Timber supply implications of natural disturbance management

by Glen W. Armstrong¹, Steven G. Cumming² and Wiktor L. Adamowicz³

The timber supply implications of applying an interpretation of the natural disturbance model (NDM) of forest management were examined, using a computer model simulating forest growth and harvest. Under the natural disturbance model, much less timber was available for harvest than under maximum sustained timber yield management. Several questions relating to implementation of the natural disturbance model of management are raised with the intent of stimulating some discussion.

Les implications sur l'approvisionnement en bois suite à l'implantation de l'interprétation d'un modèle de perturbation naturelle (NDM) à titre d'aménagement forestier ont été étudiées, au moyen d'un modèle informatique simulant la croissance forestière et la récolte. Selon le modèle de perturbation naturelle, il y a beaucoup moins de bois disponible pour la récolte que selon un aménagement maximal soutenu de rendement en matière ligneuse. Plusieurs questions se rapportant à l'implantation d'un modèle de perturbation naturelle sont soulevées dans le but de stimuler la discussion.

Introduction

The natural disturbance model (NDM) of forest management (Hunter 1993) is the basis of many of the ecosystem management approaches being proposed for the boreal forest (Haila *et al.* 1994, Gauthier *et al.* 1996). The central assumption behind this model is that timber harvest practices designed to mimic natural disturbances will help achieve the goal of a sustainable ecosystem while providing timber and other goods and services. Hunter identifies three properties of natural disturbance that could be mimicked by harvesting: spatial pattern, residual material, and rates of disturbance. Hunter focuses on spatial pattern, Lee *et al.* (1997) discuss residual material, and this paper focuses on rates of disturbance.

Most of the discussion of NDM management in the boreal forest has focused on emulating the effects of stand-replacing wildfire, possibly because

- 1) wildfire is the most important (or at least, most obvious) non-anthropogenic agent of change in the boreal forest (Johnson 1992),
- 2) to the degree that fire suppression efforts are successful, timber harvest can be compensatory to wildfire, and
- 3) emulation of a stand-replacing fire may allow for harvest techniques similar to those used in clearcut harvesting.

Natural disturbances operate over a continuum of spatial scales – the stand (patch or block scale) and the forest (estate or landscape scale) are particularly relevant to forest management decisions. Stand level considerations will affect cutblock layout and the amount of timber removed from a particular site. For example, one would expect that maintenance of residual structure in a cutblock would reduce the harvested yield (measured in $m^3 ha^{-1}$). Forest level considerations will affect

Glen W. Armstrong

Steven G. Cumming

the size and spatial distribution of harvested areas, the distribution of cover types and age classes over the landscape, the type of stands scheduled for harvest, and the rates at which they are harvested. These harvest-scheduling considerations are very important as they relate directly to the allowable cut for an area and the distribution of this cut in space and time.

Wiktor L. Adamowicz

One strategy for setting timber harvest levels under a natural disturbance model is to dictate that the average annual area disturbed under management should equal the average annual area disturbed under natural conditions. This presupposes that forest protection activities have had the effect of reducing the annual area disturbed. The allowable annual harvest area is then the difference between the average area disturbed under natural conditions and the average area disturbed given the level of forest protection. In order to use this strategy, one must be able to determine average annual disturbance rates with and without fire suppression.

¹Department of Rural Economy, University of Alberta, Edmonton AB, T6G 2H1; email: glen.w.armstrong@ualberta.ca

²Department of Renewable Resources, University of Alberta, Edmonton AB, T6G 2H1; email: steve.cumming@ualberta.ca

³Department of Rural Economy, University of Alberta, Edmonton AB, T6G 2H1; email: vic.adamowicz@ualberta.ca

Table 1. Net area (ha) of starting inventory by age class and conifer content

Age(yrs.)	Conifer Content (percent)									
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
0-4	9 521	1 065	0	750	290	37	702	41	647	6 697
5-14	60	0	0	254	10	0	43	4	0	256
15-24	2 161	225	34	199	62	23	506	99	112	2 104
25-34	8 417	2 730	182	1 648	123	118	1 389	73	1 238	5 521
35-44	14 199	5 412	264	3 877	292	600	1 728	638	1 580	15 775
45-54	37 855	16 309	239	10 554	1 581	823	8 127	879	6 813	23 082
55-64	40 285	18 546	612	12 907	1 681	2 258	10 848	2 099	8 249	34 851
65-74	36 096	20 151	128	8 227	1 601	666	3 486	460	4 072	11 185
75-84	29 269	12 088	143	7 326	714	1 563	3 626	526	3 210	12 597
85-94	13 347	9 369	366	5 733	1 167	450	3 780	835	3 103	12 583
95-104	12 798	15 648	896	12 299	870	593	7 363	1004	4 536	27 612
105-114	3 723	3 391	437	5 142	483	355	5 444	871	4 253	12 076
115-124	2 931	1 985	611	4 910	576	645	7 888	1 220	2 689	13 796
125-134	1 431	1 110	185	2 689	477	189	7 582	662	6 014	12 221
135-144	2 032	1 217	926	3 653	900	1 682	6 974	2 819	6 319	14 464
145-154	144	174	30	207	39	182	1 127	681	1 386	3 038
155-164	343	310	49	607	125	117	1 378	787	1 431	2 036
165-174	6	36	9	64	0	0	166	29	158	562
175-184	217	0	0	5	0	7	173	0	31	119
184-194	191	38	0	5	0	0	14	28	28	142
195+	0	0	0	3	0	0	0	2	10	46

Alberta-Pacific Forest Industries Inc. (APFI) has proposed to use this strategy for determining annual harvest levels for their Forest Management Agreement Area in northeastern Alberta. They plan research to "determine the differences in disturbance rates across the FMA, so that harvest rates and methods can emulate the disturbance rate for each 'disturbance rate' zone" (Alberta-Pacific Forest Industries Inc., undated). This approach to allowable cut determination is very different from the usual methods used in Alberta. In essence, the "natural rate" approach assumes that the natural rate of disturbance can be determined for a forest area, and that this rate of disturbance should be applied to the managed forest. In other words, the annual area disturbed (harvested and burned) under management should equal the annual area disturbed (burned) under natural conditions. To date, no examination has been made on the potential effects on timber supply resulting from the implementation of this approach.

Van Wagner (1983) presented a forest level simulation model incorporating a natural disturbance process similar to that modelled in this paper, and timber harvest. The purpose of his model was to examine the effects of different annual rates of burn on the long-term equilibrium timber supply of a forest. Reed and Errico (1986) examined a similar problem using an optimization framework. In both these papers, the objective was to determine the appropriate level of harvest given that a specified proportion of the forest was expected to burn each year.

Our model is less ambitious and serves a different purpose. We develop a simple simulation model of forest growth and disturbance. It is used to compare the areas and volumes disturbed under different estimates of the natural disturbance rate with results from a sustained timber yield model (without disturbance). The areas and volumes disturbed under the natural disturbance scenarios can be usefully thought of as defining the upper limits to areas and volumes harvested under the AFPI approach to natural disturbance management. The sustained yield scenario is intended to represent the *status quo* for

harvest level determination in Alberta. We will show that the schedules of harvest area and volume for the different scenarios are strikingly different. The analysis presented here is not a methodological advance, but is an example of how a simple model can be a useful tool for evaluating the effects of a change in forest policy or practices. The results presented here provide a starting point for discussion of the relationship between the natural disturbance model of forest management and timber harvest levels.

Model Development

The model is a straightforward representation of forest growth and disturbance. The initial forest is represented as a matrix of productive area indexed by age and conifer content. Each year, a proportion of the area is disturbed and regenerates according to our regeneration assumptions. The portion of the area that is not disturbed increases in age by one year. A proportion of the area in each conifer content class moves to the next highest conifer content class. This sequence is repeated for each year in the specified simulation period. The inputs to the model used here consist of a set of forest inventory data, timber yield tables, succession and regeneration assumptions, and annual disturbance probabilities. These are described in this section.

We obtained forest inventory data for a portion of the boreal forest in northeastern Alberta covering 300 townships (15 townships north by 20 townships east), or approximately 2.8×10^6 ha. The stand listings include a description of the forest cover type including species composition, stand age, and gross stand area as interpreted from aerial photographs. As part of a timber supply analysis for the area, the net productive land base of the study area was determined. Areas considered unmerchantable (including wetlands, swamps, and bogs), inoperable, or as part of reserves or buffers are excluded from the net productive land base. The net land base of the study area consists of 785 042 ha. We describe the forest in terms of the area in ten-year-wide age classes and ten-percent-wide

Table 2. Softwood volumes ($\text{m}^3 \text{ha}^{-1}$) by age and conifer content

Age(yrs.)	Conifer Content (percent)									
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	1	1	1
60	0	0	0	0	0	0	13	25	38	51
70	0	7	14	21	27	34	50	66	82	98
80	0	15	30	45	60	75	92	109	125	142
90	0	22	45	67	90	112	130	147	165	182
100	0	29	58	87	116	145	164	182	201	219
110	0	35	70	104	139	174	194	213	233	252
120	0	40	80	120	160	200	220	241	261	282
130	0	45	89	134	178	223	244	265	287	308
140	0	49	97	146	195	243	265	287	310	332
150	0	52	104	157	209	261	284	307	330	353
160	0	55	111	166	222	277	301	324	348	371
170	0	58	117	175	233	292	316	340	364	388
180	0	61	122	183	244	305	329	354	379	403
190	0	63	127	190	254	317	342	368	393	418
200	0	66	132	198	264	330	356	382	407	433

Table 3. Hardwood volumes ($\text{m}^3 \text{ha}^{-1}$) by age and conifer content

Age(yrs.)	Conifer Content (percent)									
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
40	43	32	21	11	0	0	0	0	0	0
50	99	80	61	42	23	18	14	9	5	0
60	144	120	96	72	48	39	29	19	10	0
70	180	153	127	100	73	59	44	29	15	0
80	209	181	153	124	96	77	58	38	19	0
90	233	204	174	145	116	93	69	46	23	0
100	253	222	192	162	132	105	79	53	26	0
110	269	238	207	176	145	116	87	58	29	0
120	283	251	219	187	155	124	93	62	31	0
130	295	262	229	196	163	130	98	65	33	0
140	306	271	237	203	168	135	101	67	34	0
150	315	279	244	208	173	138	104	69	35	0
160	322	286	249	213	176	141	106	70	35	0
170	329	292	254	216	178	142	107	71	36	0
180	336	297	258	219	180	144	108	72	36	0
190	341	301	261	220	180	144	108	72	36	0
200	347	305	264	222	180	144	108	72	36	0

conifer content classes. Conifer content classes are used here because stand inflammability is assumed to be related to conifer content, and they provide us with a way of tracking forest succession. The distribution of the inventory by age class and conifer content as of 1996 is presented in detail in Table 1.

Forest growth is modelled through the application of softwood and hardwood yield tables. The yield tables used here were derived by Joy (1995) from the Alberta Phase 3 white spruce, mixedwood, and hardwood yield tables (Alberta Forest Service 1985) calculated to the 13+7 cm utilization standard. The softwood and hardwood yield tables used here are presented in Tables 2 and 3.

The succession model used here was developed by Cumming *et al.* (1995). They estimated a simple linear relationship between the photo-interpreted white spruce content of inventoried stands and the photo-interpreted age. Based on this rela-

tionship, the annual percentage increase in white spruce content of stands is estimated to be 0.37%. In the application used here, 3.7% of the area in each conifer content class moves to the next highest content class each year of the simulation.

Cumming (1997) also developed the regeneration model used here. The model assigns an age of zero to disturbed stands and allocates the area proportionately to conifer content classes using the proportions shown in Table 4. This empirical distribution was developed by examining the conifer content of stands originating in the 1960s and growing them backwards to age zero using the succession model described above. Using this model the probability of initial conifer content is independent of the conifer content of existing stands or management prescription.

We compare four different representations of disturbance regimes in this paper. The sustained yield regime (scenario SY) is intended to represent sustained yield management as cur-

Table 4. Proportion of disturbed stands regenerating to each conifer content class

Conifer Content	Proportion
0–10	0.5500
11–20	0.1738
21–30	0.1018
31–40	0.0125
41–50	0.0739
51–60	0.0134
61–70	0.0233
71–80	0.0486
81–90	0.0028
91–100	0.0000

rently practised in Alberta. Murphy (1985) estimates the average annual pre-suppression disturbance rate for northern Alberta to be approximately two percent: we represent this regime as scenario M2. Cumming (1997), using different methods, estimates conifer content-specific disturbance rates for the region. His average annual disturbance rate is less than 0.5%: we represent this as scenario C1. For comparative purposes, we also develop a scenario using Murphy's model with a one percent annual disturbance rate (scenario M1).

We refer to areas and volumes *disturbed* rather than harvested or *burnt*. The area disturbed in any particular year will be equal to the sum of the areas burnt and harvested, because fire suppression will never be completely effective. This relates directly back to the idea that if timber harvest is to be compensatory to wildfire, fire suppression must be effective enough to reduce the disturbance rate.

Comparing the Murphy and Cumming regimes (M2, M1, and C1) to the sustained yield regime (SY) will provide some information on the timber supply implications of implementing a harvest scheduling system based on natural disturbance rates. Comparing the Murphy and Cumming regimes to each other may also be informative in that it provides a comparison of two independent estimates of the natural disturbance regime for the study area.

The disturbance schedule for sustained yield management (Scenario SY) was developed using a variant of the area-volume check (Davis 1966) developed by one of the authors (Armstrong). A standard area-volume check takes as input a table of forest area by age class and a yield table. Through an iterative procedure it finds the even-flow level of harvest which will result in the entire forest area being cut over exactly during a specified rotation period. This model rations out "surplus" old-growth volume over the rotation period.

Our variant of the area-volume check allows for the multiple yield tables and succession assumptions required by the growth models used in the NDM representation described below. We also allow for land base discrimination. Stands are classed as part of the hardwood land base if the conifer content is 50% or less; otherwise they are part of the softwood land base. In hardwood stands, even flow of hardwood volume is required; softwood volume is treated as incidental. The opposite applies to softwood stands. We chose to analyze a rotation of 100 years. This scenario is intended to represent harvest levels under the sustained yield management model as currently applied in Alberta.

The interpretation of NDM management examined here requires that the selection of stands for harvest should approximate nature's "selection" of stands for stand-replacing fires.

Table 5. Mean disturbance rates based by conifer content class

Conifer Content	Type of Fire Year		
	Average	Background	Event
<10	0.0027	0.00174	0.0104
10–20	0.0027	0.00174	0.0121
20–30	0.0027	0.0017	0.0139
30–40	0.0027	0.0017	0.0156
40–50	0.003	0.0017	0.0173
50–60	0.003	0.0017	0.0211
60–70	0.003	0.0017	0.0249
70–80	0.0045	0.0017	0.0287
80–90	0.0055	0.00408	0.0325
>90	0.008	0.00408	0.0363

This requires a model of the probability of occurrence of stand-replacing fire in a particular stand under natural conditions (i.e., without the effect of fire suppression).

Murphy (1985) applies the methods of Van Wagner (1978) to estimate disturbance rates from inferred age-class distributions of Alberta's forests as of the years 1969, 1949, 1929, and 1909. He uses the disturbance rate as of 1949 to represent the pre-suppression disturbance rate. If one assumes that photo-interpreted age accurately represents years since disturbance and that the probability of a stand-replacing fire is independent of stand characteristics, the age class distribution can be described using a negative exponential probability density function. The parameter of the distribution represents the annual probability of any hectare in the forest being burnt by a stand-replacing fire. Based on the inferred age class distribution as of 1949, Murphy estimates a fire probability for Alberta's northern forest of 0.0196. We use a disturbance rate of 0.02 to approximate this pre-suppression rate in Scenario M2.

Using the inventory as of 1969, Murphy estimates a fire probability of 0.011. In scenario M1, we approximate this with a burn rate of 0.01. This rate is examined because it represents an intermediate level between Murphy's and Cumming's pre-suppression rates of disturbance. The fire return interval implied by the 1% disturbance rate also corresponds with the 100-year return interval explicit in the sustained yield scenario.

Cumming (1997) develops his estimates of fire probability from maps of the areal extent of all known fires in his study area between the years 1940 and 1993. Based on statistical models of the types of stands burned in the years 1980 through 1993, he develops models of the composition of fires and, thus, stand type-specific disturbance rates. He uses a statistical model based on changes in the fire size distribution to correct for the effects of fire suppression. He differentiates between background years and event years, where event years are those years with extreme fire rates; the years 1940–1941 and 1980–1982 are the event years in Cumming's analysis. Fire events are assumed to occur every 30 years or so, and last an average of two to three years. Disturbance probabilities based on the conifer (specifically white spruce) content of stands are presented in Table 5. The average disturbance rates from this table are used in scenario C1.

⁴The sawtooth pattern apparent in these figures is due to the way volumes are assigned to the inventory. Volumes are tabulated by 10-year age classes. In each year of the planning horizon, each inventory record is assigned a volume based on age rounded to the nearest decade, leading to jumps in volume disturbed.

Fig. 1. Annual area disturbed (10^3 ha) under each disturbance regime.

Fig. 2. Annual softwood volume disturbed (10^3 m³) under each disturbance regime.

Simulation Results

The annual area disturbed under each of the four scenarios is presented in Fig. 1. In scenario M1, 7 850 ha of forest is disturbed each year. In scenario M2, 15 700 ha are disturbed each year. There is no variation in annual area disturbed under these scenarios because they assume constant rates of disturbance independent of forest composition or age-class structure. In scenario SY, the annual area disturbed closely approximates that in scenario M1, although there is some slight variation between years. In scenario C1, the annual area disturbed starts at about 3 500 ha and declines very slightly over the 100 year planning horizon. The rate of disturbance for scenario C1 is less than half that in the other scenarios.

The softwood and hardwood volumes disturbed annually are presented in Figs. 2 and 3 respectively.⁴ Under the SY scenario, approximately 1.6×10^6 m³ of softwood 850×10^3 m³ of hardwood are disturbed each year of the planning horizon. Under the M1 scenario, between 600×10^3 m³ and 1.0×10^6 m³ of softwood and 400×10^3 m³ to 700×10^3 m³ of hardwood are disturbed annually. In scenario M2, the disturbed softwood volume decreases from 1.2×10^6 m³ to about 800×10^3 m³ over the planning horizon. The disturbed hardwood volume decreases 1.3×10^6 m³ to a low of about 550×10^3 m³. In scenario C1, the softwood volume disturbed increases from about 350×10^3 m³ to about 850×10^3 m³ over the planning

horizon. The hardwood volume disturbed is nearly constant at about 200×10^3 m³.

Even though the annual areas disturbed under scenarios M1 and SY are similar, the volume disturbed in scenario M1 is about half that in SY. This occurs because in scenario SY area is scheduled for harvest on an oldest (i.e., highest volume) first basis, and in scenario M1 areas are disturbed proportionally across the age class distribution.

The average volume per hectare disturbed in each year of the planning horizon is presented in Fig. 4. For most of the planning horizon, an average of about 310 m³ ha⁻¹ is harvested under scenario SY. At the beginning of the planning horizon, nearly 370 m³ ha⁻¹ are disturbed; at the end, about 240 m³ ha⁻¹ are disturbed. These changes reflect the "rationing out" of over-mature volume by the area-volume check procedure over the planning horizon. The 240 m³ ha⁻¹ disturbed at the end of the planning horizon is very near the long run average for this forest managed on a 100-year rotation. In scenario M1, the average volume disturbed is fairly stable over the planning horizon at about 180 m³ ha⁻¹. In scenario M2 the average volume disturbed declines from about 160 m³ ha⁻¹ to 90 m³ ha⁻¹. In scenario C1 the average volume disturbed increases from about 160 to about 300 m³ ha⁻¹ over the planning horizon. The increase in disturbed volume in scenario C1 is related to the small annual area disturbed; more of the forest gets a chance to age.

Fig. 3. Annual hardwood volume disturbed (10^3 m^3) under each disturbance regime.

Fig. 4. Average volume per hectare disturbed ($\text{m}^3 \text{ ha}^{-1}$) under each disturbance regime.

Discussion

The results presented above provide some starting points for a discussion of natural disturbance management. There should not be too much weight placed on the numerical results: the important information is the relative magnitudes.

Perhaps the most striking differences in the results presented here are between the two pre-suppression natural disturbance regimes: Murphy's two percent model (scenario M2) and Cumming's conifer content specific model (scenario C1). The annual area disturbed in scenario M2 is 4.5 times as great as that disturbed in scenario C1. Given the differences in estimated disturbance rates, how does a manager decide which rate, if any, is appropriate for management? It could be that one of the rates is "more correct" than the other and that further investigation could help determine which is the appropriate rate. It is also possible that the mean rates reported by Cumming and Murphy are simply different outcomes of the same stochastic process. A recent simulation study conducted by Armstrong (1999) indicates that this could indeed be the case. In a Monte Carlo simulation of annual area burned, the mean area burnt from a pair of randomly generated 50 year series differed by a multiplicative factor of four, in one out of three draws.

If the rates proposed by Cumming are close to correct, many of the stands in the study area must be much older than is record-

ed in the forest inventory. It is important to make the distinction between stand age and tree age. Stand age is the number of years between the most recent stand-replacing disturbance and the present time. Individual trees within a stand could have germinated or sprouted in the interim. The age recorded on the inventory records is determined through photo-interpretation, typically by estimating the height and the species of the canopy, assigning a site productivity class to the stand, and using height-age curves indexed by site class to stand age. The resulting estimate is more directly related to the age of the canopy trees than it is to the number of years since a stand-replacing event.

Divergence between photo-interpreted stand age and the number of years since a stand-replacing event could occur for a number of reasons. It is possible that white spruce could germinate in an aspen stand a number of years after the stand-replacing event. Through succession, white spruce could eventually dominate the stand. The photo-interpreted age of such a stand would reflect the age of the spruce trees, not accounting for the lag between stand initiation and spruce germination. Another possibility is that some aspen stands develop into uneven-aged stands through a process of gap phase dynamics (Shugart 1984). Again the photo-interpreted age would be based on the age of the canopy trees which would be in a continual state of replacement, resulting in an underestimate of stand age.

Cumming (1995) presents some evidence that this occurs in the study area.

If Cumming's natural disturbance regime is approximately correct, the annual area disturbed would be 22 percent of that suggested by Murphy's natural disturbance regime, and about 45% of that scheduled under sustained yield management with a 100-year rotation. This clearly has some important timber supply implications, especially if forest tenures were allocated on the assumption of sustained yield management. In Alberta, most of the boreal forest has been allocated to industry through long term forest management agreements: there is little or no room to increase harvest levels in any part of the province given natural timber growth rates. Large-scale industrial development has occurred on the assumption of a timber supply level appropriate to sustained yield management. Would society be willing to pay for the perceived benefits of NDM management with a drop in harvestable area and economic activity of such magnitude? Alternatively, would society be willing to accept intensive management on part of the land base to make up the shortfall (if biologically possible and financially feasible)?

The effects of strict NDM management are even more pronounced when we consider annual harvest volume rather than annual harvest area. This occurs because in the sustained yield scenario, the oldest (and by our yield tables, highest volume) stands are disturbed first. In Murphy's characterization of natural disturbance, the disturbance rate is independent of age, so age classes are being disturbed in proportion to their representation in the inventory. This means that very young stands with no merchantable volume will be scheduled for disturbance. The effects of this show up in the lower average volumes per hectare disturbed (Fig. 4) under the natural disturbance scenarios.

This raises another important point. Nature would "schedule" some low volume, low value stands for disturbance. How important is it to emulate these "unprofitable" disturbances in a natural disturbance model? At the extreme, it may be desirable from an ecological point of view to deliberately burn or otherwise disturb some areas of immature forest in order to simulate the natural disturbance regime. This deliberate disturbance would be required to offset the reduction in fire rates due to fire suppression. Who should pay for the additional cost of these objectives? Timber harvest occurs only on the net productive land base. If the rate of disturbance on the non-productive area has been reduced through fire suppression efforts, should there be planned disturbances (e.g., prescribed burning) introduced to the unproductive land base?

Another characteristic of the natural fire regime is the variability in the disturbance rate from year to year. Given this variability, and assuming that the forest products industry requires some stability in the year-to-year flow of timber, which rate is the appropriate one on which to base management: the overall mean, the mean for background years, the mean for event years, or some other statistic (e.g., the median)? This becomes a risk-risk trade off decision. If one chooses too high a rate for timber harvest under a natural disturbance model, then some ecological benefits may not occur. If too low a rate is chosen, perhaps the risk of fire and severity of fires will increase, also reducing ecological benefits. Perhaps "the rate" is not an appropriate objective in any case: it is conceivable that the variability in annual area disturbed is as important ecologically as its average.

Given the difficulty in determining the average natural rate of disturbance, and the extreme year to year variability in the rate, the natural disturbance rate should not be the sole determinant of harvest rate. Other alternatives include variable rotation management strategies (Stelfox 1995), or using models which constrain the forest structure (defined, for example, by proportion of area within age class and spruce content) to fall within acceptable bounds (see, e.g., Cumming *et al.* 1994). "The rate" or some measure of risk/hazard should perhaps be an integral element in forest structure approaches and in determining the expected value of choices: it should not be the only objective of management.

As with any modelling exercise, the analysis presented here is a much-simplified representation of reality. The spatial elements of disturbance are ignored completely in this study, and may be worth examining. It is conceivable that timber harvest can mimic some forms of natural disturbance other than wildfire (e.g., windthrow, insect attack, gap dynamics), but these were not examined here. We have ignored management activities that may affect the probability of disturbance or growth rates (e.g., silviculture, changes in fire suppression strategy). Despite these omissions, we conclude that moving from sustained yield to natural disturbance models of forest management can have tremendous implications for the timber supply potential of an area, and that choosing the natural disturbance rate appropriate for a forest is both difficult and risky.

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