) of the area of habitat available for five vertebrate species in each year of the projection period. Habitat is defined in terms of cover group and age ranges. This proves to be a convenient shorthand representation of the structure of the forest. The simulation model actually tracks the structure of the forest in terms of the area in 1-year wide age class in each cover type. It would be possible to determine EDFs for each of these combinations. However,

[1]There is a number of reasons for the choice of an aggregated aspatial representation for the system modeled here. There is a limited understanding of the biophysical relationships between neighboring forest stands, and the wildlife species that inhabit them. In many cases, the level of detail tracked by spatially explicit models is not warranted by the questions being asked of the models, or by the level of understanding of inter-stand relationships. The questions being asked in this study do not require a spatial model.

Highly detailed, spatially explicit models of large forest areas are very expensive to run in terms of time and computing power. There is a trade-off between the number of runs that can be made and the level of spatial detail tracked. This limits the number of alternative scenarios that can be examined. This makes it more difficult to recognize forest level patterns and implement Monte Carlo analysis.

Optimization of forest activity schedules in a spatially explicit framework is difficult. The types of spatial optimization models described by Hof and Bevers (1998) work for very small problems, but are currently inappropriate for forests comprised of several thousand stands. Optimization models are more appropriate than simulation models for analyses of trade-offs between competing values.

Most importantly, for a system subject to a stochastic disturbance regime (*e.g.* the boreal mixedwood forest), any projection of a spatially explicit model will represent just one possible outcome of the stochastic process. Accurately predicting the spatial location and extent of the forest fires that will occur 50 years in the future, or even next year, is impossible, or at least very difficult. In a system such as this, a statistical characterization of the range of possible outcomes will be more useful than one spatially explicit projection of one possible outcome. The large number of runs required to characterize the distribution of outcomes for a large forest area is likely to be prohibitively expensive with a high resolution, spatially explicit model.

In summary, the speed of analysis that is possible with a highly aggregated aspatial representation of the forest allows for a better understanding of the range of possible outcomes of a highly stochastic system. Spatially explicit models are useful tools for many types of analysis. However, there are some questions more appropriately addressed with aggregated aspatial models.

it would be difficult to make sense of 1000 projected EDFs (200 years by 5 cover groups). Aggregating this information in terms of distributions of habitat area for a handful of species allows for easier interpretation of the results.

The projected EDFs for each period are described using quantiles. The quantile x, where x is a real number between 0 and 1, is expressed as the area of habitat y, where the proportion x of the simulation realizations are less than y ha. These quantiles apply to each habitat level, for each species, and for each time step of the simulation.

A linear programming based optimization model is used to quantify the trade-offs between financial objectives of forest management and habitat areas for each of the five vertebrate species. The objective of the model is to maximize the net present value (NPV) of forest management activities. The projected EDFs for habitat areas are used to set periodic constraints on wildlife habitat. Several optimization runs are made, with habitat area constraints set to reflect different quantiles from the EDFs. For example, in one run the habitat areas for each of the five species are simultaneously constrained to be at least the 0.10 quantile from the projected EDFs. In another run, habitat areas are constrained to be at least the 0.40 quantile. By repeating this process for several quantile levels, a trade-off curve between net present value and habitat availability quantiles can be developed. It could be argued that the most important forest management decision is the desired position on this trade-off curve.

The remainder of this paper is organized as follows. The next section describes the input data used for the simulation and optimization runs. This is followed by a section describing the simulation model and the results of the Monte Carlo simulations. The optimization model and the construction of the trade-off curves are then presented. The paper concludes with a summary discussion and suggestions for further research.

Input Data

The inventory 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 Area in north-central Alberta, Canada. The area is an important timber producing area for a pulp mill and several sawmills. The study area is approximately bounded by 56^oN and $57^o40'$N latitude and 115^oW and 117^oW longitude. The starting inventory is shown in Table 1. This inventory 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 available for timber harvest activities. The area is net of stands which are considered never merchantable due to low projected volume, muskegs and and other wetlands, and areas deleted for stream and lake buffers, and other operational considerations. Softwood volumes are assumed to change with stand age according to the yield tables presented in Figure 1. Hardwood volumes develop as shown in Figure 2.

The most striking feature of the starting inventory presented in Table 1 is the large area of forest in the 60 year 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. Most of the yield curves presented in Figures 1 and 2 show declining volumes somewhere between 100 and 150 years of age. These declines reflect stand break-up.

Cumming *et al.* (1994) used a deterministic simulation framework to project the

Table 1: Starting inventory for study area. Area (ha) by age and cover type

Age (years)	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	4 748
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

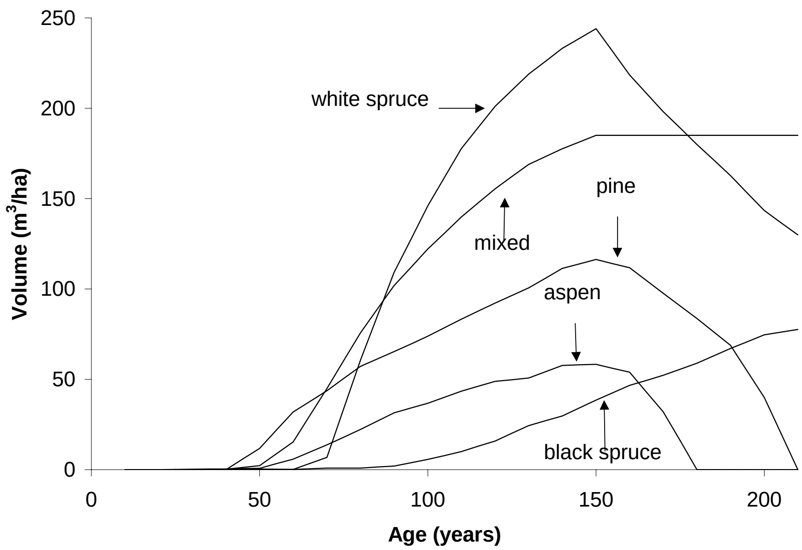

Figure 1: Softwood volume yields (m^3 ha^{-1} by cover type and age (years)).

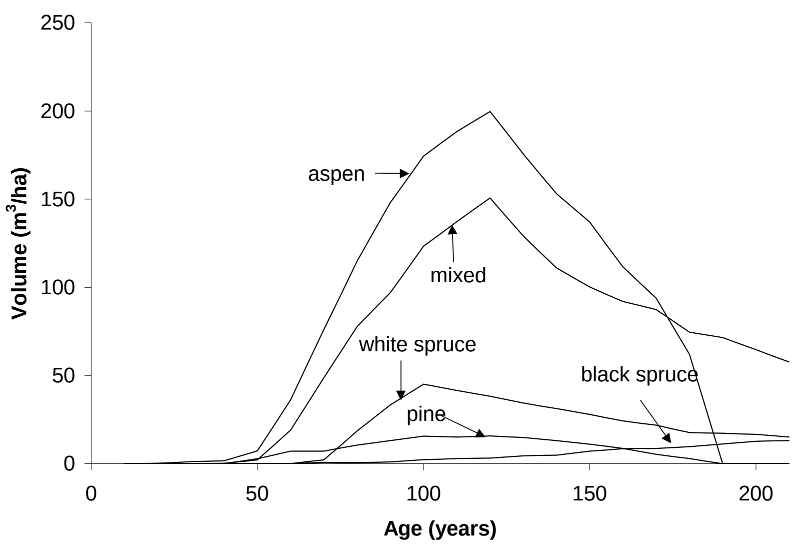

Figure 2: Hardwood volume yields (m^3 ha^{-1} by cover type and age (years)).

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

Habitat stage		Age range (years)	
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+

development of part of the boreal mixedwood to examine potential conflicts between wildlife habitat and timber supply. Their representation of habitat quality is used for the current study. Cumming *et al.* (1994) described the forest in terms of area in cover type by habitat stage combinations. The cover types were based on species composition of stands. 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 group comprises mesic stands with 80% or more of the crown area occupied by softwood species; the aspen group comprises mesic stands with 80% or more of the crown area occupied by hardwood species; and the mixed group 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 Cumming *et al.* (1994) to stand age and cover type as shown in Table 2.

Cumming *et al.* (1994) relate cover type and habitat stage to habitat quality for five vertebrate species: pine 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 were selected because of the diversity of their habitat requirements and because of their relatively small territories which better allows for representation of habitat quality in an aspatial model (as opposed to large mammals which may require a spatially arranged diversity of habitat types). Cumming *et al.* (1994) justify their choice of species as follows:

> The pine 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 tree-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.

For the remainder of this paper, the vertebrate species will be referred to by the following abbreviations: PIMA (pine marten), MEVO (meadow vole), BWHK (broad-winged hawk), TTWP (three-toed woodpecker), and BTGW (black-throated green warbler).

The habitat quality indices developed by Cumming *et al.* (1994) and presented in Table 3 were based largely on a literature review. 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.

Table 3: Habitat quality index by vertebrate species, cover type, and habitat stage. Blank entries represent a habitat quality index of 1. Reproduced from Cumming *et al.* (1994), Table 3.

		Habitat stage					
Species	Cover type	1	2	3	4	5	6
PIMA	Pine			2	2	2	2
	White spruce			2	3	4	6
	Mixed				2	3	4
MEVO	Pine	3	2				
	White spruce	6	3				
	Aspen	6	3				
	Mixed	6	3				
	Black spruce	3	2				
BWHK	Aspen					4	6
	Mixed				4	5	4
TTWP	Pine	4			2	4	5
	White spruce				3	4	6
	Mixed				2	3	4
	Black spruce	3			2	4	6
BTGW	White spruce			2	4	5	4
	Mixed			2	4	6	6

Monte Carlo Simulation

Monte Carlo simulation is a technique 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 inventory projections were run, each of which projected the development of the forest for 100 years. The starting point of each projection was taken to be the current inventory (Table 1). In each year of each simulation, the annual burn rate (λ_t) was drawn from the lognormal distribution identified by Armstrong (1999).

$$\lambda_t = \min(0.20, \exp x), \quad x \sim N(\mu, \sigma^2), \quad t = 1, 2, \ldots, 100. \tag{1}$$

These simulations use $\mu = -8.096$ and $\sigma = 2.853$ as determined by Armstrong (1999). 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 1000 simulation runs
    (a) Retrieve the initial inventory as area in cover type by age combinations.
    (b) For each of the 100 years 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 the remainder by one year.
        iii. Use Table 2 to assign a habitat stage to each new cover type by age cell.
        iv. Use Table 3 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 process
            B. Store the results for later processing.
2. For each of the 100 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. Assign a quantile to each item in the sorted list (position in the list divided by 1000)
            C. Store the results

In each year, each cover type by age combination was assigned a habitat stage according to Table 2. The projected habitat quantiles under natural disturbance for PIMA, MEVO, BWHK, TTWP, BTGW are shown in Figures 3 through 7. These simulations represent the development of the forest in the study area over a 100 year period in response to the natural fire regime. No timber harvest or fire protection activities occur in the simulations.

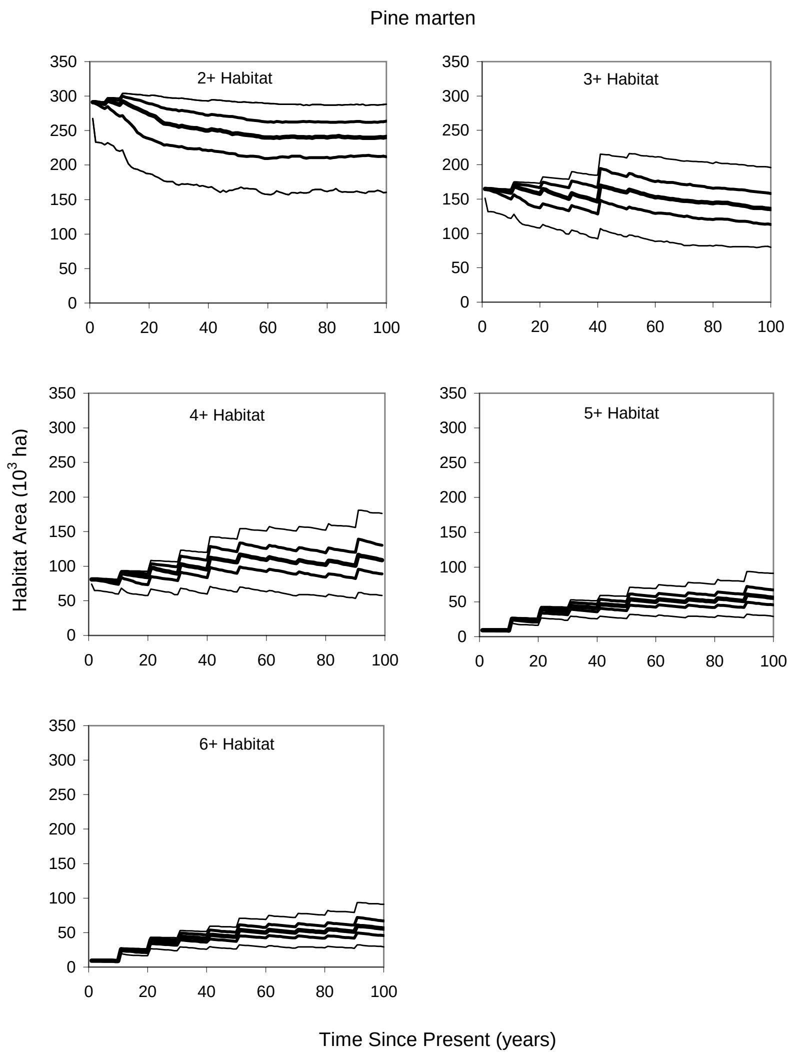

Figure 3: Projected habitat quantiles for PIMA. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. The panel titles indicate habitat quality (*e.g.* "2+ Habitat" indicates habitat with a quality index of 2 or greater).

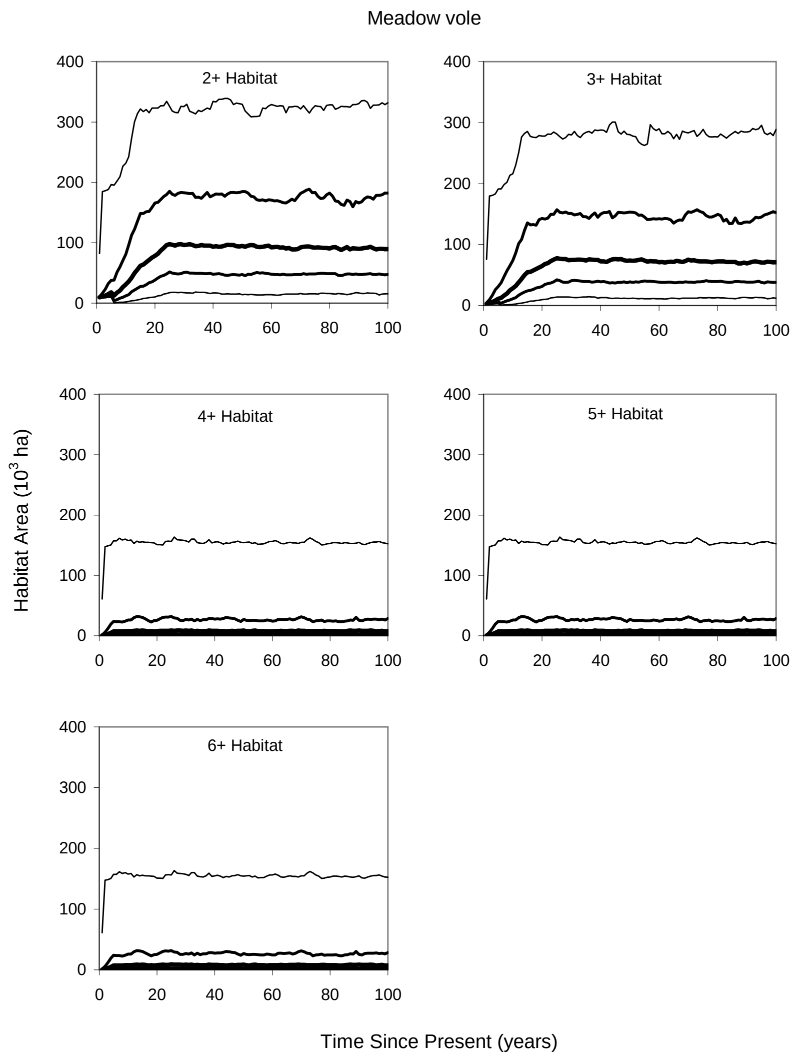

Figure 4: Projected habitat quantiles for MEVO. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. The panel titles indicate habitat quality (*e.g.* "2+ Habitat" indicates habitat with a quality index of 2 or greater).

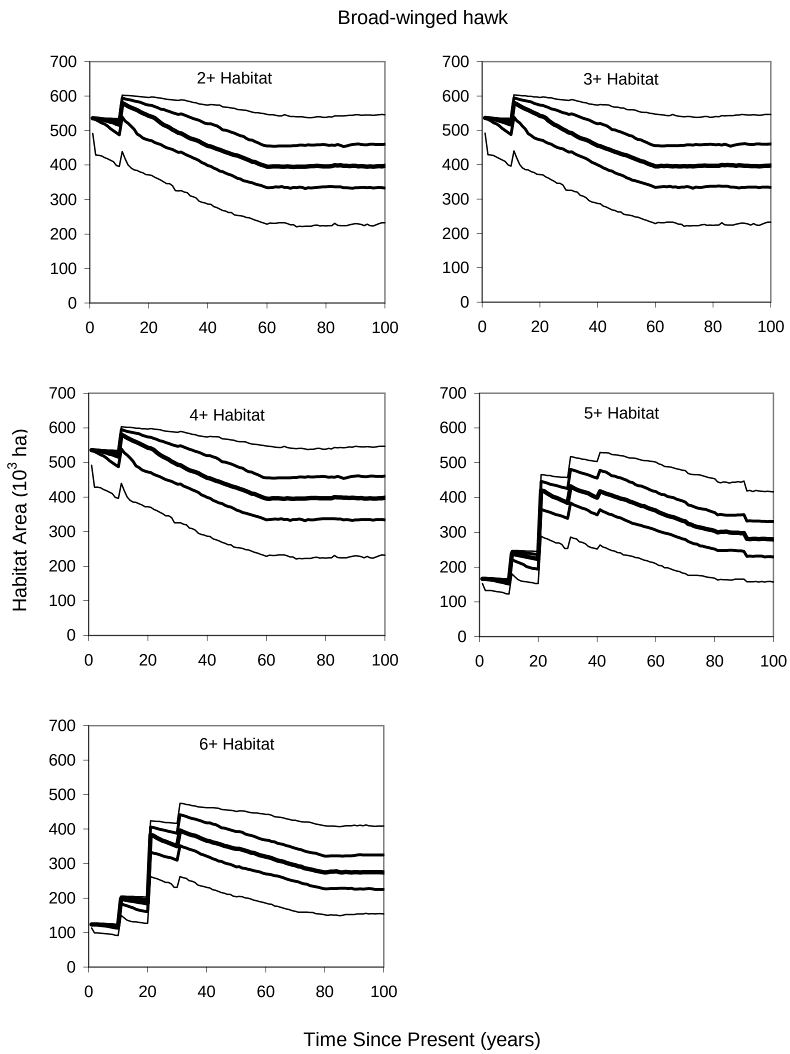

Figure 5: Projected habitat quantiles for BWHK. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. The panel titles indicate habitat quality (*e.g.* "2+ Habitat" indicates habitat with a quality index of 2 or greater).

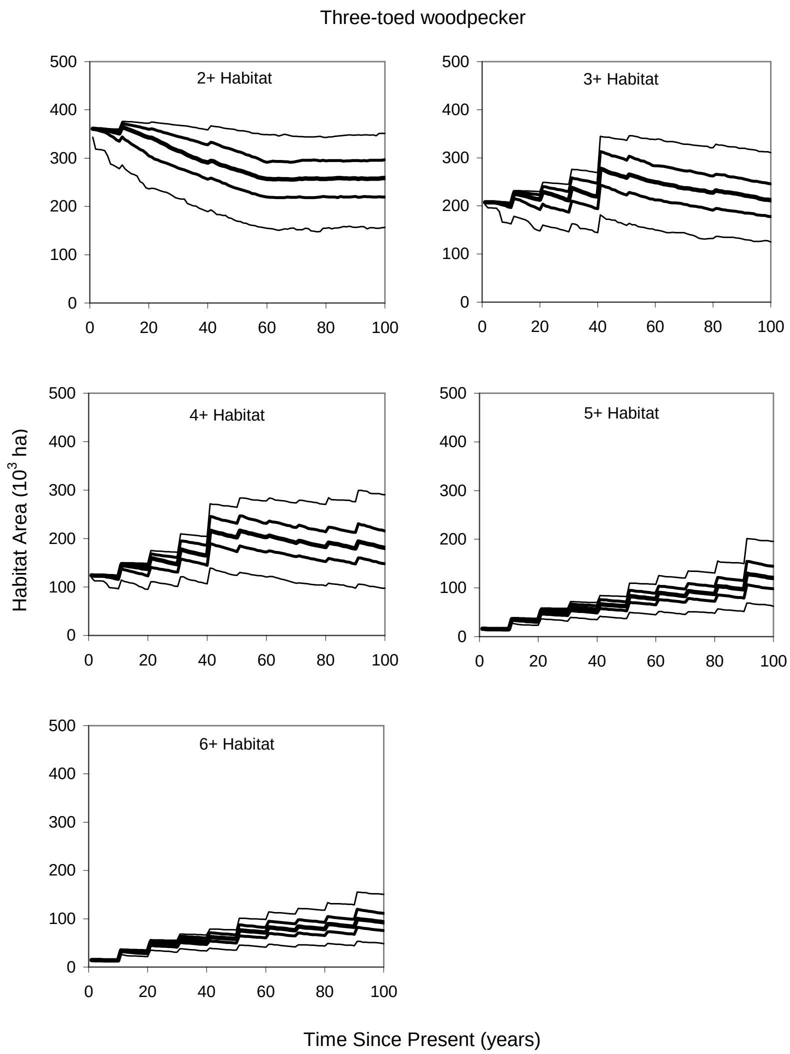

Figure 6: Projected habitat quantiles for TTWP. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. The panel titles indicate habitat quality (*e.g.* "2+ Habitat" indicates habitat with a quality index of 2 or greater).

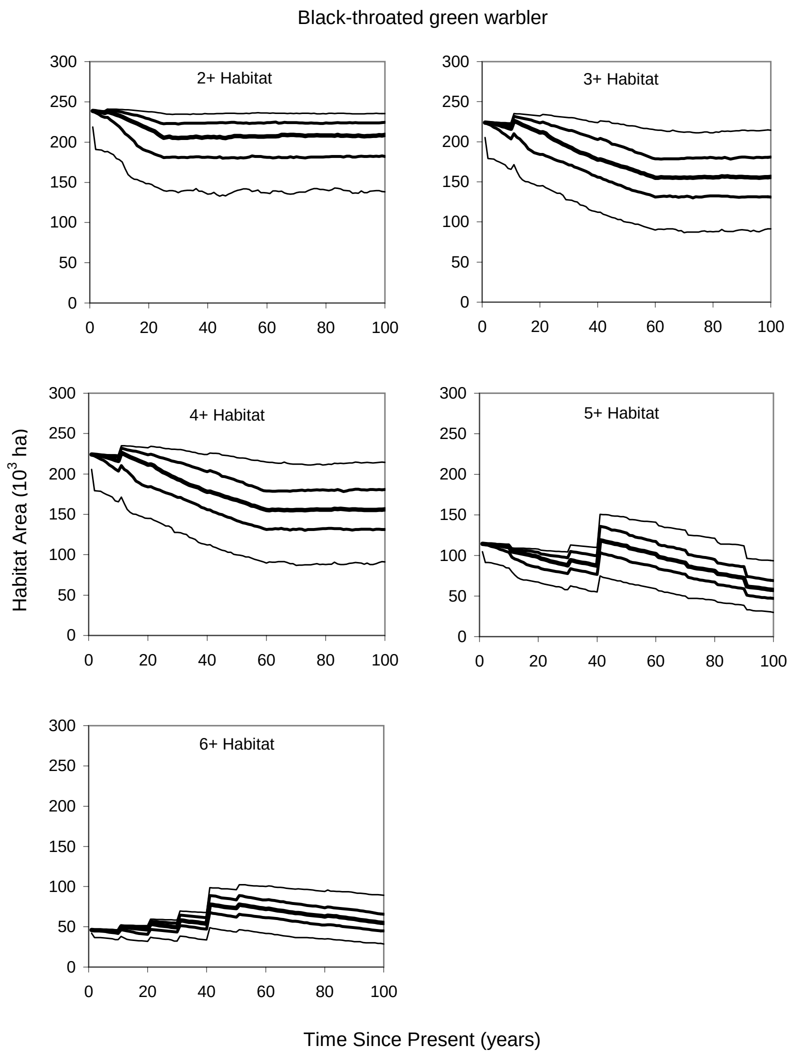

Figure 7: Projected habitat quantiles for BTGW. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975. The panel titles indicate habitat quality (*e.g.* “2+ Habitat” indicates habitat with a quality index of 2 or greater).

For the remainder of this paper, the focus is on good habitat, that is, habitat with a quality index of five or greater. The information for good habitat for all five species is duplicated in Figure 8 for convenient reference. Figure 8 represents the empirical distribution functions of habitat quality used in remainder of this paper. The age class and and tree species combinations are summarized in terms of area of good habitat for five different vertebrate species, over a period of 100 years.

The habitat area projections for BWHK and for BTGW show a large jump at 20 and 40 years, respectively. This reflects the transition of a large area of aspen from habitat stage 5 to habitat stage 6 (ideal habitat for BWHK) at 20 years from present, and the transition of a large area of mixed from habitat stage 4 mixed to habitat stage 5 at 40 years from present. Both transitions reflect the spike in the age class distribution at 60 years of age. In both cases, the habitat quality index changes from 4 to 6 at the time of the transition.

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 years). 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 non-equilibrium nature of the system.

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 one "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 PIMA and TTWP, but less than ideal for MEVO, BWHK, and BTGW. Allowing white spruce stands to reach overmaturity delays the creation of new good MEVO, BWHK, and BTGW habitat.

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. Fire suppression occurs, and is believed to reduce the occurrence of fire relative to natural conditions, although there is no published evidence to support this belief. The goal of the Alberta Land and Forest Service is to keep the annual area burned to be less than 0.1% of the productive forest area. Assuming that this goal is met, the impact of fire becomes negligible. I ignore the effects of fire in the optimization model.

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

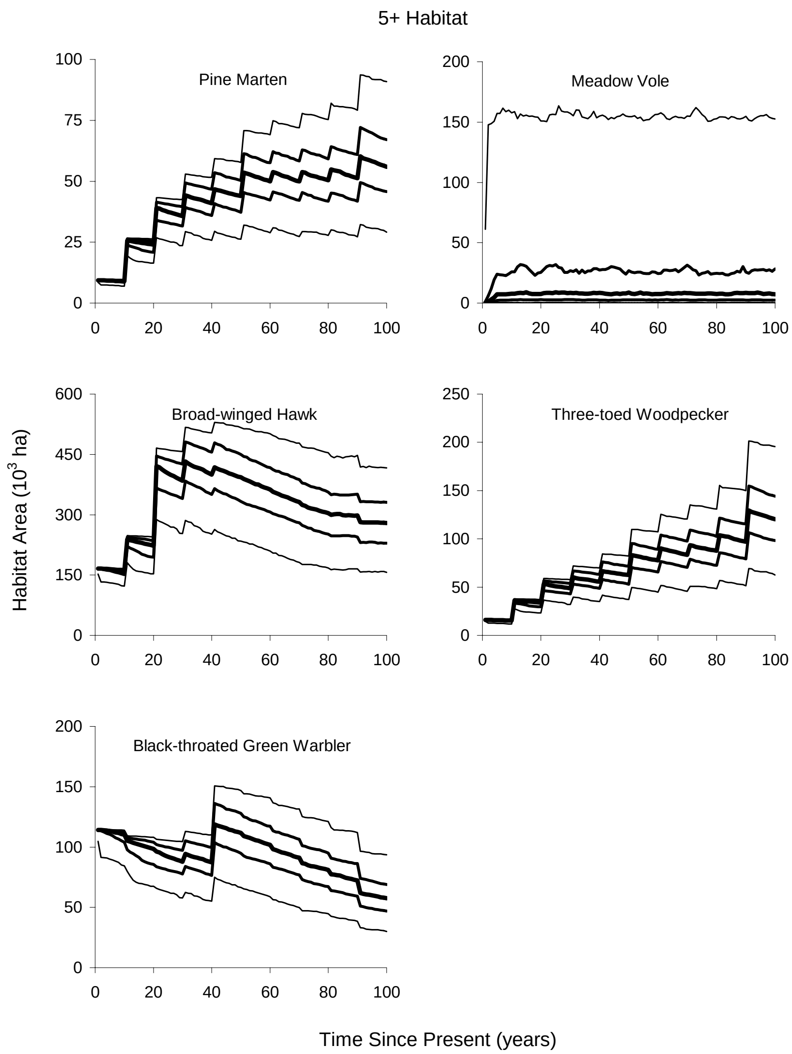

Figure 8: Projected habitat area quantiles for habitat quality indices of five or greater for five vertebrates. The quantiles shown are 0.025, 0.25, 0.5, 0.75, and 0.975.

variable costs of milling and marketing the product, expressed on a per cubic metre of roundwood basis (Davis and Johnson 1987). All softwood and hardwood volume is taken from every harvested stand. Stands are assumed to regenerate to the same cover type after harvest. No regeneration lag is modeled. Regeneration costs are assumed to be incorporated into harvest costs. Timber harvest costs are assumed to be 5000 \$ ha^{-1}. Non-declining yield constraints are applied to both types of timber: the harvest volume in any one period is constrained to be at least the harvest volume in the previous period.

The EDFs for wildlife habitat developed through Monte Carlo simulation are used to set constraint levels 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 5+ 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, 0.45, and 0.50. The 0.0 quantile represents no habitat constraints (pure timber emphasis). The optimization problem is infeasible for all habitat constraint levels of 0.45 or greater with and without non-declining yield constraints. This means that it is not possible for the forest to simultaneously provide good habitat for all five vertebrate species over all periods in the planning horizon. The habitat area for any species can only be increased at the expense of another species.

The system was modeled using the Woodstock forest modeling package (Remsoft Inc. 1998) and solved using the C-WHIZ linear programming (LP) solution software (Ketron Management Science 1998). Woodstock provides a convenient way of specifying a forest management problem using a flexible syntax. It can generate a 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 year) planning horizon were used for all the Woodstock models. The extra five periods (25 years) relative to the simulations were added to the planning horizon in order to reduce the effect of end of planning horizon timber anomalies typical of optimization-based timber harvest scheduling models without ending inventory constraints.

Habitat projections under management, relative to the projected 95% confidence limits for natural conditions, are summarized in Figure 9 for habitat quantile constraints of 0, 0.025, and 0.25. In the timber emphasis run (quantile constraint level 0) good (5+) PIMA habitat is eliminated fairly quickly. This occurs because ideal PIMA 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 BWHK, TTWP, and BTGW also fall below the lower confidence limit for natural conditions when the forest is managed without consideration of habitat. Habitat for the MEVO under all quantile constraint levels is well within the confidence intervals for natural conditions.

The trade-offs between timber supply and habitat considerations are summarized in Figures 10 – 14. These graphs also show the effect of the relaxation of non-declining yield constraints. With non-declining timber yield constraints in place, the net present value of forest management activities is \$ 1.363×10^9 with no habitat quantile constraints. The NPV declines to \$ 0.621×10^9 at the 0.40 habitat constraint level, less than half the unconstrained value. Hardwood and softwood harvest volumes also decline with the imposition of tighter habitat area constraints.

A useful output of most LP solvers is a listing of the shadow prices of each of the

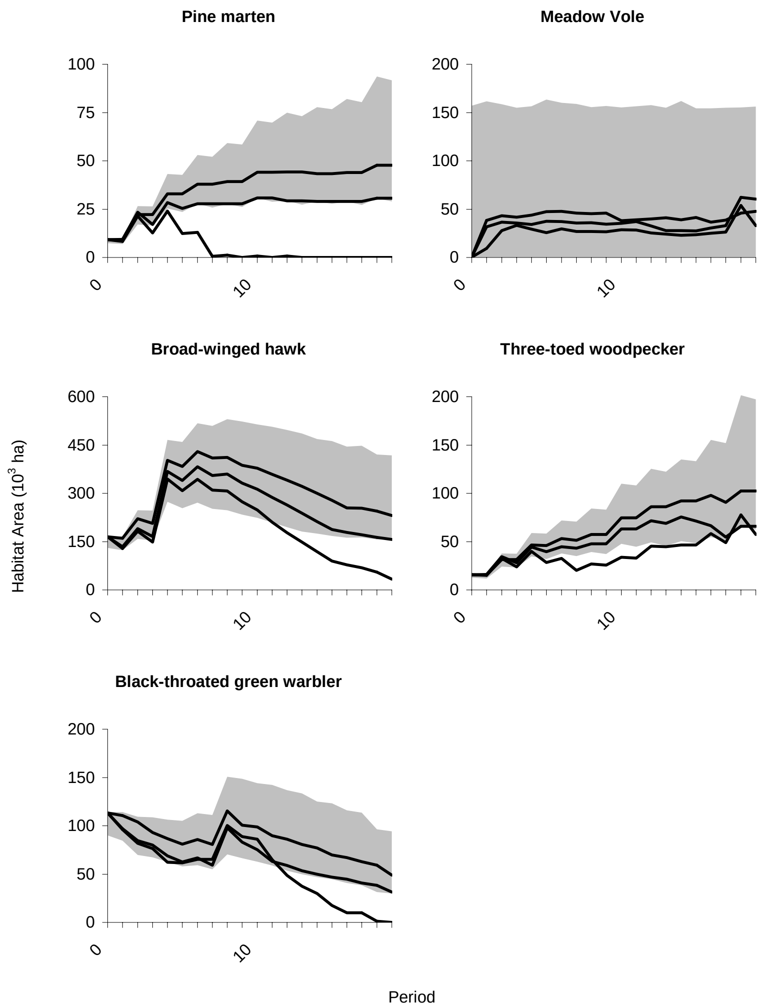

Figure 9: Habitat projections under habitat quantile constraints of 0, 0.025, and 0.25. The 95% confidence limits are shaded grey.

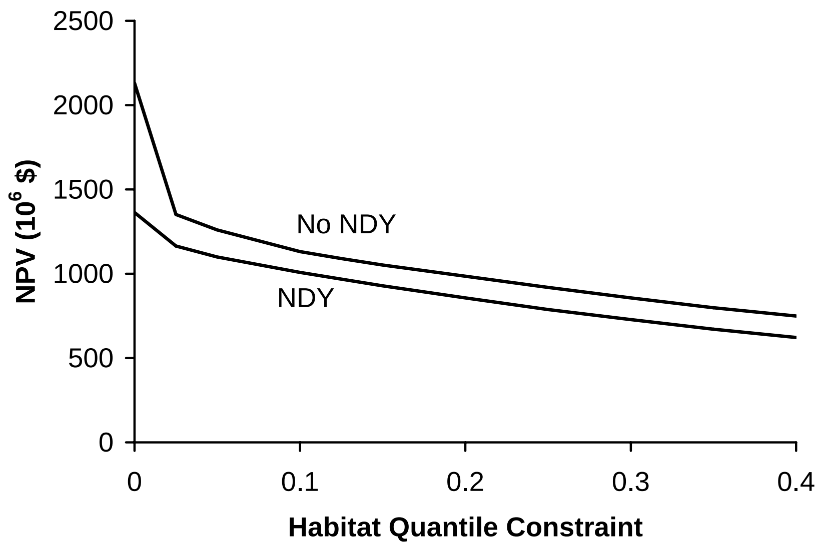

Figure 10: Net present value by quantile constraint level for runs with and without non-declining yield constraints.

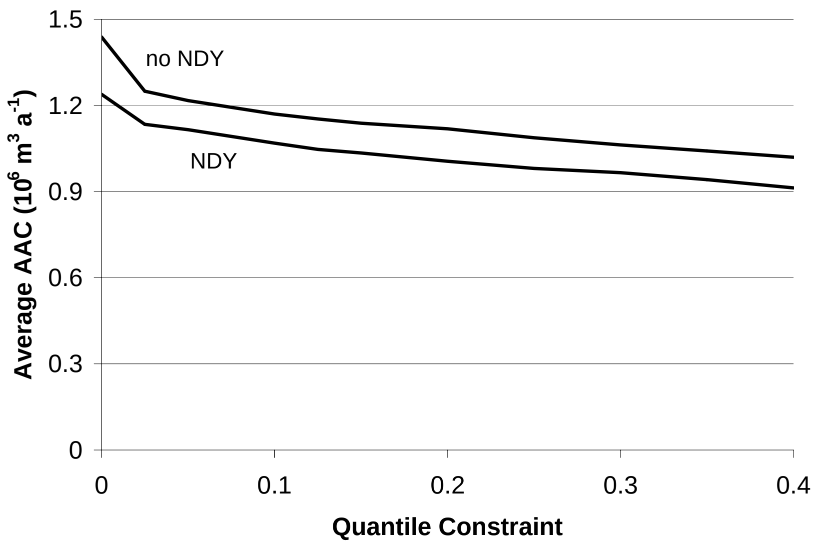

Figure 11: Average hardwood annual allowable cut by quantile constraint level for runs with and without non-declining yield constraints.

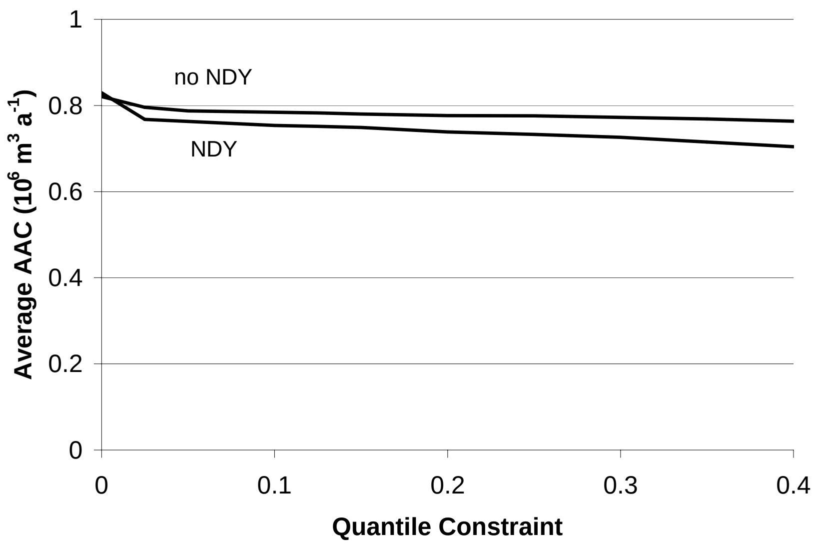

Figure 12: Average softwood annual allowable cut by quantile constraint level for runs with and without non-declining yield constraints.

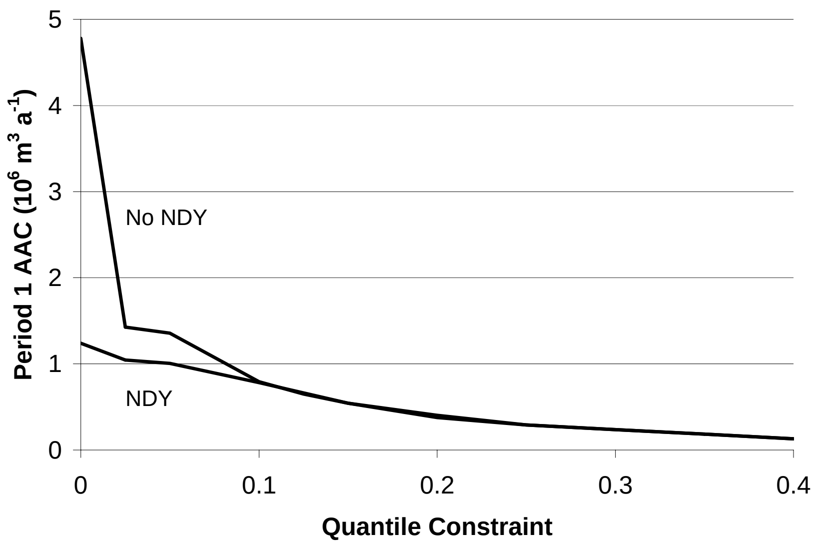

Figure 13: First period hardwood annual allowable cut by quantile constraint level for runs with and without non-declining yield constraints.

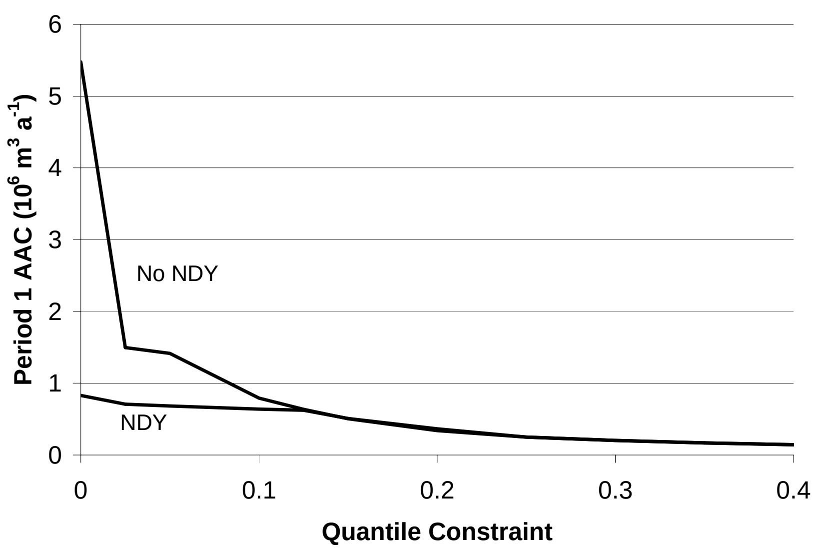

Figure 14: First period softwood annual allowable cut by quantile constraint level for runs with and without non-declining yield constraints.

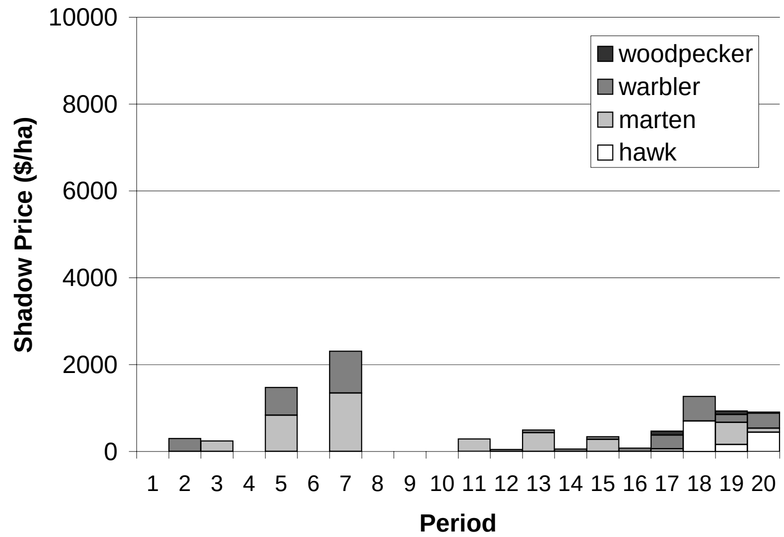

Figure 15: Shadow prices by 5-year period for the 0.025 quantile constraint run. The shadow price for MEVO habitat is zero in all periods.

constraints in the model. The shadow price of a constraint represents the increase in the objective function value that could be achieved if the constraint was relaxed by one unit, all other things being equal. Figures 15, 16, and 17 present 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. And, in all cases, the shadow price for MEVO habitat is zero.

For the quantile 0.025 constraint (Figure 15), the largest shadow prices are associated with PIMA and BTGW in the early periods of the planning horizon. This is not surprising as ideal PIMA habitat is overmature white spruce and ideal BTGW habitat is overmature mixed stands. The yield curves in Figures 1 and 2 show that total volume declines with increasing age for overmature timber. Net present value maximizers would prefer not to let this timber fall down and rot, so there is an incentive to log and regenerate these stands. Not harvesting the stands in order to provide PIMA and BTGW habitat therefore has a cost.

The shadow prices increase dramatically in the earlier periods when the habitats are constrained to the 0.250 quantile (Figure 16). The constraints on PIMA and BTGW are still costly, but constraints on BWHK habitat are extremely costly in periods 1 and 3. BWHK 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 (Figure 17) except that the BWHK constraints in period 3 are noticeably more expensive.

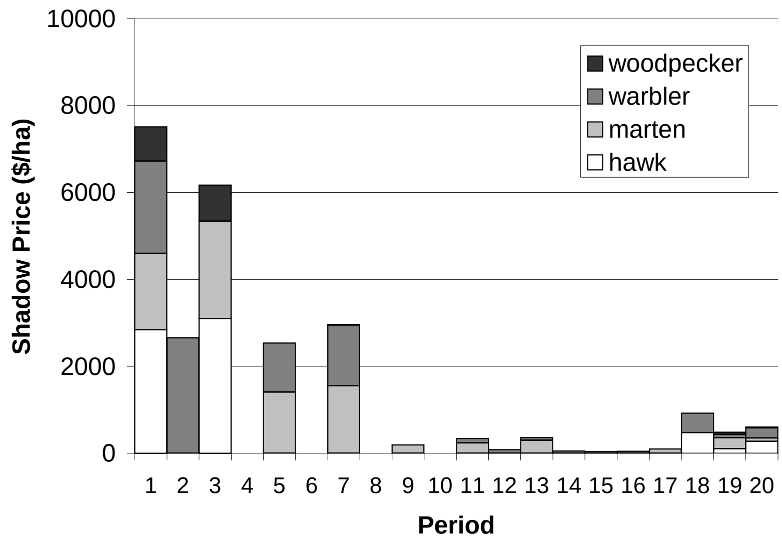

Figure 16: Shadow prices by 5-year period for the 0.25 quantile constraint run. The shadow price for MEVO habitat is zero in all periods.

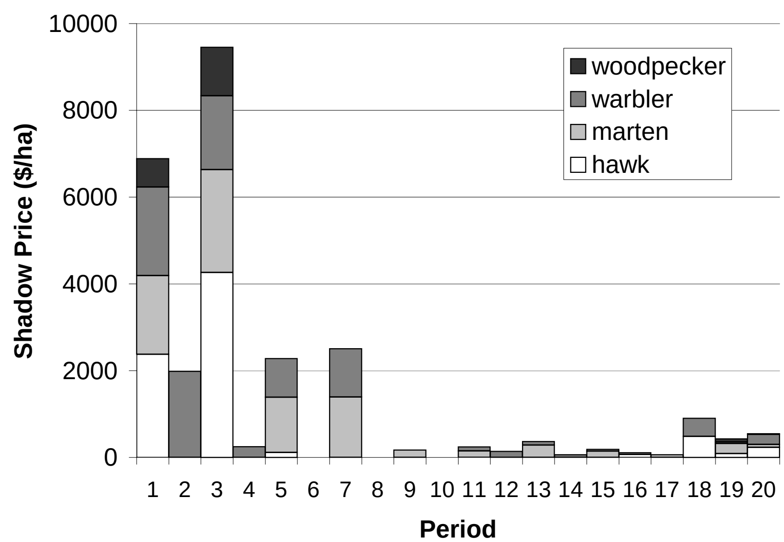

Figure 17: Shadow prices by 5-year period for the 0.40 quantile constraint run. The shadow price for MEVO habitat is zero in all periods.

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

Concluding Comments

This paper 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 forest subject to a lognormal 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 curve 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 in this paper is that it explicitly recognizes the variability in a highly variable ecosystem. 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 certainly have spatial components. Addition of some level of spatial detail to the modeling system may be worth considering. However, 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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