

Spatial Modeling of Harvest Constraints on Wood Supply Versus Wildlife Habitat Objectives

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ABSTRACT / We studied the effects of spatial and temporal timber harvesting constraints on competing objectives of sustaining wildlife habitat supply and meeting timber harvest objectives in a boreal mixedwood forest. A hierarchical modeling approach was taken, where strategic and tactical level models were used to project blocking and scheduling of harvest blocks. Harvest block size and proximity, together with short- and long-term temporal constraints, were adjusted in a factorial manner to allow creation of response-surface models. A

new measure of the habitat mosaic was defined to describe the emergent pattern of habitat across the landscape. These models, together with multiple linear regression, were used to provide insight on convergence or divergence between spatial objectives. For example, green-up delay (defined as time required before a harvest block adjacent to a previously logged block can be scheduled for harvest) had an adverse effect on the amount of annual harvest area that could be allocated and blocked spatially, and habitat supply responded in an opposite direction to that of wood supply, where caribou, moose wintering, and marten habitat supply increased when harvest blocks were further apart, maximum block size smaller, and both a green-up delay and mesoscale stratification were applied. Although there was no "solution space" free of conflicts, the analysis suggests that application of the mesoscale stratification, together with a diversity of harvest block sizes and a between-harvest block proximity of 250 m, will perform relatively well with respect to wood supply objectives, and at the same time create a less fragmented landscape that better reflects natural forest patterns.

Sustaining both timber supply and wildlife habitat involves competing spatial objectives. Planning solutions are provided as alternative forest management planning scenarios, but comparative analysis of these alternatives requires innovative analytical approaches to help decision-makers decide where the best balance lies. There are two general analytical approaches to the problem: (1) develop a spatial harvest planning model that attempts to simultaneously optimize for multiple spatial objectives (e.g., Arthaud and Rose 1996, Naesset 1997, Baskent 1997, Hochbaum and Pathria 1997, Liu and others 2000; Wightman and Baskent 1994, Kurttila 2001, Van Deusen 2001, Boston and Bettinger 2001) or (2) simulate alternative harvest strategies through time and then assess the solutions in terms of conflicts among the multiple spatial objectives (e.g., Jenkins and Starkey 1996, Gustafson 1996, Naesset 1997, Kliskey and

others 1999, Carlsson 1999, Puttock and others 1998, Gustafson and others 2000, Rohweder and others 2000, Gustafson and Crow 1996).

Although research is progressing well on the optimization approach, with combinatorial methods such as simulated annealing gaining much attention, most organizations are still planning with harvest allocation models that focus on a single objective such as timber supply. In many cases, computer harvest scheduling models, regardless of the methodological approach, simply provide potential solutions or starting points. Other nonecological factors, such as socioeconomic and political objectives, as well as road-building and existing road access, modify the final suite of proposed harvest scenarios (Young and Duinker 1998). Consequently, techniques that can assess, post-hoc, alternative scenarios in terms of multiple objectives continue to play a useful role in forest management, even as multiple-objective optimization programs develop in sophistication and usability (e.g., Tittler and others 2001).

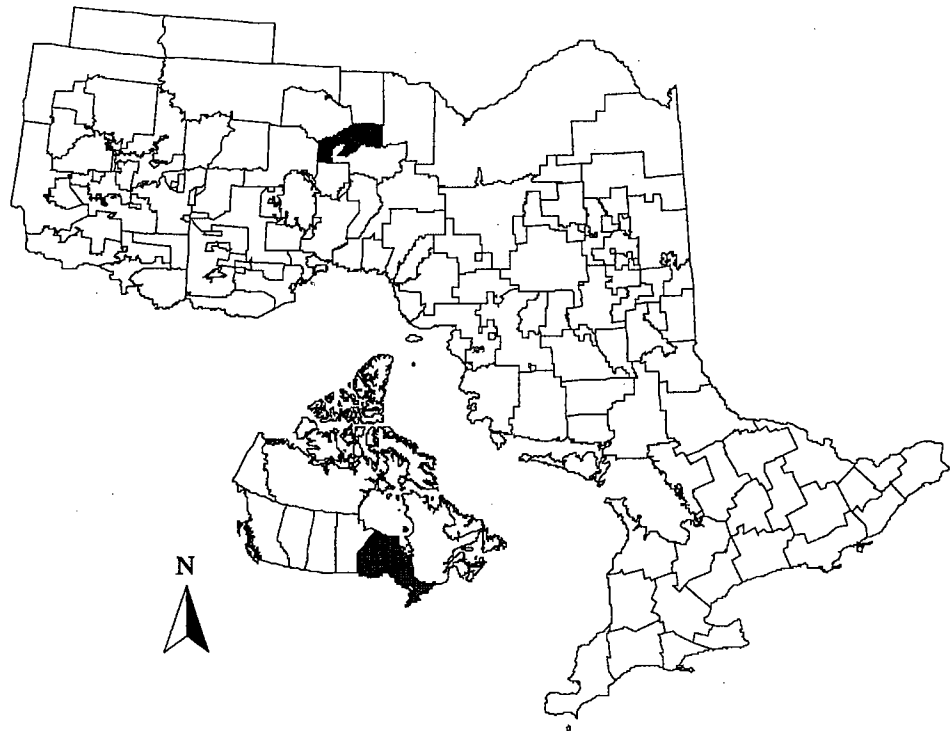
Perhaps the most pressing spatial problem in forest management planning today is the issue of size and placement of forest harvest blocks (Walters and Holling 1990). The relative effect of small versus large harvest

KEY WORDS: Wood supply; Habitat supply; Habitat suitability modeling; Spatial constraint modeling; Landscape pattern; Forest management; Tradeoff analysis; Marten; Woodland caribou; Moose; Ovenbird

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Figure 1. Location of Nakina Forest Management Unit (FMU) in Ontario, Canada (shaded in insert). The FMU is located north of Lake Superior (black shading), and represents an averaged sized FMU in the boreal forest region of Ontario.



blocks, with aggregated or dispersed placement across the landscape, presents a critical uncertainty to sustainable forest management. Over the past 20 years, forest management policy has moved from promoting large, widely spaced progressive clearcuts, to promoting smaller, more closely spaced harvest blocks, to promoting a mix of widely spaced larger cuts and aggregated smaller cuts (Slocombe 1998, Botton and others 2002). Even though policy shifts have been relatively rapid, there still is little quantitative data to identify which strategy provides the best solution to satisfy multiple spatial objectives in sustainable forest management. These policy directions are often given in the form of forest management guidelines and in terms of ecological objectives. This often reflects a shift from management to create habitat edge for specific featured species (e.g., OMNR 1998) to a more comprehensive biodiversity strategy that attempts to emulate natural landscape patterns in support of broader habitat and ecosystem-function objectives (e.g., OMNR 2002). In terms of wildlife habitat, the “natural disturbance” approach of larger and more aggregated harvest blocks attempts to create a landscape pattern to accommodate both edge-dependent and edge-avoiding species (Hunter 1993).

In this study, we present a quantitative approach to assess and provide insight into the relative effects of size and placement of harvest blocks on timber supply and habitat supply objectives. These competing objectives

are cast in a spatially explicit context, and the comparison of solutions is provided by a response-surface graph. Rather than comparing one specific forest management approach to another, we have generalized the problem of forest harvest allocation into four component parts: harvest block size, harvest block proximity (distance between cuts), green-up delay (time required before a harvest block adjacent to a previously logged block can be scheduled for harvest), and mesoscale stratification (logging restricted to one of several large zones within a forest management unit for about 20 years). An emergent characteristic of the four components is the overall landscape mosaic, and here we present a new spatially explicit technique to describe and analyze the habitat mosaic profile. Utilizing a factorial design and multiple linear regression, we present a general solution space that can give guidance to decision-makers on the relative effect of one strategy versus another, where the competing spatial objectives are timber supply and habitat supply.

Methods

Study Area

The study area was the Nakina Forest Management Unit (FMU) located in the boreal forest of northwestern Ontario, Canada (Figure 1). This area has little

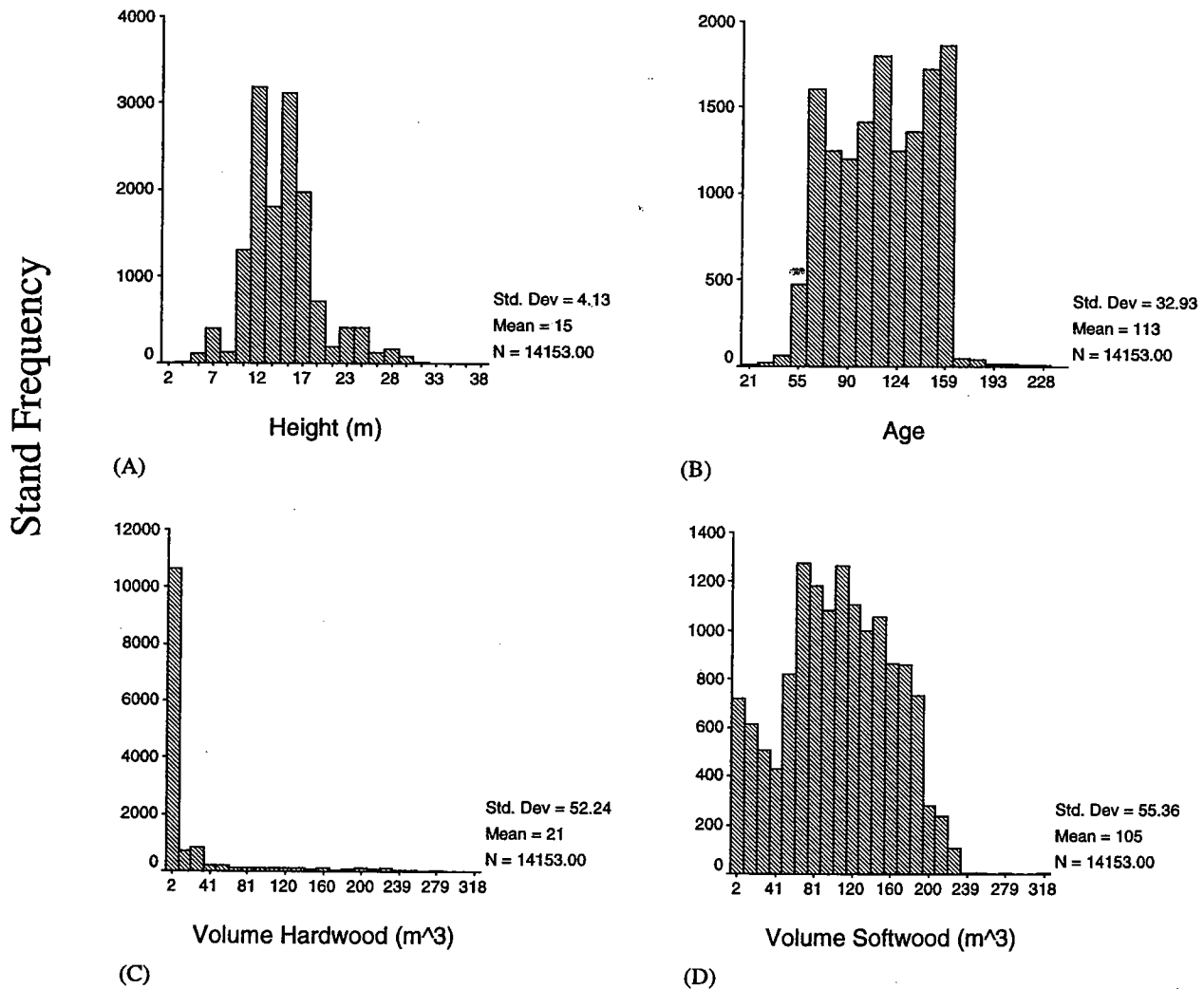


Figure 2. Stand level profiles for Nakina FMU. Summary of all stands eligible for harvest (99.86% of total forested area); 129 forest reserve stands excluded.

timber harvesting history and only a single road corridor. The area is predominantly boreal and is characterized by white spruce (*Picea glauca*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), eastern white pine (*Pinus strobus*), aspen (*Populus* spp.), birch (*Betula* spp.), balsam (*Abies balsamea*), white cedar (*Thuja occidentalis*), and larch (*Larix laricina*). Approximately 87% of the forest is comprised of toniferous working groups (stands with mostly coniferous composition), with this working group dominating the volume profile of the forest (Figure 2C, D). The forest is relatively old and even-aged due to large fires in the late 1800s, with an average age of 113 years, and a tight profile of average height centered at 15 m (Figure 2A, B).

The FMU is within the range of the woodland caribou in Ontario, and there is concern that since the early 1900s the range of the woodland caribou in the boreal forests in northern Ontario has been receding (Cumming and Beange 1993). As part of a management strategy to conserve caribou while allowing for timber harvesting in the FMU, three large tracts (greater than 10,000 ha) of mature coniferous forest with attributes that provide thermal protection and access to terrestrial lichen forage were identified (Figure 3). A proposed strategy was to limit harvesting for discrete time periods to only one of these blocks at a time, thus reducing the spatial extent of fragmentation and direct disturbance of the forest to more localized

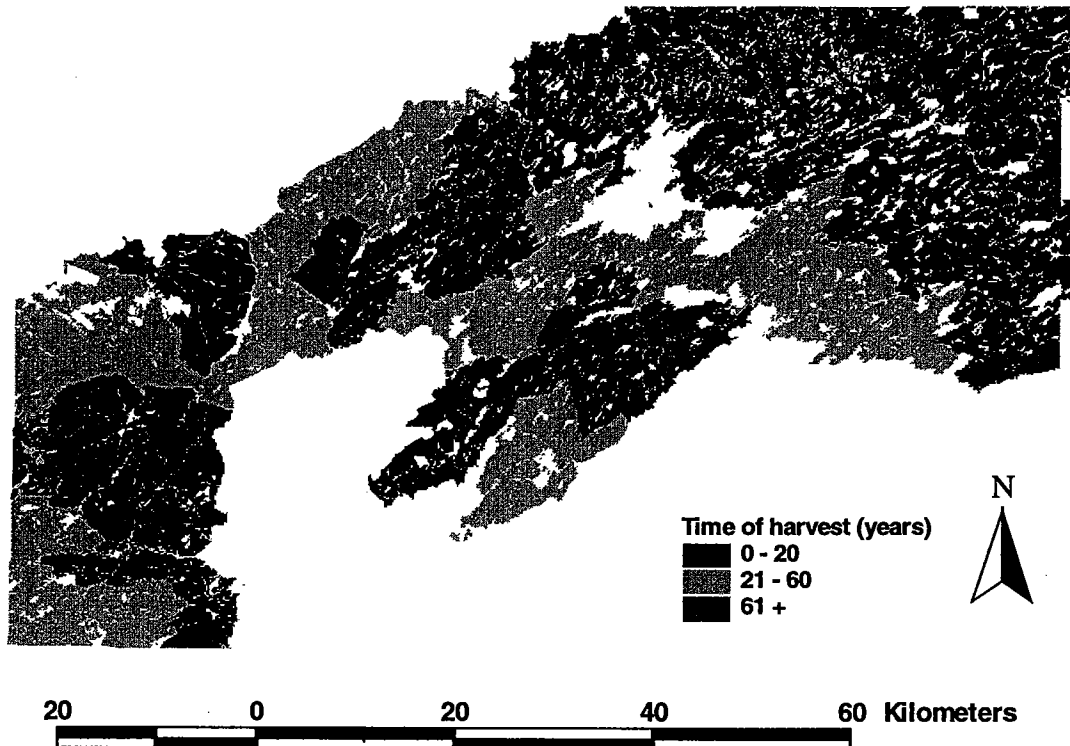


Figure 3. Mesoscale stratification of the Nakina FMU, used for harvest scenarios to conserve woodland caribou habitat. When the stratification is applied, harvest block scheduling is temporally constrained to like-shaded areas within a stratum for 20-year time periods.

areas within the overall forest management unit. The implications of this mesoscale stratification were explored in our study.

Wood Supply and Harvest Schedule Modeling

A hierarchical modeling approach was used in the study, which involved first determining the annual available harvest based on a strategic modeling analysis, and then planning and scheduling the harvest using a tactical model.

Strategic modeling. The annual harvest area (AHA) for each of the two alternative forest management scenarios, harvesting with and without the mesoscale stratification, was determined using the Strategic Forest Management Model (SFMM) (Davis 1997). This linear optimization model uses the AIMMS linear programming engine and CPLEX algorithms to solve simultaneous equations where all eligible harvesting, renewal, mid-rotation tending, and non forest rehabilitation treatments are assessed on an equal basis (Davis 1997). This approach aids development of forest management alternatives that address an array of values.

Model inputs include: (1) landbase definition (forest considered available for silvicultural options, reserve

forest, and nonforested land); (2) forest dynamics (forest succession, natural disturbance, growth and yield, and potential habitat areas); and (3) silvicultural options (harvesting, renewal, mid-rotation tending, and nonforest rehabilitation). A habitat unit matrix specifies potential habitat areas, where the matrix relates forest composition and age to habitat value for each polygon. Current areas (supply) of habitat are subsequently tracked but are not used as a solution objective. The habitat units and matrix values for moose, caribou, marten, and ovenbird are specified in Tables 1 and 2. The habitat unit matrix was developed by Ontario government staff, is coarse and untested, but does provide an initial means for quantifying changes in forest structure as it is expected to relate to wildlife habitat (Davis 1997, Kauffman 2000). The strategic model creates a solution or choices file that links harvest and other silvicultural options to each polygon (or stand) in the forest GIS inventory, which is subsequently used by the tactical harvest-scheduling model.

Tactical modeling. Spatial blocking and harvest scheduling was modeled using the program Stanley (Remsoft Inc. 1998). This program uses the overall AHA and harvest options for individual stands (as de-

Table 1. Habitat unit definitions

Habitat unit codes	HU number	Description	Age (years) at which seral stage begins for each habitat unit ^a				
			P	S	I	M	L
CuPjw Conifer Upland Jack Pine-White Pine	HU1	Pr + Pw \geq 20%; PFR or PF	0	5	20	60	110
CuPjS Conifer Upland Jack Pine-Spruce	HU2	Pj or Sb WG; PFR or PF	0	5	20	50	90
CuPwr Conifer Upland White Pine-Red Pine	HU3	Pr + Pw \geq 20%; SC 1,2,3	0	5	20	80	140
Cu_Pj Conifer Upland Jack Pine	HU4	Pj > 50%; hardwood less than 50%, SC 3	0	10	30	70	120
Mi_PS Mixedwood Pine-Spruce	HU5	Pj or Sb WG; hardwood < 50%; SC 2,3	0	10	30	70	120
HuBIS Hardwood Upland Balsam Fir-Spruce	HU6	Hardwoods (excl Ab) > 50%; SC 2,3	0	5	10	60	90
Cu_Ce Conifer Upland Cedar	HU7	Ce WG; upland site	0	10	30	70	130
MiCBS Mixedwood Conifer Balsam Fir-Spruce	HU8	Bf or Sw WG; conifer > 50%; SC 2,3	0	5	10	60	90
Cu_PS Conifer Upland Pine-Spruce	HU9	Pj or Sb WG; hardwood < 50%; SC 1	0	10	30	70	120
MiBfS Mixedwood Balsam Fir-Spruce	HU10	Bf or Sw WG, conifer > 50%; SC 1	0	5	10	60	90
MiHBS Mixedwood Hardwood Balsam Fir Spruce	HU11	Hardwoods (excl Ab) > 50%; SC 1	0	5	10	50	70
HL_Ab Hardwood Lowland - Black Ash	HU12	Ab WG	0	5	20	60	120
ClSb1 Conifer Lowland Black Spruce Richer Sites	HU13	Sb or Pj; lowland site; SC 1,2	0	10	30	70	120
ClSb3 Conifer Lowland Black Spruce Poorer Sites	HU14	Sb; lowland site; SC 3,4	0	10	30	70	120
Cl_Ce Conifer Lowland Cedar	HU15	Ce + T > 30%; lowland site	0	10	30	70	130
CuPjw Conifer Upland Jack Pine-White Pine	HU1	Pr + Pw \geq 20%; PFR or PF	0	5	20	60	110
CuPjS Conifer Upland Jack Pine-Spruce	HU2	Pj or Sb WG; PFR or PF	0	5	20	50	90
CuPwr Conifer Upland White Pine-Red Pine	HU3	Pr + Pw \geq 20%; SC 1,2,3	0	5	20	80	140
Cu_Pj Conifer Upland Jack Pine	HU4	Pj > 50%; hardwood less than 50%, SC 3	0	10	30	70	120
Mi_PS Mixedwood Pine-Spruce	HU5	Pj or Sb WG; hardwood < 50%; SC 2,3	0	10	30	70	120

^aSeral stage codes: P, presapling; S, sapling; I, immature; M, mature; L, late.

terminated in the choices file created by the strategic model), and the specified spatial harvesting constraints (as defined for the tactical model) to block and schedule harvest blocks. The model has five phases of operation (Remsoft Inc. 1998):

1. Stands are randomly selected from the eligible stand list, and harvest units are then developed using an accretion algorithm.
2. Initial scheduling of harvest units begins, where harvest units with neighbours are randomly selected. A heuristic algorithm is used to combine harvest blocks so as to minimize the requirements

for green-up delay and to maintain harvest block size with maximum allowable opening size.

3. An algorithm is used to better balance output flows so as to match the strategic schedule by either changing the harvest timing choice of harvest blocks or by disaggregating the harvest unit back into component stands, and then reallocating the individual stands to harvest units.
4. To reduce road access problems caused by combining proximate harvest units into a single harvest block, an algorithm attempts to incorporate stand fragments into the "spaces" between proximate harvest blocks.

Table 2. Habitat suitability matrix, by seral stage

	Habitat Unit ^a																																			
	CuPjw (HU1)					CuPjS (HU2)					CuPwr (HU3)					CuPi (HU4)					MiPS (HU5)					HuBfS (HU6)					Cu Ce (HU7)					
	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	
Marten											1	2	2			1	2	2			1	2	2			1	1	1			1	1	1			
Caribou (w) ^b						1	2	2								1	2	2								1	1									
Caribou (s)						1	1	2	2	2						1	1	2	2	2						2	2	2								
Moose (w)											2	2	2			2	2	2			2	2	2			1	1	1			1	1	1			
Moose (s)	1	1				1	1				1	1				1	1	1			2	2				2	2	2	2	1	1					

^aNil = not used; 1 = used, 2 = preferred.

^bWinter (w) and summer (s) habitat is separated for caribou and moose.

- An algorithm attempts to balance output flows by deallocating blocks until the flow fluctuations are within range of the specified tolerance. This deallocation reduces the objective function; hence the objective function (e.g., timber volume) may be reduced lower than the current best solution.

A single model run is a simulation defined by an AHA goal, a combination of spatial/temporal constraint variables, and a computational solution (harvest schedule). The harvest constraint variables include: (1) stand proximity (minimum distance allowed between two harvest blocks that will be harvested in the same time period); (2) target block size (preferred size of harvest blocks); (3) maximum block size (usually specified by policy); (4) minimum block size (usually reflecting economic feasibility); and (5) green-up delay (time period that must elapse before a harvest block that is proximate to a previously harvested block can be cut). Mesoscale stratification was also an optional harvest scheduling constraint, and this constraint was included at the strategic modeling stage, which then defines the time period that individual stands within the FMU become eligible for harvest. The program then respects the defined availability of these stands for blocking. Note that the reported "average block size" is determined by statistical analysis of the resulting solution and is not a specified harvest constraint.

For each run, the blocking program allocated the harvest for five 10-year terms. Although the SFMM provides an AHA for a 200-year period, there is no vegetation community succession model encoded in the harvest allocation program. Hence, we decided that five 10-year terms of harvest was the maximum acceptable time period to conduct harvest allocation without accounting for major changes in stand-specific composi-

tion and condition that would be expected under natural conditions.

The harvest-blocking model was run 64 times—once for every spatial/temporal constraint variable combination, with and without the mesoscale stratification. The reported result of the run is the best solution obtained after approximately 1000 individual runs.

Habitat Supply Analysis

In the context of sustainable forest management, habitat refers to a set of forest and environmental attributes that provide for the needs of a specific species throughout its life history, and habitat supply refers to the area of forest that can function as habitat for a specific species. In practice, a forest stand is assigned to a habitat class value with reference to a specific species, and the area of forest within this class (e.g., highly suitable) is calculated. This value is the supply of forested habitat for that species (which may actually represent only a subcomponent of overall habitat needs), and this value will change over time as the forest changes and forestry activities are undertaken. The habitat requirements of species can be grouped to reflect general patterns of forest structure dependencies. In this research we studied the area of preferred habitat (habitat supply) for four selected wildlife species that represent a diverse group of such forest structure dependencies: moose (young/mature forest edge), caribou (interior late-seral-stage conifer), pine marten (mixed edge and interior forest) and ovenbird (mature and late-seral-stage deciduous). In that the habitat suitability models, which form the basis of the habitat supply analysis, have not been fully field tested, the analyses presented here should be viewed from the perspective of a strategy for conducting trade-off analyses between timber supply and habitat supply objec-

Table 2. Continued

Habitat Unit ^a																																												
MiCBS (HU8)					CuPS (HU9)					MiBfS (HU10)					MiHBS (HU11)					HL_Ab (HU12)					CISb1 (HU13)					CISb3 (HU14)					Cl_Ce (HU15)									
P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L	P	S	I	M	L					
	1	2	2			1	2	2			1	2	2			1	2	2								1	2	2			1	1	1			1	1	1			1	1	1	
	1	1				1	1	1			1	1														2	2	2	2		2	2	2	2		2	2	2	2					
	2	2	2			2	2	2			2	2	2			1	1	1			1	1				1	1	1			1	1	1			1	1	1						
1						1	1				2	2				2	2	2	2		2	1	1	1		1	1	1	1												1	1		

tives, and as general principles derived from consideration of species representing a range of forest structure dependencies.

We analyzed 64 simulated landscapes in terms of habitat supply for the four selected species. A habitat suitability index in the range 0–2 was assigned to each stand, or polygon, within the forest resource inventory GIS database (Table 1). Suitability is defined in terms of overstory composition, and each habitat unit has associated with it five seral stages (pole, sapling, immature, mature, and late). Each stand is assigned a suitability value of 0 (not used), 1 (used) or 2 (preferred) for each of the four wildlife species (Table 2). For example, preferred marten habitat includes mixed wood pine–spruce in the mature and late seral stages, so stands with this combination would be assigned a marten habitat suitability value of 2. Although both “used” and “preferred” habitat are assigned to each stand, we restricted analysis in this study to potential preferred habitat based on the assumption that the availability of preferred habitat would be most limiting in this area for the selected species. Note that the categories are an expert (theoretical) opinion that if the animal were presented with both types of habitat in equal availability, it would choose category 2 (preferred) over category 1 (used) habitat. The term “preferred” is used in its proper context, but the evidence to support the interpretations is incomplete.

Highly fragmented habitat is often of less value to wildlife than more aggregated habitat. To account for habitat fragmentation, we summarized habitat supply in such a way as to give higher values to less fragmented solutions. Habitat supply was calculated separately for each of the four species as the sum of preferred habitat, weighted by the degree of local fragmentation:

$$WHS_s = \sum_{i=1}^N PH_s * PPH_s$$

where *S* is one of the 4 species, *WHS* is an index of the

weighted habitat supply, *N* is the number of hexagon cells in the overlay, *PH* is the area of preferred habitat in a cell, and *PPH* is the weighting factor for local fragmentation within a hexagon cell (proportion of preferred habitat within a cell).

Habitat Mosaic Analysis

The habitat mosaic describes the emergent pattern of patches across the landscape. Harvest block size, shape, proximity, and short-term temporal constraints on harvest (green-up delay), and broader scale constraints (mesoscale stratification) collectively contribute to the emergent landscape pattern. We define a new, spatially explicit measure of the mosaic profile, where the landscape pattern is described by a scale-dependent frequency distribution of landcover classes. The scale is defined by an overlay of hexagon grids of arbitrary size and where the percent composition of landcover classes is determined within each hexagon cell (Figure 4). The hexagon overlays were created using the Patch Analyst extension to ArcView (Rempel and others 1999). We chose to use hexagons of 100 ha in area because this is the approximate home range size of marten (Thompson and Colgan 1987). The frequency distribution is presented as a histogram. For example, the histogram for marten (Figure 5) describes the relative frequency of small to large fragments, as visualized in Figure 4. A landscape with many small fragments of habitat will have a higher frequency in the first column (Figure 5A), while a coarser landscape will have a more even distribution among columns (Figure 5C). To compare the habitat mosaic profile between scenarios, we used a simple χ^2 contingency table analysis, where the “expected” and “observed” values were based on analysis of the pre- and postharvest histograms, respectively. The inverse of the χ^2 value was then calculated. The higher the value, the closer the pre- and postharvest habitat profiles.

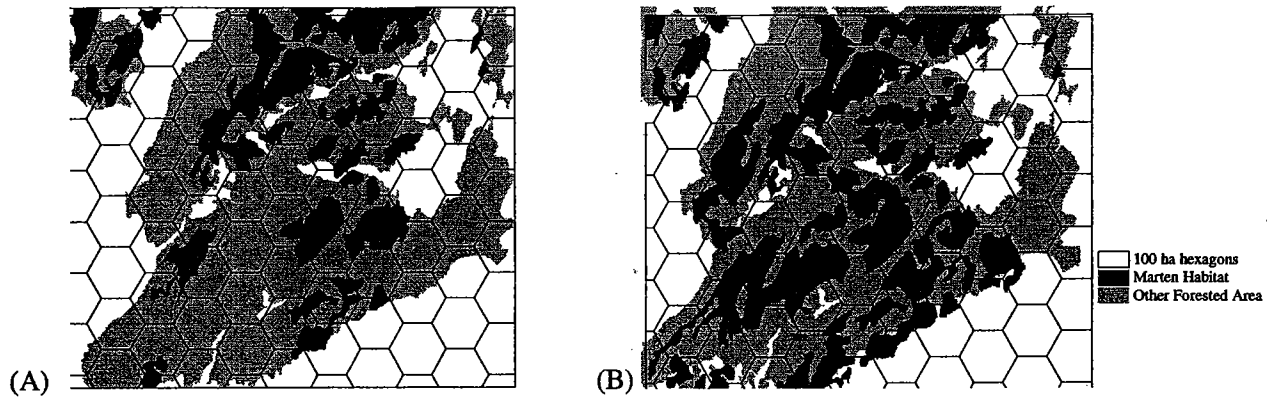
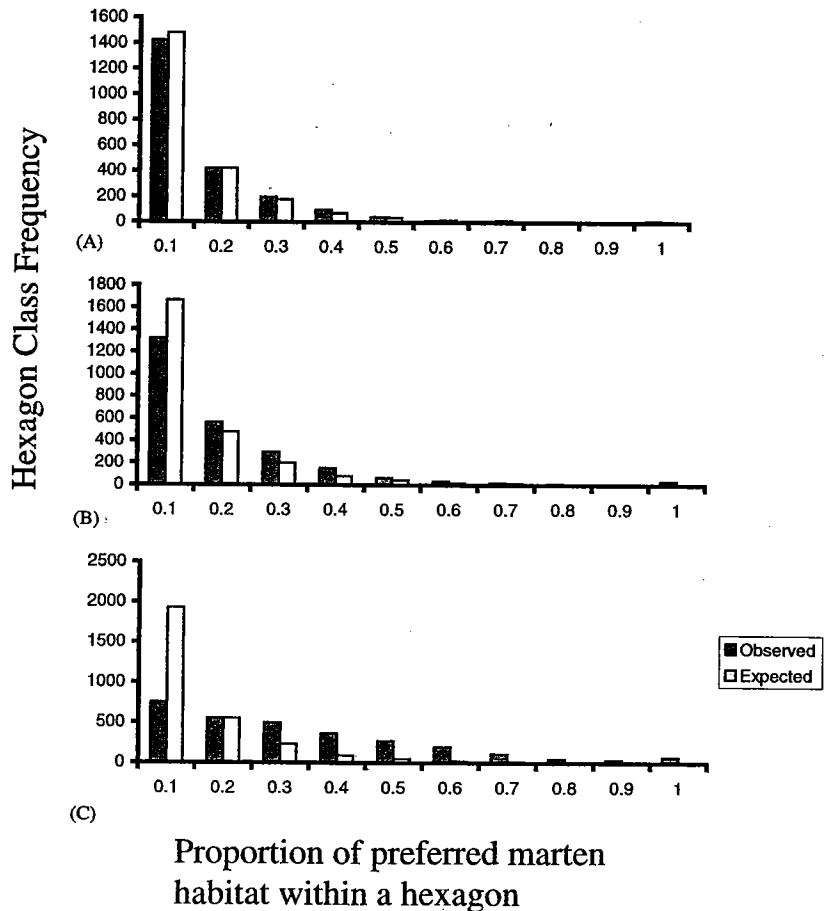


Figure 4. An example of the hexagon pattern overlay (100-ha grid cells) for potential preferred marten habitat (in dark tone) after simulated harvest for a portion of the Nakina North Forest with mesoscale stratification: (A) harvest block proximity = 100 m; (B) harvest block proximity = 2000 m.

Figure 5. Histograms depicting pattern of habitat mosaic profile for marten, 1-term green-up delay, in the Nakina FMU: (A) without mesoscale stratification, and (B) and (C) with mesoscale stratification; (A and B) proximity 1000 m, target block size 1000 ha; (C) proximity 1000 m, target block size 250 ha. Frequency of the 0–0.1 range represents the number of hexagons whose area comprise < 10% marten habitat. Weighted sum of the histogram columns is habitat supply. Expected value is derived from the preharvest forest and observed value from the postharvest model run. The pattern of relative frequencies in each size range quantifies habitat mosaic profile.



Results

Wood Supply

Multiple linear regression of AHA-achieved (the percent of annual harvest area that could be realized

through spatial harvest blocking) versus harvest variables (proximity, maximum block size, green-up delay, and forest management scenario) reveals that more of the annual harvest can be achieved when blocks are closer together, there is no green-up delay, maximum

Table 3. Effect of harvest scheduling variables on wood and habitat supply^a

	% AHA	Caribou	Moose winter range	Moose summer range	Marten	Ovenbird
Proximity	-0.516	0.482	0.377	-0.238	0.365	-0.45
Green-up delay ^b	-0.323	0.357	0.183	—	0.242	—
Max. block size	0.464	-0.441	-0.448	0.268	-0.345	—
Stratification ^c	-0.425	0.341	0.600	-0.434	0.561	—

^aValues are standardized slope coefficients for the multiple linear regression (significant values only).

^bGreen-up delay of one 10-year term = 1; without green-up delay = 0 (defined as time required before a harvest block adjacent to a previously logged block can be scheduled for harvest).

^cWith mesoscale stratification = 1; without stratification = 0.

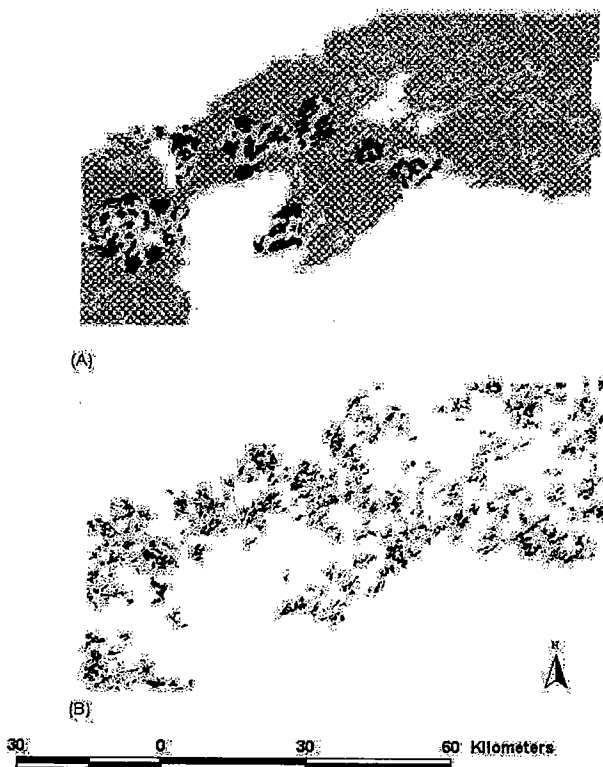


Figure 6. Harvest block allocation (dark shading) for terms 1–2 (where 1 term = 10 years) for the Nakina FMU (A) with mesoscale stratification, and (B) without stratification, after 2 terms of harvest. Approximately 57,000 ha were scheduled for harvest in (A) and 85,000 ha in (B). For both analyses, harvest block proximity could not be closer than 1000 m, and target block size was 1000 ha (see Figure 8).

block size is high, and no stratification is applied (Table 3). Both the stratification and green-up delay constraint limit cut-block allocation temporally and spatially (Figure 6). Without the constraints, the block scheduling program has more flexibility in forming harvest blocks and is more likely to achieve the AHA target (Figure 7A).

A linear regression of proportion AHA achieved versus harvest constraints estimates the predicted loss of wood supply resulting from the harvest constraints:

$$Y = -0.000132 * P - 0.1175 * D + 0.0001167 * S + 1.00795$$

where Y is the proportion of non-spatial AHA achieved, P is harvest block proximity (meters), D is green-up delay (0 = no delay, 1 = 1 term delay), and S is the target block size (hectares). For this model, stratification was not applied. All coefficients with $P < 0.001$, $R = 0.81$.

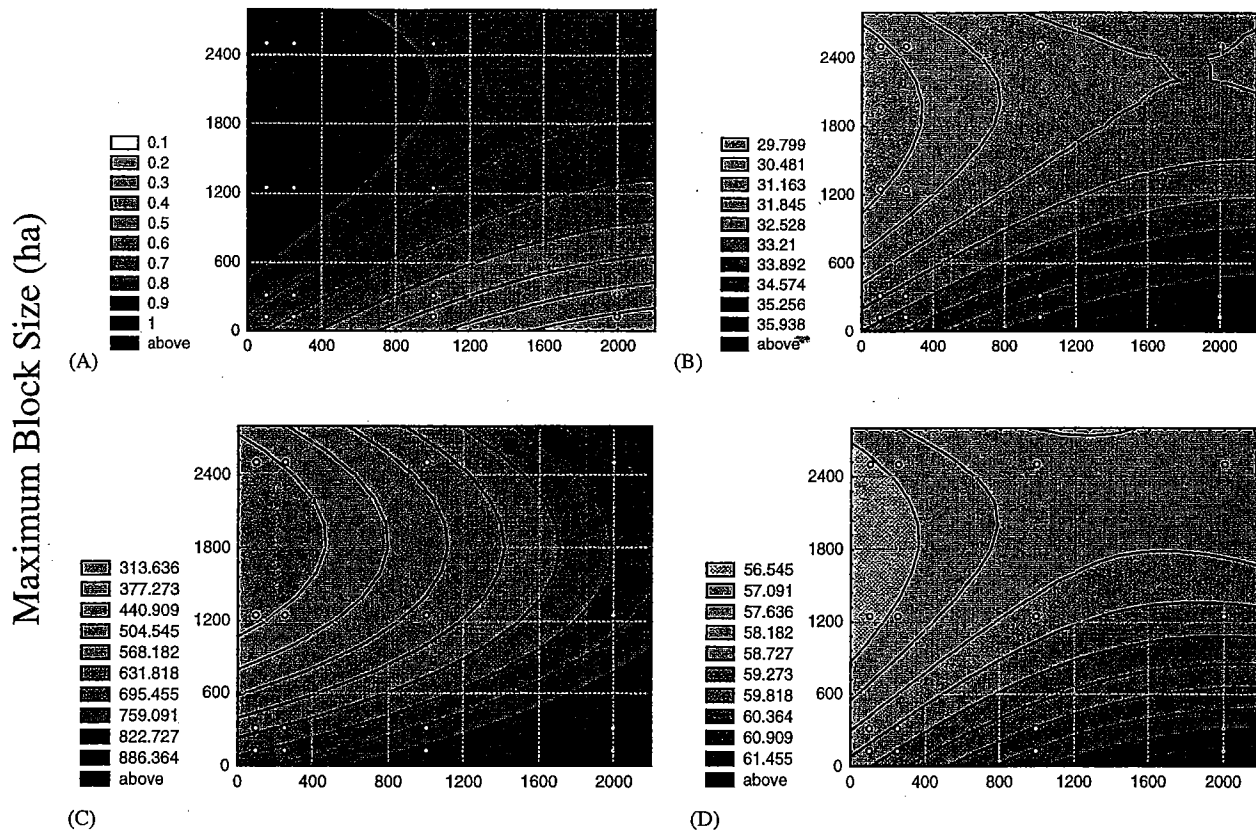
We expect this model to be fairly representative for similar types of relatively unaccessed forest, and it could be used to roughly estimate expected loss in nonspatial estimates of wood supply caused by spatial blocking constraints. A different model would be required for a forest with a longer history of forest management.

Response-surface graphs for wood supply indicate that the maximum proportion of AHA achieved occurs when proximity is < 1000 m and when maximum block size is greater > 500 ha (Figure 7A). When the blocking program is allowed to create large blocks close together, the target AHA is more likely to be achieved. This result is affected by the initial state of the Nakina FMU, i.e., the lack of industrial forest development and the large component of overmature conifer stands. As harvesting progresses in the area, it is expected that the blocking program will have more difficulty in finding and scheduling large eligible blocks while meeting spatial and temporal constraints.

Three different distributional patterns emerge from histograms depicting harvest block size distribution: (1) the majority of the area is in small block sizes; (2) the majority of the area is in fewer larger block sizes; or (3) a more even distribution where a similar amount of area is harvested across a range of block sizes (Figure 8).

Habitat Supply

Multiple linear regression of spatially defined habitat supply (weighted-area sum) indicates an almost inverse response to that of wood supply. For caribou, moose winter range, and marten habitat, a greater



Proximity (m)

Figure 7. Response-surface graph for the Nakina North Forest, with mesoscale stratification and a green-up delay of one 10-year term. Contours depict the relationship between proximity (x axis), maximum block size (y axis) and (A) proportion of AHA achieved, (B) caribou habitat supply, (C) marten habitat supply, and (D) moose winter range habitat supply (z axes).

supply of habitat occurs when harvest blocks are further apart, maximum block size is smaller, and both a green-up delay and stratification are applied (Table 3). This is further illustrated by the response-surface graphs, where harvest block proximity and maximum block size is plotted against habitat supply (Figure 7). The best habitat supply is found in the lower right corner, where distance between harvest blocks (proximity) ranges from 400 to 2000 m, and maximum harvest block size ranges from 100 to 1000 ha.

Although spatial harvest variables were significantly related to habitat supply, the magnitude of the effect was relatively small for caribou, moose winter, and moose summer habitat, where values generally differed $< 10\%$ between their original habitat amounts and the amounts predicted under the various simulated harvest conditions. However, for ovenbird the model suggests that $> 90\%$ of its habitat is lost regardless of the harvest variables. For marten, the response is variable, with

predicted habitat supply increasing between 2 and 4 times, depending on the harvest variables. The reduction in ovenbird habitat is a result of the conversion of a limited supply of mixed wood and hardwood forest types to conifer under all simulations.

Habitat Mosaic

For each model run, we compared how the new habitat pattern differed from the original habitat pattern. Multiple linear regression of the habitat mosaic profile index (i.e., inverse of χ^2 value) indicated that of all the forest harvest variables, only "forest management scenario" was significant. The harvest block distribution maps for the first 10 years of cutting illustrate the dramatic difference in landscape pattern created by the two scenarios (e.g., Figure 6). The mesoscale stratification results in a more aggregated cutting pattern and leaves much of the FMU undisturbed. In contrast, the more traditional scenario leaves the forest more frag-

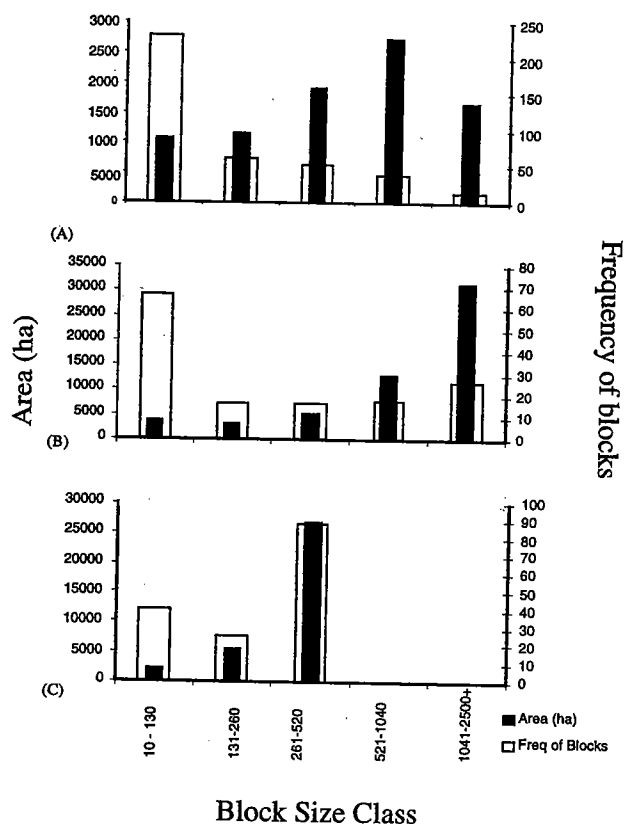


Figure 8. Harvest block size-class distribution in terms of area (solid bars) and frequency (open bars) resulting from harvest in terms 1–5 (50 years allocation) in the Nakina FMU (A) without mesoscale stratification, and (B and C) with mesoscale stratification; (A and B) proximity 1000 m, target block size 1000 ha; (C) proximity 1000 m, target block size 250 ha.

mented, with harvest blocks dispersed across the landscape.

Analysis of mosaic values between scenarios (using 100-ha hexagon cells), with and without the mesoscale stratification, revealed significant differences only for caribou, moose winter range, and marten habitat (Table 4). For all of these, a greater similarity with the original landscape pattern was found when the stratification was not applied. Habitat mosaic profile charts illustrate this for marten, where for larger target block sizes the pattern differed slightly from the preharvest state (1000-m proximity, 1000-ha maximum harvest block size, and 1-term green-up delay) (Figure 5A, B), while for smaller target harvest block sizes, the pattern differed substantially from the preharvest condition (Figure 5C). The stratification, together with larger target harvest blocks, resulted in a less fragmented, coarser-grained landscape, where less of the marten habitat was found in small fragments (Figure 5B). Strat-

Table 4. Effect of mesoscale stratification on habitat mosaic profile (landscape pattern), relative to the preharvest condition

Forest management strategy ^a	Caribou ^b	Moose		Marten	Ovenbird
		Winter range	Summer range		
0	93.1	103.2	20.6	19.2	44.7
1	8.6	12.2	34.0	0.2	41.2

^a1 = with mesoscale stratification, 0 = without stratification.

^bValues are mean estimates of similarity to the original forest condition ($1/\chi^2 * 1000$); higher values indicate greater similarity. Values in italic are not different between scenarios.

ification also left the northeast section of the Nakina unharvested in the first 60 years; so even though a similar volume of wood was scheduled for harvesting, forest management under this scenario affected less of the overall landscape.

Discussion

The modeling approach and analyses presented here provide insight into the consequences of creating differing forest patterns through harvest block allocation. Many logistical elements must be considered in blocking and scheduling timber for harvest, including access to road building materials, proximity to major highways, waterway crossing-points, etc. Although these considerations were not included in the model, the results presented here are generalizations and thus can provide insight and guidance for more complex real-life decisions. We found in this study of the Nakina FMU that wood supply and habitat supply objectives conflict with respect to optimal harvest block size. In this FMU, it is easier to spatially allocate stands if harvest blocks are large and located close together; however, habitat supply for the range of study species increases if harvest blocks are smaller and spaced further apart. The forest is less fragmented, and greater extents of wilderness area remain, if mesoscale stratification is applied, but this also resulted in a greater divergence from the preharvest forest pattern. As well, habitat supply increased with smaller, widely spaced harvest blocks, but this also required an assumption of uninhibited access to the entire forest. No broad zone of convergence, where both objectives were equally well met, was found.

The appropriateness of using the current forest condition as the ecological benchmark, given the relative lack of disturbance caused by aggressive fire suppression, is questionable. An alternative approach would be to define a benchmark based on more extensive anal-

ysis of natural patterns, and through more intensive research into the relationship between landscape pattern and ecosystem function. The comparative maps in Figure 6 provided perhaps the most compelling evidence of how the mesoscale stratification affects the landscape mosaic. The stratification introduces a hierarchical driving factor, causing landscape pattern to be organized first at a mesoscale and then second at a stand-scale. This nested set of patterns also occurs in systems driven by natural disturbance dynamics (Elkie and Rempel 2001) and is an important element for emulating natural landscape patterns. Without the stratification, a dispersed and relatively uniform network of patches is created, with an associated high road density.

Analysis of a dispersed pattern of harvest blocks in northwest Ontario revealed substantial dissimilarity from natural patterns relative to wildfire, and the high road density had a negative effect on moose populations (Gluck and Rempel 1996, Rempel and others 1997). This analysis also revealed that larger, progressive clear-cuts were more similar to natural patterns created by wildfire. Although our modeling analysis revealed conflicts for the competing objectives, the analysis also suggests a reasonable compromise. Application of the mesoscale stratification, together with a diversity of harvest block sizes and a between-harvest-block proximity of 250 m, will perform relatively well with respect to wood supply objectives (ca. 86% of nonspatial AHA) and at the same time create a less fragmented landscape that better reflects natural forest patterns. This compromise emphasizes coarse filter landscape patterns over fine filter species-specific habitat supply values. It should be noted, however, that a management strategy should consider the temporal pattern of change over several rotations. Although forest succession cannot yet be modeled over such time frames, simple rules of forest aging can be used to provide insight to the sustainability of a landscape management strategy.

There are a number of other species-specific interpretations that can be made from the response-surface analysis of habitat. All of these, of course, are subject to the validity of the driving habitat suitability model. For example, the modeling suggested very little change in habitat supply for caribou and moose, an increase for marten, and a large decline for ovenbird. Regardless of the harvest regime, very little potential preferred ovenbird habitat remained after harvest. This indicates that species requiring 100-ha patches of mature hardwood forest may be adversely impacted once harvesting commences in this management unit. However, it should also be noted that there are relatively few hardwood

stands in the FMU (Figure 2), so any harvest of these will result in substantial impact. Further study and protection measures may be in order if there is a designated species in the area that has similar habitat requirements. The predicted response for ovenbird certainly needs to be tested through studies using model-based field sampling.

While forest management is improving through better use of information (Baskent and Yolasigmaz 1999), it is clear that great uncertainty still plagues the long-term results of management decisions. Although the best learning comes from carefully controlled replicated experiments, in forest and wildlife management this is inhibited at large scales due to limited resources (financial and otherwise) and the long time frames required to see results. In addition, social values and goals are constantly changing, and the quality of information for forest management planning is always improving. Adaptive management allows forest managers to proceed with decision-making, despite uncertainty, incomplete information, and disagreements over particular management regimes (Taylor and others 1993). One of the first stages in an adaptive management cycle is to "identify major uncertainties by trying to predict the outcome of policy alternatives" (Walters 1995). Some of the uncertainties identified through this modeling study are:

1. An extreme decline in habitat values was predicted for wildlife species requiring mixed wood and hardwood stands with the onset of timber harvests in the FMU. While this is a function of the forest composition prior to harvest, it is a concern that requires further investigation. How will this change affect the long-term survivorship of ovenbird in the FMU, and is the habitat suitability model accurate?
2. The stratification constraint will apparently benefit both moose and caribou. If this true, what are the consequences to caribou if moose populations rise? Will wolf populations also rise, and, if so, will they then drive caribou numbers down through the process of predator switching (Bergerud and others 1984)?
3. Applying the stratification may increase supply of marten habitat but may also change the configuration of that habitat relative to the preharvest state. How important is it for the long-term viability of marten to maintain the current forest state, and how has fire suppression altered the current forest relative to a natural state? Will a nested natural disturbance pattern provide an improved habitat pattern for marten?

The uncertainties identified in this project are not definitive but rather serve as red flags that need to be addressed in future research or through monitoring of alternative large-scale management actions. Further enhancements to the mosaic profile analysis procedure should be pursued. The 100-ha grid cell analysis is certainly not appropriate for all species, and analyses at different scale may reveal quite different perspectives of landcover and wildlife response relationships. The 100-ha cell size was probably too small to capture some of the emergent patterns created by the mesoscale stratification. A more robust analysis would be achieved if calculations were conducted across multiple scales and if window offsets were used to estimate profile variance. This modification would facilitate more in depth analysis for both research and forest management planning.

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