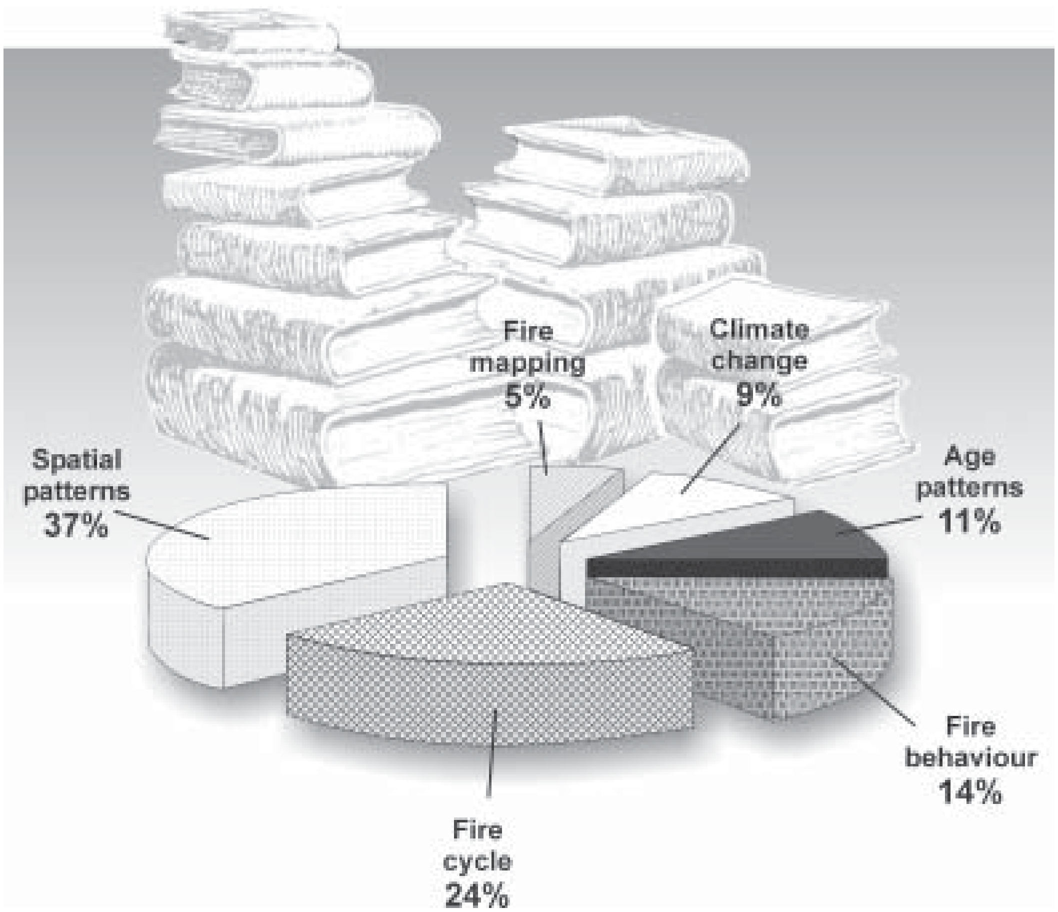
Forest Research Information Paper No. 159

An analysis of literature on natural fire disturbances

in relation to Ontario's Forest Management Guide for Natural Disturbance Pattern Emulation



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by

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Abstract

Ontario's Forest Management Guide for Natural Disturbance Pattern Emulation (NDPE Guide v. 3.1, 2001) provides direction for emulating natural fire disturbances in forest management planning. We examined the North American scientific literature on natural fire disturbances in relation to the directions in this guide for: (1) landscape harvest size patterns, (2) landscape harvest patch separation, (3) residual stands, and (4) residual trees and downed woody debris. An associated trend analysis, annotated bibliography, and list of related references are provided. Publications on natural fire disturbances are abundant, with an exponential increase after 1990, focusing mainly on stand-replacing fires in boreal forests. Literature related to NDPE Guide directions constitutes 37% of the publications, most becoming available since the development of the guide. In spite of the abundance of literature related to natural fire disturbances, many gaps exist in the published knowledge, especially on the spacing of burned patches. As well, the potential variability in fire regimes is not captured adequately because most studies were based on analyses of historical fire data. Reports on simulation studies that can capture sources of variability in fire regimes are just beginning to emerge. Variability associated with post-fire residual patches is not adequately addressed in the literature, and less information is available about peninsular residuals than insular residuals. Although many publications on post-fire residual trees and downed woody debris have been published in the last five years, this information is often based on studies of single fires. As a result, knowledge of post-fire residuals and their causal factors cannot be generalized. Overall, the published knowledge is not adequate to understand the stochasticity and variability in spatial patterns of fires and post-fire residuals associated with fire regimes in boreal and near-boreal forests.

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Contents

Introduction

Following directions from the Crown Forest Sustainability Act of Ontario[1] and the Class Environmental Assessment for Timber Management[2], the Ontario Ministry of Natural Resources (OMNR) developed the Forest Management Guide for Natural Disturbance Pattern Emulation[3] (NDPE Guide). This is the main policy document guiding forest management practices in Ontario, within the context of the Forest Management Planning Manual[4], to emulate natural disturbances.

As part of the eight-year review of the Class Environmental Assessment and the subsequent declaration order of 2003[5], OMNR is required, as stated in Condition 39(c), to investigate the effectiveness of the direction in the NDPE Guide through a series of scientific studies. Given the goal of the NDPE Guide, which is to create forest landscapes that "resemble more closely the landscapes recently created naturally by fire … with respect to the location and sizes of disturbances, residual stand structure, …," these scientific studies were to focus specifically on expanding the knowledge of natural stand-replacing fire disturbance regimes in boreal and near-boreal forests in Ontario to test the effectiveness of the NDPE Guide's directions. The *Action Plan for Scientific Studies to Assess the Effectiveness of Directions in the Forest Management Guide for Natural Disturbance Pattern Emulation* (OMNR 2004; http://www.mnr.gov.on.ca/mnr/forests/public/publications/ActionPlan_EN.pdf) was developed and submitted to the Ministry of Environment in June 2004.

The first step in developing the scientific study plans was to collate and review the published literature on natural fire disturbances in North America to examine the state of the scientific knowledge. This review focussed on the directions for landscape harvest patterns and structural legacy detailed in the NDPE Guide, captured by four major criteria: (1) landscape harvest size patterns, (2) landscape harvest patch separation, (3) residual stands, and (4) residual trees and downed woody debris.

In this context, the purpose of this report is to detail the process of collating and reviewing the relevant literature. Specifically, we describe (a) the methods used in the literature search, (b) the filtering logic, (c) the results of the search, including a trend analysis, (d) a partially annotated bibliography, and (e) a complete list of the published literature relevant to NDPE Guide directions. In addition, a provisional list of ongoing research studies relevant to the NDPE Guide directions is provided.

Literature Search

The objective of the literature search was to locate all scientific literature on fire disturbance regimes, primarily in the boreal and near-boreal (i.e., Great Lakes-St. Lawrence, Acadian) forest regions in Canada (after Rowe 1972[6]), and similar forest cover types that extend into the United States. During the initial stages of the search, we broadened the geographic area to include other forest cover types where stand-replacing fire regimes are prevalent, such as lodgepole pine (*Pinus contorta* Dougl.), a fire-dependent species autecologically similar to jack pine (*Pinus banksiana* Lamb.). The literature search was conducted in two stages: a search of primary literature databases based on keywords and an ad hoc search of Internet and other ancillary sources. In our search, we defined *scientific literature* as documents that report scientific analyses of data or discussion of concepts and that are readily available. These included journal papers, books, book chapters, graduate theses, conference proceedings, research reports, technical reports, and web-based research/technical notes. The only exception is OMNR 1997, which is an unpublished document but provided base information for the NDPE Guide. We did not screen these publications for their quality, veracity, or rigour.

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[1] Statutes of Ontario. 1995. Crown Forest Sustainability Act, revised. R.S.O. 1998. Chapter 25 and Ontario Regulation 167/95.

[2] Ontario Environmental Assessment Board. 1994. Reasons for decision and decision. Class environmental assessment by the Ministry of Natural Resources for timber management on Crown lands in Ontario. Ontario Environmental Assessment Board, Toronto, Ontario, Canada.

[3] Ontario Ministry of Natural Resources. 2001. Forest management guide for natural disturbance pattern emulation. Version 3.1. Ontario Ministry of Natural Resources, Toronto, Ontario, Canada.

[4] Ontario Ministry of Natural Resources. 1996. Forest management planning manual for Ontario's Crown forests. Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, Canada.

[5] Ontario Environmental Assessment Board. 2003. Declaration order regarding MNR's Class Environmental Assessment Approval for Forest Management on Crown Lands in Ontario, MNR-71. Ontario Environmental Assessment Board, Toronto, Ontario, Canada.

[6] Rowe, J.S. 1972. Forest regions of Canada. Canadian Forest Service, Ottawa, Ontario, Canada. Publication 1300.

Electronic database search

Four categories of keywords (Table 1) were used to search several major electronic databases (SilverPlatter® TreeCD, Biblioline® Wildlife and Ecology: Studies Worldwide, and the National Library of Canada). TreeCD was the primary source of peer-reviewed literature, and the National Library of Canada provided an archive of Canadian graduate theses titles and abstracts. The search covered literature published from 1939 (TreeCD) to May 15, 2004.

Ad hoc literature search

Given that electronic databases do not include all types of relevant publications and may not include recent releases, we searched other sources of literature including the Internet, government publication listings, libraries, and other repositories. These were the primary sources for citations from recent books, journal issues, conference proceedings, technical reports, and web-based documents. Internet searches provided information about publications by public/industry-funded organizations such as the Model Forest Network (http://www.modelforest.net) and the Sustainable Forest Management Network (http://sfm-1.biology.ualberta.ca). To capture in press publications, we consulted researchers working on forest fire regimes. The ad hoc search included information available up to May 15, 2004.

Filtering the Literature

Literature collected from both steps were combined and screened using a hierarchical filter. First, abstracts were reviewed for relevance to natural fire regimes in boreal and near-boreal forest types (as defined earlier), and non-relevant publications were eliminated from further consideration. The latter included publications that covered studies outside the geographic area of interest or were focused on fire suppression, post-fire vegetation and forest floor dynamics; effects of forest fire (e.g., on wildlife habitat); forest management planning related to emulating fire disturbances; or prescribed burning. During the second screening step, the full text of all remaining publications was examined for relevance to the NDPE Guide directions and its major criteria: (1) landscape harvest size patterns, (2) landscape harvest patch separation, (3) residual stands, and (4) residual trees and downed woody debris. Publications that did not address these criteria were excluded. Finally, the publications were scrutinized for information related to the empirical directions in the NDPE Guide. Only this final group of publications, which contained quantitative experimental results, were reviewed in detail and included in assessing the certainty of the directions in the NDPE Guide, and used to formulate the hypotheses for scientific studies described in the *Action Plan for Scientific Studies to Assess the Effectiveness of Directions in the Forest Management NDPE Guide for Natural Disturbance Pattern Emulation* (OMNR 2004; http://www.mnr.gov.on.ca/mnr/forests/public/publications/ActionPlan_EN.pdf).

Table 1. *Keywords used to search the electronic literature databases (* ensures all forms of word found in search).*

Category	Keywords
Forest type	boreal, northern forest*, Great Lakes-St. Lawrence forest, Great Lakes forest, Great Lakes region, northeastern hardwood*, northern hardwood*, northern temperate forest
Location	Ontario, Quebec, Manitoba, Saskatchewan, Minnesota, Alberta, Labrador, New Brunswick
Disturbance type	fire, fire disturbance*, forest disturbance*, post-fire, wildfire*
Other disturbance-related terms	age class, coarse woody debris, corridor*, cycle, dead wood, deadwood, distance, distribution, downed woody debris, dynamics, emulat*, fine woody debris, insular, interval, island*, model*, neighbourhood, neighborhood, nearest neighbour*, nearest neighbor*, patch size, pattern*, peninsular, peninsula*, pattern*, regime*, residual*, salvage, separation, simulat*, size*, snag*, spac*, spatial, stand*, structur*, suppression, unburned

Survey of Ongoing Research Studies

A list of ongoing research studies on topics related to the NDPE Guide directions was compiled by consulting the following sources:

1) individual researchers (as summarized in Table 2 and detailed in Appendix I);
2) review of projects funded through major Ontario forest science project funding sources (OMNR ProGrid®[7], the Forestry Research Partnership [FRP][8], Sustainable Forestry Management Network [SFMN][9]); and
3) queries to science-based listserv discussion groups – ECOLOG® (host Ecological Society of America) and TWS® (host The Wildlife Society).

***Table 2**. Summary of number of individuals contacted about ongoing fire-regime studies.*

Affiliation	Canada	USA
Government	25	7
Academic	16	5
Private sector	3	0

Results of the Literature Search

Literature on fire disturbances in North America

The initial literature search yielded 1078 publications (945 from electronic databases and 133 from ad hoc sources) available prior to May 15, 2004. These publications included journal papers, books, book chapters, conference proceedings, graduate theses, government research and technical reports, private consultant reports, and documents not published in primary literature. The complete database is available on request[10]. Review of abstracts revealed that most (794) of these publications were from outside the geographic area of interest or addressed fire suppression; post-fire vegetation and forest floor dynamics; effects of forest fire (e.g., on wildlife habitat); forest management planning related to emulating fire disturbances; or prescribed burning. Only 284 of the 1078 publications focused on natural fire regimes in boreal and near-boreal forest types.

Literature on natural fire disturbance regimes in boreal North America

We examined the full text of these 284 publications (see Appendix II for citations) for information relevant to the NDPE Guide directions, which addressed spatial patterns (i.e., fire size, spacing, residual area, and residual structure) of natural fire regimes. Other general topics addressed in this literature included:

- fire cycle, i.e., fire interval, fire frequency, and fire history
- fire behaviour, i.e., fire growth modelling and causal factors of fire growth
- forest age patterns, i.e., forest age structure and succession related to time since fire
- fire mapping, i.e., detecting and mapping techniques of fire scars and modelling of fire occurrence
- climate change

The composition of the literature relative to these general topics is presented in Figure 1 (if a paper fell under more than one topic, we used the most relevant based on our judgement).

[7] Lianne Vipond, OMNR, Sault Ste. Marie, Ontario
[8] http://forestresearch.ca/partnership_projects/index.htm
[9] http://sfm-1.biology.ualberta.ca/english/research/en_projcodes.htm
[10] To obtain copy of CD-ROM, e-mail request to information.ofri@mnr.gov.on.ca.

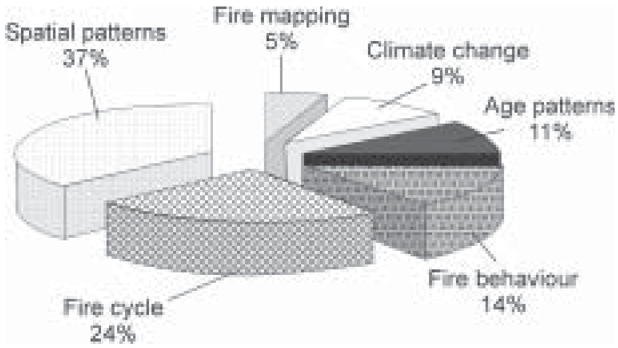

Figure 1. *Composition of the North American publications on boreal forest fire disturbances from literature search.*

Literature on spatial patterns of natural fire regimes in boreal North America

The NDPE Guide's direction at the landscape scale is "to move towards a more natural landscape pattern." However, the NDPE Guide does not specifically address temporal variations in fire regimes (e.g., fire cycles, return intervals), post-fire age class patterns, causal factors of change (e.g., climate change, fire behaviour, fire mapping, and fire cycle). It focuses only on spatial patterns of fire disturbance, albeit at several scales. At the landscape scale, it addresses size-class distribution of forest fire patches, and at the sub-landscape scale, the spacing among those fire patches. At finer spatial scales, the NDPE Guide directions deal with post-fire residual structures, such as shapes of the unburned forest patches, live and snag trees, and downed woody debris.

More than one third of the publications (104) on natural fire regimes in boreal North America addressed the spatial patterns of fire as directly relevant to the NDPE Guide. The citations and abstracts for these publications are listed in the annotated bibliography in the final section of this report. Figure 2 illustrates the proliferation of fire regime-related literature over the last seven decades and the proportion of guide-related publications compared with other categories.

Literature containing experimental evidence relevant to NDPE Guide directions

Among the 104 publications mentioned above, only 48 contained original experimental evidence on fire size, spacing of burned patches, post-fire residual area, post-fire residual trees, and post-fire downed woody debris (Table 3). These experimental studies represent a range of locations across Canada and the Lake States of the United States (Figure 3).

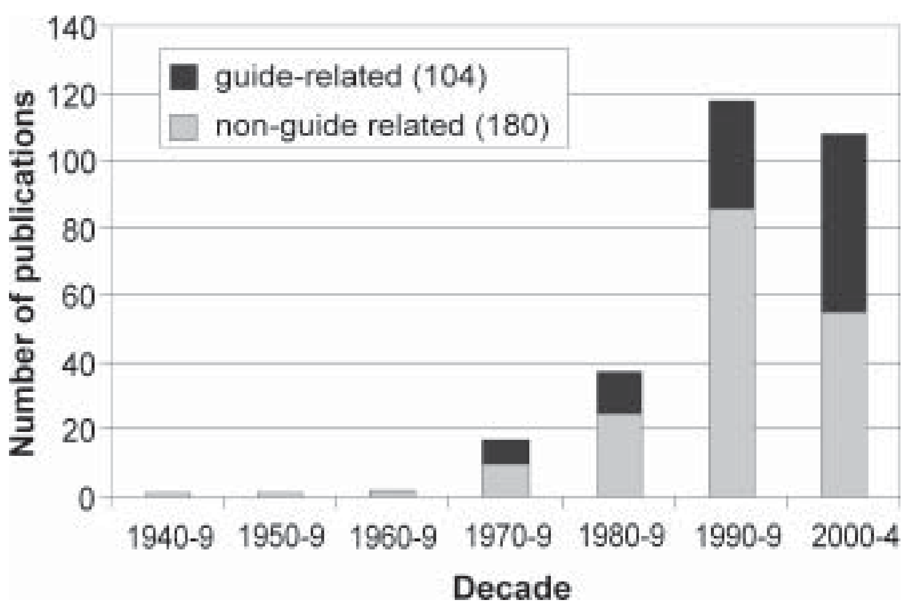

Figure 2. *North American publications on boreal forest fire disturbances, by decade, from literature search, illustrating the number of NDPE Guide-related publications to non-guide related publications. (Guide-related publications are listed in the annotated bibliography; all citations are provided in Appendix II.)*

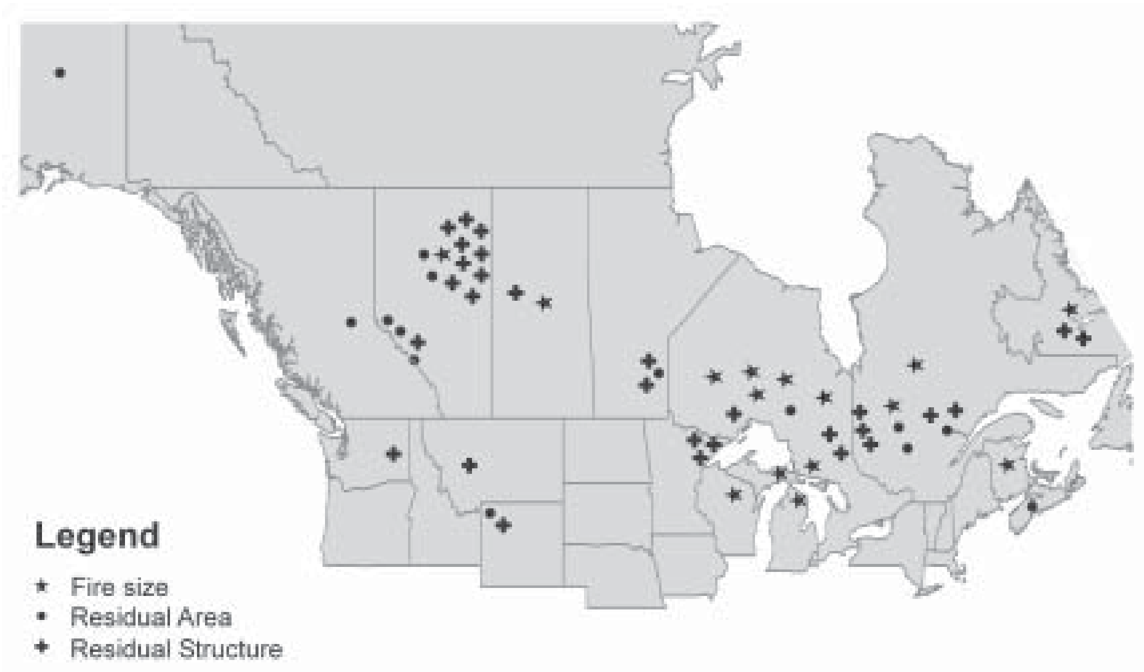

Figure 3. *Location of studies that include experimental evidence relevant to NDPE Guide (when no specific location given and when studies included more than one location, symbols are located centrally within jurisdictions).*

Table 3. *Summary of literature that includes experimental evidence relevant to NDPE Guide directions by forest type and publication type. (Numbers in parentheses indicate non peer-reviewed documents; DWD = downed woody debris.)*

Forest type	Publication type	Criteria in NDPE Guide directions				
		Fire size	Spacing	Residual area	Residual trees	DWD
Boreal	Journal article	4	0	6	9	7
	Book, chapter, conference proc.	4	0	0	(1)	(1)
	Published research/tech. report	0	0	(4)	(2)	(1)
	Unpublished govt. report	(1)	(1)	(1)	0	0
	Thesis	1	0	2	2	3
Great Lakes-St. Lawrence	Journal article	4	0	0	2	1
	Published research/tech. report	0	0	(1)	0	0
	Unpublished govt. report	(1)	0	0	0	0
Total*		15 (2)	1 (1)	14 (6)	16 (3)	13 (2)

* Based on 48 publications; total is higher because some documents provide information for more than one category.

Overview of Publications Containing Experimental Evidence Directly Related to NDPE Guide Criteria

Criterion 1: Landscape harvest patterns – Size patterns

The NDPE Guide's primary management guidance (pp. 3-5, Table 2, OMNR 2001) relates to the size-class distribution of planned clearcuts. As a standard, the NDPE Guide requires "eighty percent (80% -- boreal forest) or ninety percent (90% -- Great Lakes-St. Lawrence forest) of planned new clearcuts determined by frequency, …, should be less than 260 ha in size." The premise is that this standard, among others, will emulate natural fire disturbance patterns.

The published literature on size-class distribution of natural fire disturbances in boreal or near-boreal forests related to the NDPE Guide's size-pattern criterion ranges from Wein and Moore (1977) to Perera et al. (2004). Among these, 14 publications address size-class distribution of fire disturbance patterns in boreal forests, and five publications address size-class distribution of fire disturbance patterns in Great Lakes-St. Lawrence forests. Much of this literature is based on analyses of historical data on forest fires (seven in boreal and five in Great Lakes- St. Lawrence), with few studies reporting simulation modelling results (three in the boreal and none in the Great Lakes-St. Lawrence). A summary of this literature is provided in Table 4.

Only one publication (Zhang et al. 1999), contained results that support the NDPE Guide's premise for natural disturbance emulation (i.e., 80% of natural disturbances below 260 ha in boreal and 90% below 260 in Great Lakes-St. Lawrence forests). This information is summarized in Table 5.

Results presented in the literature mentioned above indicate much variability in possible size-class distributions for forest fires in the boreal and Great Lakes-St. Lawrence forests. Some of this disparity may be due to the inherent differences in data sources, analytical methods, and geo-climatic differences within the broad forest types and to the random and stochastic nature of forest fires; however these results also demonstrate the value of addressing variability associated with forest fire patterns in future management guides.

Table 4. *Publications on forest fire size-class distributions in the boreal and Great Lakes-St. Lawrence forests.*

Publication	Study location	Forest type	Nature of the study
Wein and Moore 1977	New Brunswick	Acadian (Great Lakes-St. Lawrence)	Analysis of fire history
Simard and Blank 1982	Michigan	Great Lakes-St. Lawrence	Analysis of fire history
Foster 1983	Labrador	Boreal	Analysis of fire history
Payette 1989	Quebec	Boreal	Analysis of fire history
Stocks 1991	Canada	Boreal	Analysis of fire history
Weir 1996	Alberta	Boreal	Analysis of fire history
OMNR 1997	Ontario	Boreal and Great Lakes-St. Lawrence	Analysis of fire history
Zhang et al. 1999	Michigan	Great Lakes-St. Lawrence	Analysis of fire history
Li 2000a	Ontario	Boreal	Simulation modelling
Cardille and Ventura 2001	Lake States	Great Lakes-St. Lawrence	Analysis of fire history
Ward et al. 2001	Ontario	Boreal	Analysis of fire history
Perera et al. 2004	Ontario	Boreal	Simulation modelling
Li 2004	Alberta	Boreal	Simulation modelling
Bergeron et al. in press	Quebec	Boreal	Analysis of fire history

Criterion 2: Landscape harvest patterns – Patch separation

The NDPE Guide's primary management guidance (pp. 3-5, Table 2, OMNR 2001) relates to the spacing of planned clearcuts. As a standard, the NDPE Guide requires that "new clearcuts must be separated in time from older clearcuts either long enough to allow vegetation in the old clearcut to reach 3 m in height or 20 years, whichever occurs first." As a guideline, the guide states as an alternative that: "10-260 ha clearcuts should be separated an average of 200 m; for every 100 ha increase in the size of clearcuts separate by an additional 50 m …." The premise is that this standard and guideline, among others, will emulate natural fire disturbance patterns.

The literature on spacing and patch separation of natural fire disturbances in boreal or near-boreal forest is virtually non-existent. The sole publication related to the patch separation criterion is OMNR (1997), which contains unpublished results from an analysis of boreal forest fires in Ontario. No publications are available on this topic for Great Lakes-St. Lawrence forests. Thus, the spacing and separation patterns of forest fire patches requires immediate and direct research attention.

Criterion 3: Structural legacy – Residual stands

The NDPE Guide's primary management guidance (pp. 9-11, Table 3, Figures 4-6, OMNR 2001) relates to the extent of residual area retained after forest harvest. As a guideline, the NDPE Guide requires resource managers to retain 2-8% of planned disturbance area (minimum size 0.25 ha) in insular residual patches and 8-28% of planned disturbance area in peninsular residual patches, both based on specific forest cover types. The premise is that these guidelines, among others, will emulate natural fire disturbance patterns.

The published literature on insular and peninsular post-fire residual patches has addressed primarily boreal forests and ranges from Gasaway and Dubois (1985) to Perron (2003). Among these 13 publications, five are from forest types where lodgepole pine is dominant. A summary of this literature is provided in Table 6.

Except for one (Andison 2003c), all reviewed publications present results that support the NDPE Guide's premise for natural disturbance emulation with residual patch areas (i.e., 2-8% in insular patch area and 8-28% in peninsular patch area). This information is summarized in Table 7.

Table 5. *Congruence of publications with the NDPE Guide directions on forest fire size-class distribution.*

NDPE Guide direction	Relationship to NDPE Guide's directions	Publications
Boreal – 80% of fires < 260 ha	Literature in agreement with NDPE Guide's directions – 80% fires are < 260 ha	None
	Literature in conflict with NDPE Guide's directions – fewer than 80% fires are < 260 ha	Foster 1983, Payette et al. 1989, Stocks 1991, OMNR 1997, Ward et al. 2001, Perera et al. 2004
	Literature in conflict with NDPE Guide's directions – more than 80% fires are < 260 ha	Weir 1996, Li 2000a, Li 2004, Bergeron et al. in press
Great Lakes - St. Lawrence – 90% of fires < 260 ha	Literature in agreement with NDPE Guide's directions – 90% fires are < 260 ha	Zhang et al. 1997
	Literature in conflict with NDPE Guide's directions – fewer than 90% fires are < 260 ha	Wein and Moore 1977, OMNR 1997
	Literature in conflict with NDPE Guide's directions – more than 90% fires are < 260 ha	Sinard and Blank 1982, Cardille and Ventura 2001

Table 6. *Publications on post-fire residual stand area in boreal forests.*

Publication	Study location	Forest type	Number of fires studied
Gasaway and Dubois 1985	Alaska	Boreal	1
Eberhart and Woodward 1987	Alberta	Boreal	69
Turner et al. 1994	Wyoming	Lodgepole pine	1
Delong and Tanner 1996	British Columbia	Lodgepole pine	9
OMNR 1997	Ontario	Boreal	42
Smyth 1999	Alberta	Boreal	20
Ecostem 2000	Manitoba	Boreal	6
Kafka et al. 2001	Quebec	Boreal	1
Bergeron et al. 2002	Quebec	Boreal	16
Andison 2003b	Alberta	Lodgepole pine	24
Andison 2003c	Alberta	Lodgepole pine	170
Andison 2003d	Alberta	Lodgepole pine	1
NSDEL 2003	Nova Scotia	Acadian (boreal)	1
Perron 2003	Quebec	Boreal	35

Table 7. *Congruence of publications with the NDPE Guide directions on post-fire residual stand area.*

NDPE Guide direction	Relationship to NDPE Guide's directions	Publications
Insular patches – 2-8%	Literature in agreement with NDPE Guide's directions	Gasaway and Dubois 1985, Eberhart and Woodward 1987, Turner et al. 1994, Delong and Tanner 1996, OMNR 1997, Smyth 1999, Ecostem 2000, Kafka et al. 2001, Bergeron et al. 2002, Andison 2003b, NSDEL 2003, Perron 2003
	Literature in conflict with NDPE Guide's directions	Andison 2003c
Peninsular patches – 8-28%	Literature in agreement with NDPE Guide's directions	OMNR 1997, Ecostem 2000, Andison 2003d
	Literature in conflict with NDPE Guide's directions	None

Relatively little information on peninsular residual patches is available. Given the variability associated with the results reported in these publications, it is important to understand the spatial biases and other causal factors of the unburned residual areas within a forest fire.

Criterion 4: Structural legacy – Residual trees and downed woody debris

The NDPE Guide's primary management guidance (pp. 11-13) consists of the number of residual trees (both live trees and snags) and the types of downed woody debris (both coarse and fine). For residual trees, the NDPE Guide requires retention of a minimum of 25 residual well-spaced trees per hectare harvested, including six live, large-diameter trees, based on fire tolerance of the tree species. For downed woody debris, the NDPE Guide requires leaving different types of coarse and fine debris in harvested areas. The premise is that these guidelines, among others, will emulate natural fire disturbance patterns.

The published literature on residual trees and downed woody debris ranged from Lyon (1977) to Harper et al.

(2004). Among these 21 publications, four are from forest types where lodgepole pine is dominant. A summary of this literature is provided in Table 8.

No reviewed publication provided data that conflicted with the NDPE Guide directions given for residual trees and downed woody debris. However, in the case of residual trees, all publications contained results that indicated post-fire live tree and snag densities are much higher than the minimum density directed by the guide. This information is summarized in Table 9.

Results presented in the above literature indicate post-fire residual tree densities vary widely in boreal and near-boreal forests. It is difficult to generalize on this variability because only three of the 21 publications reported data gathered from more than one fire.

Ongoing Research Studies

Of the 55 requests for information sent, 14 responses were received, and eight sources provided information of ongoing studies relevant to the NDPE Guide directions (Table 10). Five ongoing studies focus on fire size-class distribution, four on post-fire residual area, and five on post-fire residual trees and downed woody debris. Similar to the results of the literature search no ongoing studies addressed spatial separation of fire patches. However, additional studies on this topic may exist, as only a few research contacts responded to the survey. Despite the abundance of information presented on the Internet, no centralized listings of funded research on related topics exist.

Table 8. *Publications on post-fire residual trees and downed woody debris in boreal and near-boreal forests (X indicates that the topic is addressed in the publication).*

Publication	Study location	Forest type	Years since fire	Number of fires studied	Number of snags	DWD
Lyon 1977	Montana	Lodgepole pine	1	1	X	-
Apfelbaum and Haney 1981	Minnesota	Great Lakes	1	1	X	-
Schulte and Niemi 1998	Minnesota	Great Lakes	2-3	1	X	X
Everett et al. 1999	Washington	Lodgepole pine	1+	26	X	-
Hobson and Schieck 1999	Alberta	Boreal	1	1	X	X
Lee and Crites 1999	Alberta	Boreal	1	n/a	X	X
Hoyt 2000	Alberta	Boreal	2	1	-	X
Tinker and Knight 2000	Wyoming	Lodgepole pine	7-9	n/a	-	X
Ecostem 2001	Manitoba	Boreal	1	1	X	X
Hoyt and Hannon 2002	Alberta	Boreal	2	1	X	-
Morissette et al. 2002	Saskatchewan	Boreal	3	1	-	X
Pedlar et al. 2002	Ontario	Boreal	1	1	-	X
Simon et al. 2002a	Labrador	Boreal	5	1	X	-
Simon et al. 2002b	Labrador	Boreal	5	1	-	X
Stuart-Smith et al. 2002	Alberta	Boreal	5-6	1	X	-
Larivee 2003	Quebec	Boreal	2	n/a	X	X
Nakamura et al. 2003	Alberta	Lodgepole pine	1	1	X	-
Nappi et al. 2003	Quebec	Boreal	1	1	X	-
Sander 2003	Alberta	Boreal	8-10	n/a	X	X
Haeussler and Bergeron 2004	Ontario	Boreal	3	4	X	X
Harper et al. 2004	Quebec	Boreal	3-4	2	X	X

Table 9. *Congruence of publications with the specific directions on post-fire residual trees and downed woody debris in the NDPE Guide.*

NDPE Guide Direction	Relationship to NDPE Guide's directions	Publications
Residual trees minimum of 25 trees/ha	Literature in agreement with NDPE Guide's directions, but the numbers vastly exceed 25 trees per ha	Lyon 1977, Apfelbaum and Haney 1981, Schulte and Niemi 1998, Everett et al. 1999,Hobson and Schieck 1999, Lee and Crites 1999, Ecostem 2001, Hoyt and Hannon 2002, Simon et al. 2002a, Stuart-Smith et al. 2002, Larivee 2003, Nakamura et al. 2003, Nappi et al. 2003, Sander 2003, Haeussler and Bergeron 2004, Harper et al. 2004
	Literature in conflict with NDPE Guide's directions	None
Downed woody debris retention	Literature in agreement with NDPE Guide's directions	Schulte and Niemi 1998, Hobson and Schieck 1999, Lee and Crites 1999, Hoyt 2000, Tinker and Knight 2000, Ecostem 2001, Morissette et al. 2002, Pedlar et al. 2002, Simon et al. 2002b, Larivee 2003, Sander 2003, Haeussler and Bergeron 2004, Harper et al. 2004
	Literature in conflict with NDPE Guide's directions	None

Table 10. *Ongoing studies related to NDPE Guide criteria. (Letters in parentheses denote the province(s) or territory where the study occurs: AB=Alberta, NB=New Brunswick, ON=Ontario, QC=Québec, SK=Saskatchewan, YK=Yukon.)*

NDPE Guide criteria	Project goal	Source
Fire size patterns	Calculate fire-size class distributions from time-since-fire data in 90,000 ha boreal mixedwood area (SK)	P. Marshall, University of British Columbia, Vancouver, BC
	Combine new and existing fire regime information (province-wide) (AB)	C. Tymstra, Forest Protection Division, Government of Alberta, Edmonton, AB
	Determine fire/flood frequency and extent in riparian zones (AB)	Sustainable Forest Management Network (SFMN), Edmonton, AB
	Simulate boreal forest fire regimes in Ontario (ON)	A. Perera, OMNR, Sault Ste. Marie, ON
	Relate large burns to budworm defoliation (NB)	D. MacLean, University of New Brunswick, Fredericton, NB
Post-fire residual stand area	Determine disturbance rate and burn patterns in riparian zones (ON)	SFMN
	Document distribution and shape of fire edges (QC/AB)	SFMN
	Document fire frequency and burn patterns from historic land survey records (ON)	F. Pinto, OMNR, North Bay, ON
	Calculate post-fire residual area (SK)	D.W. Andison, Bandaloop Landscape-Ecosystem Services, Belcarra, BC
Post-fire residual trees and downed woody debris	Estimate post-fire patch and stand structure from 60-year-old aerial photo/cruise data (NB)	D. MacLean
	Measure post-fire stand structure (SK)	D.W. Andison
	Document mortality of residual post-harvest trees (aspen, balsam fir, and white spruce) in boreal mixedwoods (QC/AB)	SFMN
	Study pre- and post-fire stand structure with a focus on overlap (within last 50 years) and non-overlap areas (YK)	J. Johnstone, Carleton University, Ottawa, ON
	Document structure and plant species composition at fire edges (QC/AB)	SFMN

Summary

This report provides supplementary information to an action plan developed by OMNR and submitted to the Ministry of Environment in June 2004 to describe scientific studies on natural fire disturbances, as a requirement of the review of Ontario's Class Environmental Assessment for Timber Management and the resulting declaration order. Specifically, the goals of the report are to describe the process of collating, filtering, and reviewing the literature and to detail the material collected as an annotated bibliography and list of references. An overview of these methods is presented in Figure 4.

Publications on natural fire disturbances in North America are abundant, with the number of publications increasing exponentially after 1990. Most of these focus on stand-replacing fires in boreal forest types as opposed to fires in Great Lakes-St. Lawrence forests. Spatial patterns of fires constitute about one third of the literature reviewed. A recent increase in the proportion of literature that addresses NDPE Guide directions was evident during our review; however, much of this literature has become available since the development of the NDPE Guide.

Few ongoing studies were identified during an informal survey of fire researchers. The study list presented cannot be considered exhaustive since the survey response rate was poor (1:4 response to contact ratio), and no comprehensive public listings of fire research studies exist.

Despite the abundance of literature related to natural fire disturbances, many gaps exist in the published knowledge. Most evident is the lack of published information regarding spacing of burned patches. As well, the potential variability in fire regimes is not captured adequately because most studies on fire size patterns are based on analyses of historical fire data. Reports on simulation studies that can capture sources of variability in fire regimes are just beginning to emerge in the published literature. Similarly, variability and uncertainty associated with post-fire residuals are also not adequately addressed in the literature. Although publications on post-fire residuals have proliferated in the last five years, these were mostly based on studies of single fires. As a result, knowledge of post-fire residual patterns cannot be generalized, and their causal factors cannot be determined. Less information is available about post-fire peninsular residual patches than insular patches.

As a result of our review of the published literature, as well as ongoing studies, we conclude that the available knowledge cannot be generalized without further studies on spatial patterns of fires and post-fire residuals, addressing stochasticity and variability associated with fire regimes in boreal and near-boreal forests.

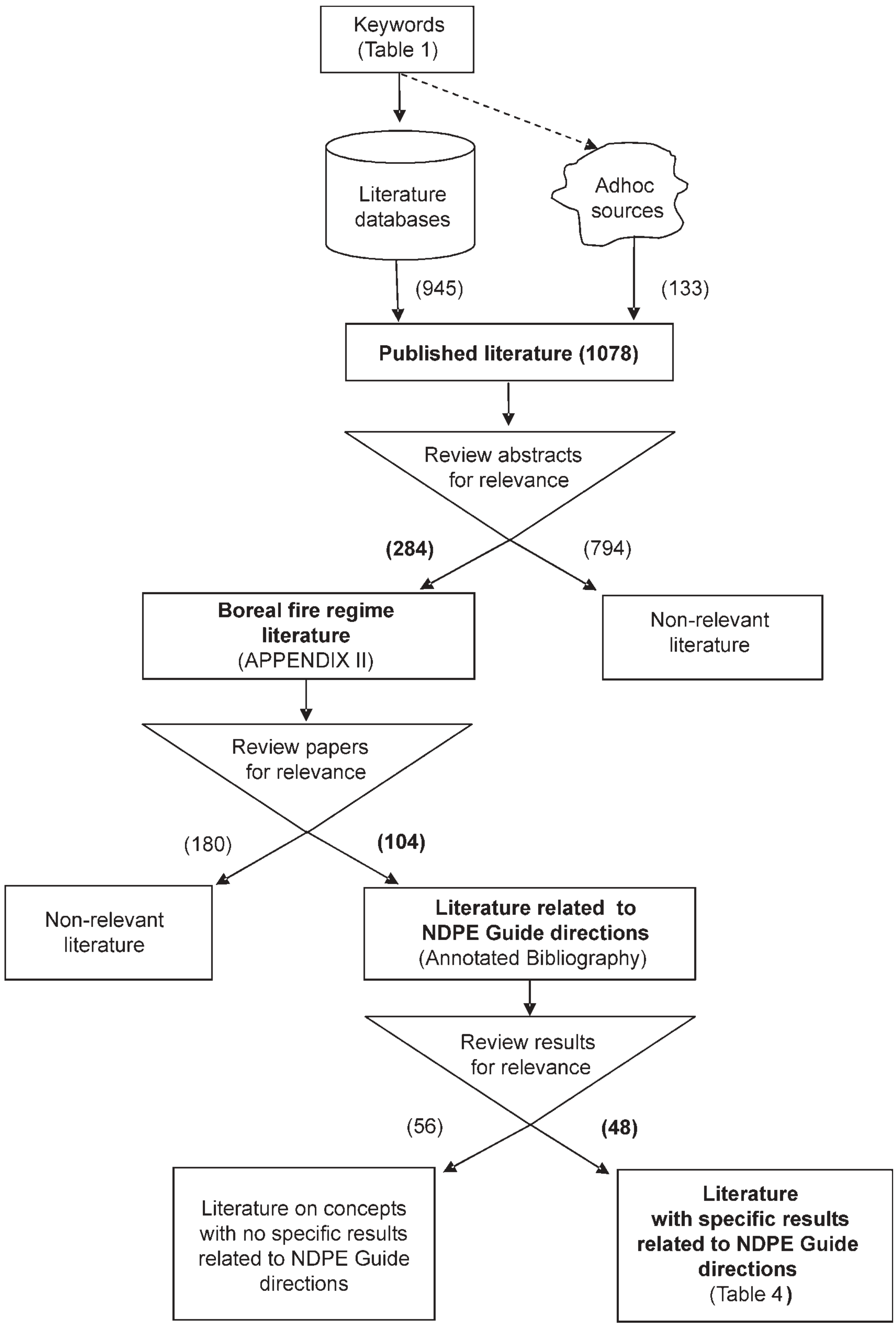

Figure 4. *Overview of literature collating and filtering (the number of publications at each step is given in parentheses).*

Annotated Bibliography

Of the 104 citations relevant to the NDPE Guide directions, 13 did not contain abstracts. The abstracts for these were written by the authors of this report and are identified by square brackets. For papers with abstracts that focussed on areas other than fire but included relevant data, a brief summary of fire-related information is provided in square brackets at the end of the original abstract. The 48 citations that provide empirical evidence directly related to the guide directions are in bold font.

Andison, D. W. 1996. Managing for landscape patterns in the sub-boreal forests of British Columbia. Ph.D. Thesis, University of British Columbia, Vancouver, BC.

Forest managers in North America are attempting to incorporate a growing number of ecological issues across many different temporal and spatial scales. In response, the traditional approach of managing for individual or groups of species and / or functions is giving way to managing for a more natural time-space array of natural resources. Better known as "landscape management", the strategy relies heavily on understanding the historical, "natural" processes and patterns at the landscape level. The objective of this dissertation is to develop a better understanding of the natural landscape-level dynamics of a fire-dominated landscape in northern British Columbia. Age-class distribution was used to show that stand replacing fires had a fire cycle of 80-100 years. Although stands much older than this average persist, there was strong evidence to suggest that very old stands become more susceptible to some form of disturbance. The most striking feature of the age-class distribution was its lack of stability. Although most disturbances were small and simple in shape, most of the landscape comprised very large disturbances. Forest fires were significantly more active in areas with dry soils. Fire activity may be higher on south and west-facing slopes. Information from the disturbance regime description was incorporated into a spatially explicit landscape model to create multiple landscape scenes of a "natural" disturbance regime. Disturbance size limits and age eligibility restrictions were then imposed in simulation. Generally as size and age restrictions increased, interior forest area decreased, edge density increased, age-class distribution favoured younger forests, spatial diversity increased, and temporal diversity decreased. Results demonstrated the importance of using a variety of pattern metrics, in different forms, to grasp the full impacts of each type and degree of restriction. This research demonstrated the dangers of using single landscape "snapshots" to represent "natural" conditions. It also raises important questions with respect to the wisdom of management practices that artificially stabilize both spatial and temporal attributes of landscapes.

Andison, D. W. 2003a. Patch and event sizes on foothills and mountain landscapes of Alberta. Bandaloop Landscape-Ecosystem Services, Belcarra, BC. Alberta foothills disturbance ecology research series: Report No. 4.

This fourth report in the Foothills Model Forest Natural Disturbance Program research series looks at size patterns over time and space for (a) disturbance patches and events, (c) old forest patches, and (d) non-operating patches. The report represents an integrated synthesis of parts of two separate research projects. While the data, assumptions and analysis used in this study were fairly complex and specific, there are several general conclusions that emerged that are relevant to planning and monitoring. Size distribution of disturbance patches was fairly typical of fire-dominated landscapes. A small number of disturbance patches larger than 2,000 ha, and in some cases over 10,000 ha, historically dominated all five landscapes. The considerable influence of these large events on modern-day disturbance patch size distributions suggests that natural disturbances such as fire still play an important role on landscapes today. However, cultural disturbance activities in the foothills since 1950 have shifted this pattern considerably, and created a prevalence of disturbance patches between 10-40 ha, regardless of harvesting history. This suggests that all forms of cultural disturbance create a single patch-size footprint.

Andison, D. W. 2003b. Disturbance events on foothills and mountain landscapes of Alberta: Part I. Bandaloop Landscape-Ecosystem Services, Belcarra, BC. Alberta foothills disturbance ecology research series: Report No. 5.

This fifth report in the FMF Natural Disturbance Program research series defines a new and important spatial scale – the "disturbance event". The rules used

to objectively define an event are detailed, along with examples, new terminology and specific details on the pattern and composition of fire events in west-central Alberta. Events tend to be dominated by a single large disturbance patch, which accounts for an average of 73% of the disturbed area. The average numbers of smaller disturbance patches of different sizes can be roughly predicted, but are highly variable. Single large undisturbed patches are uncommon in disturbance events. Undisturbed remnant patches tend to be more evenly distributed by size within events. The actual area burned or disturbed within a fire event averages only about 69% of the event, leaving an average of 31% of events as un-burnt “matrix remnant”. This is distinct from, and additive to “island remnants”, which will be discussed in the next report in this series. The number of undisturbed remnant patches over 5 ha in size within an event is about one third of the total number of disturbed patches. [The information provided in this report represents] significant new insight into the patterns of natural disturbances. At the very least, this represents a new way of considering how we think of landscape patterns since it explores the relationship of the undisturbed matrix within the more traditional spatial context of disturbance.

Andison, D. W. 2003c. Surviving as an island remnant. Bandaloop Landscape Ecosystem Services, Belcarra, BC. Natural Disturbance Program Quicknote No. 18.

Within disturbed patches of so-called stand-replacing forest fires are areas where mortality is incomplete. The occurrence of such “island remnants” is common and accounts for a substantial portion of many natural fire events. In fact, on average, island remnants account for about 12% of every fire in west-central Alberta. Even more notable is the wide variation around this average. For example, of the 170 disturbance patches used in our analysis, 17% had no (i.e., 0%) island remnants, while 8% had greater than 30% of their gross area in island remnants. In fact, 3% of our sample patches had more than 50% of their area in island remnants. Another prominent pattern to note is that the area in island remnants is not associated with fire size in west-central Alberta. In other words, there is no evidence to suggest that larger fires have proportionally more area in island remnants.

Andison, D. W. 2003d. Surviving as a matrix remnant. Bandaloop Landscape Ecosystem Services, Belcarra, BC. Natural Disturbance Program Quicknote No. 22.

Most of the unburned residual forest within a fire is not in island remnants. Far more area within a fire survives as corridors that remain attached to the forest landscape matrix. In fact, in west-central Alberta, “matrix remnants” account for an average of 26% of disturbance event areas. In a 931 ha event, the burnt area covered 681 ha and the matrix remnants covered 250 ha. Thus, 27% of this fire event was in matrix remnants (representing about 35% of the burnt area). Matrix remnants overall contribute three times as much area as do island remnants.

Andison, D. W., and P. L. Marshall. 1999. Simulating the impact of landscape-level biodiversity guidelines: A case study. Forestry Chronicle 75: 655-665.

British Columbia, along with most of the rest of North America, is becoming preoccupied with emulating natural landscape patterns under the auspices of ecosystem management. With their Biodiversity Guidebook, BC developed one of the first collections of rules for landscape management purposes. The landscape-level rules developed therein are representative of those being developed in other areas of North America. This research compared, in simulation, a range of patterns created by these guidelines for a landscape in central BC, against those created from the historical 60 ha two-pass system, and a “natural” disturbance regime. Results indicate that the biodiversity guidelines created more natural levels of patch sizes, interior forest area, and seral stage percentages compared to the two-pass system. However, the guidelines failed to create more natural rates of disturbance, or ranges of patch sizes and interior areas in old and mature forest. Furthermore, the implied degree of naturalness of the low, medium, and high biodiversity options did not necessarily hold true. The simulation results presented in this paper show that the concept of mimicry involves much more than originally proposed, and that there are limits to the degree to which mimicry can be used as a landscape management paradigm with our current knowledge and capacity. A strategy for working towards a natural landscape pattern program for forest management is discussed.

Apfelbaum, S. I., and A. Haney. 1981. Bird populations before and after wildfire in a Great Lakes pine forest. Condor 83: 347-354.

Birds in a 6.25-ha quadrat in a 73-year-old jack pine-black spruce forest in Cook County, Minnesota were intensively studied in June 1976. A wildfire burned through the area in August. The following spring we resurveyed the same quadrat to determine the first-year changes in bird populations. Species and guilds were compared by density, territorial space, existence energy, and importance values. Twelve species had territories in the study grid before the fire; six were not there the following spring, but eight additional species had established territories. Tree-foliage searchers had the greatest importance value before the fire and ground-brush foragers the greatest value afterwards. Density, total biomass, and combined existence energy of birds decreased after the fire by 50, 23, and 41%, respectively, but species using the area after the fire were 63% heavier on the average. Average energy consumption per unit of body weight was calculated to be 23% less after the fire. Fire apparently reduced the total food available for birds, but increased the kinds of food, especially at or near the ground. [Results of this study provide pre- and post-fire basal area for live and dead dominant tree species (black spruce, jack pine, and aspen). Of note, pre- and post-fire tree cover was 98% and 48%, respectively.]

Apfelbaum, S. I., and A. Haney. 1986. Changes in bird populations during succession following fire in the northern Great Lakes wilderness. Pages 10-16 *in* Proceedings - National Wilderness Research Conference: Current Research. USDA Forest Service, Intermountain Research Station, Ogden, UT. General Technical Report INT-212.

Sixteen upland communities, representing 370 years of succession following wildfire in the Boundary Waters Canoe Area Wilderness of Superior National Forest and contiguous Quetico Provincial Park of Ontario were inventoried from 1976 through 1985. Using [6.2 ha] grids, all resident bird territories were plotted in each community and transient and peripheral species were recorded. By comparing bird populations, we identified four community types. Early communities, the first 23 years after fire, had as high bird diversity but half the bird density as mature communities that developed 100 to 200 years after fire. Intermediate communities developed within 50 years as jack pine and aspen canopies matured and had a third less species, but comparable bird density as early communities. Old-growth communities, 300 or more years after fire, had lower diversity and density than mature communities with more internal variance of bird density, indicating disruption of community structure. We believe that species and communities in this region have adapted to fire and that in the long-term absence of fire, communities begin to fragment. Fire suppression will likely result in unforeseen changes in populations and community structures. [This study states that although there were abundant fire-killed trees 2 years following fire, after 10-15 years, most fire-killed trees had fallen.]

Baker, W. L. 1989. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. Ecology 70: 23-35.

Temporal change in the biosphere occurs at different rates and in different ways, depending on spatial scale. One hypothesis is that in environments where disturbances produce patches and temporal instability in small areas, the aggregate mosaic of these patches on larger areas may be constant, so that a “shifting-mosaic steady state” occurs. If so, then the appropriate minimum size for a nature reserve might be the minimum land area on which the patch-mosaic is stable. To test for a stable patch-mosaic I subdivided the Boundary Waters Canoe Area (BWCA) into smaller units at five spatial scales and used the fire history data published by Heinselman to reconstruct temporal changes in the patch-mosaic on each unit. A temporally stable patch-mosaic was not evident at any scale, largely due to (1) spatial heterogeneity in the fire-regime and/or environment, and (2) a mismatch between the grain of fire-patches and the grain of the environment. The pattern of temporal instability present on the BWCA as a whole was not replicated on smaller areas. Nature reserve design and management practices that focus on the landscape level, community level, or species level may conflict. If the management goal is to perpetuate natural fluctuations in landscape structure, then certain species dependent on landscape structure may fluctuate as well. Maintaining stable populations of these species may entail landscape manipulations that lower the value of the reserve for perpetuating landscape processes and structures.

Baker, W. L. 1992. Effects of settlement and fire suppression on landscape structure. Ecology 73: 1879-1887.

Natural landscapes subject to disturbances have a patchy structure that is important to many species living in these landscapes. This structure may be modified when the disturbance regime is altered by either climatic change or human influences (e.g., fire suppression). I used a GIS (geographic information system)-based spatial model and data on historical changes in fire sizes and intervals to simulate the effects of settlement and fire suppression on the structure of the landscape in the Boundary Waters Canoe Area, Minnesota. Settlement produced an immediate significant effect on some measures (age, shape, Shannon diversity, richness, and angular second moment), but no effect on other measures (size, fractal dimension). In contrast, suppression produced an immediate response in fewer measures (shape, Shannon Diversity, richness), a delay for several decades in the case of some measures (age, fractal dimension), and a delay for hundreds of years in the case of other measures (size, angular second moment). Landscapes that have been altered by settlement and fire suppression cannot be restored using traditional methods of prescribed burning, which will simply produce further alteration. Causes of landscape change cannot be isolated without comparison to landscapes that lack prescribed burning, fire suppression, or other alterations to the natural fire regime.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992.

Red pine and juniper are restricted to islands and peninsulas in the Lake Duparquet area, NW Quebec, and this distribution at the southern limit of the boreal forest may be due to fire regime. Fire history was studied (using dendrochronological, archival and fire scar data) for island and lakeshore stands. Dated fire scars (n = 273) revealed 82 fire years, the earliest dated AD 1593. Islands had more fire years (56) than lakeshore (37), and fire years were uncorrelated. Most (72%) lakeshore stands were initiated by a few large fires (8), whereas fire size on islands was variable (< 10% to 100% of total surface area). Fire occurrence and frequency decreased concurrently for both areas from about 120 yr ago, possibly driven by climatic change. Fire frequency was similar for all surface deposits and fuel types on lakeshore sites, whereas island fires were more abundant in pine woods on bedrock. The fire regime observed on island landscapes may be the cause of abundance of pines, whose presence may contribute, in turn, to the continuation of a regime of less intense and more frequent fires than those on the lakeshore.

Bergeron, Y., S. Gauthier, M. Flannigan, and V. Kafka. (in press). Fire regimes at the transition between mixedwood and coniferous boreal forest in Northwestern Quebec. Ecology (accepted).

Fire history was reconstructed for an area of 15,000 km^2 located in the transition zone between the mixed and coniferous forests in Quebec's southern boreal forest. We used aerial photographs, archives and dendroecological data (315 sites) to reconstruct a stand initiation map for the area. The cumulative distribution of burnt area in relation to time since fire suggests that the fire frequency has decreased drastically since the end of the Little Ice Age (about 1850) in the entire region. However, a large part of the area was burnt between 1910 and 1920 during intensive colonization and when the climate was very conducive to fire. For the period 1920-1945, large fires have mainly been concentrated in the more populated southern area while few fires have been observed in the virgin coniferous forest in the north. Despite slight differences between the south and the north, fire cycles or the average number of years since fire are not significantly different. Since 1945, there have been far more fires in the south, but the mean fire size was smaller than in the north. These results suggest that the transition between the mixed and coniferous forests observed in the southern boreal forest cannot be explained by a difference in fire frequency, at least during the last 300 years. As climatic factors and species potential distribution did not vary significantly from south to north, we suggest that the transition from mixedwood to coniferous forests is mainly controlled by fire size and severity. Smaller and less severe fires would favour species associated with the mixedwood forests as many need survivors to reinvade burnt areas. The abundance of deciduous species in mixedwood, together with the presence of more lakes that can act as firebreaks, may contribute to decreases in fire size and severity. The transition between the two vegetation zones could be related to the initial setting following the vegetation invasion of the area during the

Holocene. In this context, the limit of vegetation zones in systems controlled by disturbance regimes such as fires may not have reached a balance with current climatic conditions. Historical legacies and strong Bergeron et al. positive feedback between disturbance regimes and composition may filter and delay the responses to changes in climate.

Bergeron, Y., A. Leduc, B. D. Harvey, and S. Gauthier. 2002. Natural fire regime: A guide for sustainable management of the Canadian boreal forest. Silva Fennica 36: 81-95.

The combination of certain features of fire disturbance, notably fire frequency, size and severity, may be used to characterize the disturbance regime in any region of the boreal forest. As some consequences of fire resemble the effects of industrial forest harvesting, conventional forest management is often considered as a disturbance that has effects similar to those of natural disturbances. Although the analogy between forest management and fire disturbance in boreal ecosystems has some merit, it is important to recognize that it also has its limitations. Short fire cycles generally described for boreal ecosystems do not appear to be universal; rather, important spatial and temporal variations have been observed in Canada. These variations in the fire cycle have an important influence on forest composition and structure at the landscape and regional levels. Size and severity of fires also show a large range of variability. In regions where the natural matrix of the boreal forest remains relatively intact, maintenance of this natural variability should be targeted by forest managers concerned with biodiversity conservation. Current forest management tends to reduce this variability: for example, fully regulated, even-aged management will tend to truncate the natural forest age distribution and eliminate over-mature and old-growth forests from the landscape. We suggest that the development of strategic-level forest management planning approaches and silvicultural techniques designed to maintain a spectrum of forest compositions and structures at different scales in the landscape is one avenue to maintain this variability. Although we use the boreal forest of Quebec for our examples, it is possible to apply the approach to those portions of the boreal forest where the fire regime favours the development of even-aged stands in burns.

Cardille, J. A., and S. J. Ventura. 2001. Occurrence of wildfire in the northern Great Lakes Region: Effects of land cover and land ownership assessed at multiple scales. International Journal of Wildland Fire 10: 145-154.

Risk of wildfire has become a major concern for forest managers, particularly where humans live in close proximity to forests. To date, there has been no comprehensive analysis of contemporary wildfire patterns or the influence of landscape-level factors in the northern, largely forested parts of Minnesota, Wisconsin and Michigan, USA. Using electronic archives from the USDA Forest Service and from the Departments of Natural Resources of Minnesota, Wisconsin, and Michigan, we created and analysed a new, spatially explicit data set: the Lake States Fire Database. Most of the 18,514 fires during 1985-1995 were smaller than 4 ha, although there were 746 fires larger than 41 ha. Most fires were caused by debris burning and incendiary activity. There was considerable interannual variability in fire counts; over 80% of fires occurred in March, April, or May. We analysed the relationship of land cover and ownership to fires at two different fire size thresholds across four gridded spatial scales. Fires were more likely on non-forest than within forests; this was also true if considering only fires larger than 41 ha. An area of National or State Forest was less likely to have experienced a fire during the study period than was a forest of equal size outside National or State Forest boundaries. Large fires were less likely in State Forests, although they were neither more nor less likely to have occurred on National Forests. Fire frequency also varied significantly by forest type. All results were extremely consistent across analysis resolutions, indicating robust relationships.

Cardille, J. A., S. J. Ventura, and M. G. Turner. 2001. Environmental and social factors influencing wildfires in the Upper Midwest, United States. Ecological Applications 11: 111-127.

Although the vast majority of contemporary wildfires in the Upper Midwest of the United States have a human origin, there has been no comprehensive analysis of the roles played by abiotic, biotic, and human factors in determining the spatial patterns of their origins across the region. The Upper Midwest, a 2.8×10^5 km^2 area in the northern, largely forested parts of the states of Minnesota, Wisconsin, and Michigan, contains regions of varied land cover, soil type, human settlement densities, and land management strategies that may influence differences in the observed spatial distribution of wildfires. Using a wide array of satellite- and ground-based data for this region, we investigated the relationship between wildfire activity and environmental and social factors for > 18,000 reported fires of all sizes between 1985 and 1995. We worked at two spatial scales to address the following questions: (1) Which abiotic, biotic, and human variables best explained decade-scale regional fire activity during the study period? (2) Did the set of factors related to large fires differ from the set influencing all fires? (3) Did varying the spatial scale of analysis dramatically change the influence of predictive variables? (4) Did the set of factors influencing the number of fires in an area differ from the set of factors influencing the probability of the occurrence of even a single fire? These data suggest that there is no simple "Lake States fire regime" for the Upper Midwest. Instead, interpretation of modern fire patterns depends on both the fire size considered and the measurement of fire activity. Spatial distributions of wildfires using two size thresholds and viewed at two spatial scales are clearly related to a combination of abiotic, biotic, and human factors: no single factor or factor type dominates. However, the significant factors for each question were readily interpretable and consistent with other analyses of natural and human influences on fire patterns in the region. Factors seen as significant at one scale were frequently also significant at the other, indicating the robustness of the analysis across the two spatial resolutions. The methods for conducting this spatially explicit analysis of modern fire patterns (generalized linear regression at multiple scales using long-term wildfire data and a suite of environmental and social variables) should be widely applicable to other areas. Results of this study can serve as the basis for daily, seasonal, or interannual studies as well as the foundation for simulation models of future wildfire distribution.

Clark, D. F., D. D. Kneeshaw, P. J. Burton, and J. A. Antos. 1998. Coarse woody debris in sub-boreal spruce forests of west-central British Columbia. Canadian Journal of Forest Research 28: 284-290.

An evaluation of how coarse woody debris (CWD) changes in quantity and quality during stand development was conducted using a 426-year chronosequence of 71 stands in sub-boreal forests in British Columbia. Additional characteristics of CWD were determined in 14 of the stands. Most stands are fire initiated and input from the predisturbance stand is critical in controlling the amounts and characteristics of CWD within young stands. Log volume declines from over 100 $m^3 \cdot ha^{-1}$ in young stands (0-50 years) to just over 60 m3 ha^{-1} in stands from 51 to 200 years old, and then increases to > 140 $m^3 \cdot ha^{-1}$ in the oldest (>400-year-old) stands. Mean snag basal area is highest (31.6 $m^2 \cdot ha^{-1}$) in young, post-fire stands, decreases to a very low value (2.0 $m^2 \cdot ha^{-1}$) in stands 51-100 years old, and then reaches a second maximum (12.1 $m^2 \cdot ha^{-1}$) in stands that are 201-250 years old; it declines slightly in very old stands. The high snag basal area in stands 201-250 years old coincides with the successional transition from lodgepole pine to stands dominated by subalpine fir and interior spruce (hybrids of *Picea glauca* and *Picea engelmannii*). Stand age, characteristics of the predisturbance forest, and the disturbance history of stands subsequent to stand initiation all appear to be very important in determining variation in both the quality and quantity of CWD in these sub-boreal forests.

Cumming, S. G. 2001. A parametric model of the fire-size distribution. Canadian Journal of Forest Research 31: 1297-1303.

This paper develops statistical models of the size distribution of lightning-caused wildfires in the boreal mixedwood forests of Alberta, Canada, for the intervals 1980-98 and 1961-98. Above any minimum threshold size ♮ 3 ha, the logarithm of fire size is approximately exponentially distributed. However, computer simulations using the best-fit distribution would overpredict the frequency of large fires, and thus, the mean rate of disturbance. A truncated exponential distribution, which places an upper bound on fire size, is more suitable and, according to probability plots, provides an excellent fit to the data. The maximum fire size in the study area is estimated to be > 650,000 ha. This estimate is insensitive to the choice of lower bound for fire sizes between 3 and 1,000 ha, and to the choice of sampling interval. Parametric modelling of fire sizes using covariates derived from forest inventory data shows that the expected size of a fire is positively related to the abundance of pine forest in the vicinity of the point of detection and negatively related to the abundance of recently logged or burnt areas. This implies that variation in forest structure and disturbance history impose marked spatial variability on the fire size distribution. Other covariates, such as periodic indices of fire weather, could readily be evaluated in this framework.

Cwynar, L. C. 1977. The recent fire history of Barron Township, Algonquin Park. Canadian Journal of Botany 55: 1524-1538.

The recent fire history of Barron Township (18,600 ha) in Algonquin Park was studied by examining historical documents and dating past forest fires using dendrochronological techniques. Lightning is still a major ignition source. Over the 36 year period of 1939-1974, lightning accounted for 48.5% of all fires at a rate of 0.19 fires per year per 10,000 ha. Dendrochronological data show that 16 fires burned during the 225 year pre-suppression interval from 1696 to 1920 for a mean frequency of 14.1 years. Five major fires (1875, 1864, 1854, 1780, and 1763) each burned at least half of the township with a mean frequency of 45 years. Meteorological data show that drought prevailed across southern Ontario during 1875, when major fires burned in Barron Township and northern Minnesota, supporting the suggestion that severe fire years correspond with periods of subcontinental drought. Similarly, 1864 appears to have been a major fire year in Barron as it certainly was in Minnesota. The recent fire rotation, i.e., the average time required to burn an area equivalent to the size of the study area, is about 70 years. Field evidence and increment borings suggest that the present vegetation mostly originated as a consequence of the fire of 1875.

Dansereau, P. R., and Y. Bergeron. 1993. Fire history in the southern boreal forest of northwestern Quebec. Canadian Journal of Forest Research 23: 25-32.

Age determination of post-fire forests and the analysis of fire scars on surviving trees have allowed for the historical reconstruction and mapping of fires in a forest area of 11,715 ha in NW Quebec, south of Lake Abitibi. Balsam fir is the dominant species with black spruce, white spruce and white birch also important components of the forest. Stands of pioneer species such as jack pine and trembling aspen occupy large areas following disturbances by fire. Thirty-three trees (25 white cedar, 7 jack pine and 1 white birch) bearing fire scars were analysed to date the fires. Forests that originated after fire were located by determining the age, using cores or cross sections, of a few dominant canopy trees in a total of 171 stands. Jack pine, a species generally associated with post-fire recruitment, was chosen if present (241 trees in total). White spruce (226 trees), black spruce (174 trees) and white birch (84 trees) were sampled in the absence of jack pine. Most of the study area was burnt by two large fires (> 1,000 ha) in 1760 and 1923. All the other fires recorded (in 1797, 1823, 1870, 1907, 1919) were smaller in extent and occurred in the eastern part (1984 ha) of the study area which was fragmented by lakes. Data about area burnt per type of surficial material confirms that the physical environment exerts a stronger control on the delimitation of these smaller fires. The data do not allow for estimating fire cycle owing to the small size of the study area and possible temporal changes during the observation period. However, methodological observations are formulated for future studies covering a larger area in the bioclimatic region.

DeLong, S. C. 1998. Natural disturbance rate and patch size distribution of forests in northern British Columbia: Implications for forest management. Northwest Science 72: 35-48.

A common theme in current forest management policy is that harvesting should be designed to achieve the landscape patterns and habitat conditions that are maintained by natural disturbance regimes. This study was undertaken to determine the influence of climate and topography on disturbance rate and patch size associated with stand replacement wildfire. This will provide new information to improve forest management guidelines in British Columbia for 9 areas differing in regional climate and topography (plateau vs montane). Regression analysis was used to determine the influence of climate and gross topography on fire cycle. Patch size distribution was compared graphically and statistically. Annual disturbance rate and patch size distribution in northern natural forests in British Columbia were clearly related to regional climate and topography. In montane landscapes, a decrease in disturbance rate, a decrease in mean patch size and a decrease in proportion of area in patches > 1,000 ha was associated with increasing precipitation. For plateau areas, topographic units with intermediate precipitation regime had higher disturbance rates and a greater proportion in patches > 1,000 ha. Montane areas which were climatically similar to adjacent plateau areas had a lower disturbance rate and less area in larger patches. Current biodiversity guidelines appear to underestimate the fire cycle for many areas. Maximum allowable patch size in the current guidelines was lower than the maximum natural disturbance patch size determined for any of the landscapes examined. Current recommendations also suggest to manage for more area in 40,250 ha patches than was evident from the data.

Delong, S. C., and W. B. Kessler. 2000. Ecological characteristics of mature forest remnants left by wildfire. Forest Ecology and Management 131: 93-106.

The objective of this study was to develop a better understanding of the ecological significance of unburned forest remnants in successional sub-boreal landscapes created by fire. The study site was a moist cool sub-boreal forest dominated by lodgepole pine or hybrid white spruce (*Picea glauca* x *P. engelmannii*) in British Columbia, Canada. Remnant forest patches were characterized and compared with matrix forest in young, mature and old age classes. Remnant patches could be discriminated from matrix forest types based on variables relating to tree overstory and snag density. Some remnants displayed a unique uneven-aged pattern of lodgepole pine regeneration. Differences between remnant patches and matrix forest stands, and high variation among patches, may reflect the variable influence of the wildfires through which the patches survived. Remnants share many ecological characteristics with old forest and may provide 'bridging habitats' in landscapes recovering from large-scale disturbance. Patches of mature forest retained in logged landscapes may have the potential to substitute for wildfire remnants. However, selection and management criteria should be developed to guide the design of habitat retention and to monitor effects. The unusual regeneration dynamics demonstrated by some remnants may suggest an alternative silvicultural model for regenerating stands dominated by lodgepole pine within the boreal forest.

DeLong, S. C., and D. Tanner. 1996. Managing the pattern of forest harvest: lessons from wildfire. Biodiversity and Conservation 5: 1191-1205.

Managing forests for sustainable use requires that both the biological diversity of the forests and a viable forest industry be maintained. A current approach towards maintaining biological diversity is to pattern forest management practices after those of natural disturbance events. This paradigm hypothesizes that ecological processes will be maintained best where active management approximates natural disturbance events. The forest management model now used in most sub-boreal and boreal forests calls for regularly dispersed clearcuts no greater than 60-100 ha in size. This paper compares the spatial characteristics of the landscape produced by this model with the pattern produced by wildfires, based on data from a study area in sub-boreal spruce forest (*Picea glauca* X *P. engelmannii* with lodgepole pine, and small patches of other species) forest in British Columbia. The data were analysed using databases covering different aspects of the temporal and spatial pattern of wildfire and harvesting at different scales, generated using a geographical information system. The comparison showed that the spatial characteristics of the landscape produced by forest management with small clearcut (harvest) areas are distinctly different from the historical pattern generated by wildfire, which was heretofore the dominant stand-replacing process in these forests. Wildfire creates a more complex landscape spatial pattern with a greater range in patch size and more irregular disturbance boundaries. Individual wildfires are often over 500 ha but leave patches of unburned forest within them. The combination of these attributes is not present in recent clearcuts. Allowing a proportion of larger (i.e. > 500 ha) harvest units may provide distinct economic advantages that could outweigh the opportunity costs of leaving some patches of forest behind.

Eberhart, K. E., and P. M. Woodard. 1987. Distribution of residual vegetation associated with large fires in Alberta. Canadian Journal of Forest Research 17: 1207-1212.

Fire size and shape, number and size of areas of residual vegetation, length of fire perimeter and distances to residual vegetation were analysed for 69 fires (21-17,770 ha) that burned during 1970-83. Distribution of residual vegetation was studied for 5 fire size classes. The smallest fires (20-40 ha) did not contain any areas of unburned vegetation. The proportion of vegetation that was actually disturbed within the fire perimeter decreased with increasing fire size. The number of unburned areas per 100 ha was greatest for the 3rd and 4th largest fire size classes (201-400 and 401-2,000 ha). Median size of unburned areas per fire, fire shape index and edge index increased with fire size. Maximum distance to residual vegetation increased with fire size. Results suggest that potential for natural regeneration may decrease, while benefits to wildlife may increase as fire size increases.

Ecostem. 2000. What does a large wildfire disturb and what does it leave in the eastern two-thirds of the Manitoba Model Forest. Ecostem Ltd., Winnipeg, MB. Manitoba Model Forest Project No. 99-2-49.

Large wildfires historically created the patchwork of forest types we see when we fly over the Manitoba Model Forest. Today, large-scale timber harvesting operations have the potential to create disturbance events that approach the size of wildfires. However, there are many differences between the way wildfire and timber harvesting affects the landscape and how the forest operates. To ensure that forests continue to provide benefits to future generations, the Canadian Council of Forest Ministers agreed that the overriding objective of sustainable forest management is the maintenance of forest ecosystem health. The natural disturbance approach to maintaining forest ecosystem health attempts to design forest management practices so that their effects on ecological processes and biodiversity approximate those of the major disturbances that occur naturally in the region. This report briefly introduces the fire history and related ecology of the northeastern two-thirds of the Manitoba Model Forest. There are several fire regimes in the Model Forest area and the boundaries of the "region" included in this study is the fire regime that accounts for the largest area. This region of the Manitoba Model Forest is characterized by exposed Canadian Shield, shallow mineral soils and bogs. The report describes the size, spread patterns and other landscape relationships of large wildfires that occurred between 1955 and 1983 in this region. Information used in this study was based on information from the Forest Resource Inventory (FRI), historical fire reports and mapping historical aerial photos of the fires. Boundaries of burned and skipped (i.e., areas within the wildfire that did not burn) patches as well as different site and topographic conditions were mapped using a Geographic Information System (GIS). Computer programs such as FRAGSTATS and SPSS generated the comparative results for this study. These results were instrumental in designing timber harvest trials commenced in February 1999.

Ecostem. 2001. Harvesting to regenerate a natural forest: Comparison of study areas after fire or timber harvest and implications for site and stand level indicators of sustainable forest management [Draft Report]. Ecostem Ltd., Winnipeg, MB. Manitoba Model Forest Project No. 00-2-49.

In keeping with the natural disturbance approach to ecosystem based forest management, the Manitoba Model Forest and Tembec Paper Group-Pine Falls Operation initiated a four year project to develop a practical response to the question: 'How do we maintain forest ecosystem health while harvesting timber?'. Since large wildfires are the largest component of the region's natural disturbance regime, the focus is on developing and testing wildfire-based timber harvest guidelines for a portion of eastern Manitoba. During the first two years of the project, guidelines that are intended to approximate the effects of a large wildfire were developed and tested. A large wildfire affects spatial scales that span from landscape to site-level. The timber harvest analogues for these spatial scales are an operating area and a cut-block within the operating area. Fire behaviour in six large wildfires with a combined area of 75,000 ha was mapped, analyzed and used to establish what a large wildfire usually disturbs and what it leaves. This report presents results from the project's monitoring programme and draws preliminary implications for site-level indicators of sustainable forest management.

Everett, R., J. Lehmkuhl, R. Schellhaas, P. Ohlson, D. Keenum, H. Riesterer, and D. Spurbeck. 1999. Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington State, USA. International Journal of Wildland Fire 9: 223-234.

Snags and logs are important components of wildlife habitat and are critical for the maintenance of soil organic matter and long-term site productivity. Snag numbers and decay class were measured on a chronosequence of 26 stand-replacement wildfires (ages 1-81 years) on the east slope of the Cascade Range in Washington, USA. Sites had not experienced subsequent reburns or salvage logging. Snag longevity and resultant snag densities varied spatially across burns in relation to micro-topographic position. Longevity of snags < 41 cm diameter at breast height (dbh) was greater for thin-barked Engelmann spruce, subalpine fir

and lodgepole pine than thick-barked Douglas fir and ponderosa pine. With larger diameter snags, however, Douglas fir persisted longer than Engelmann spruce. The time period required for recruitment of soft snags > 23 cm dbh was estimated to exceed snag longevity for Ponderosa pine, Engelmann spruce, Lodgepole pine and subalpine fir, causing an 'on-site gap' in soft snags for these species. Snags of Douglas fir > 41 cm dbh stood for a sufficient time (40% standing after 80 years) to potentially overlap the recruitment of soft snags > 23 cm dbh from the replacement stand. Providing continuity in soft snags following stand-replacement events would require a landscape-scale perspective, incorporating adjacent stands of different ages or disturbance histories. Results suggest that standards and guidelines for snags on public forest lands need to be sufficiently flexible to accommodate both disturbance and stand development phases and differences in snag longevity among species and topographic positions. [The immediate post-fire density of snags for older burns was estimated by combining standing snags and stumps or logs present on the study plots].

Fahey, T. J., and W. A. Reiners. 1981. Fire in the forests of Maine and New Hampshire. Bulletin of the Torrey Botanical Club 108: 362-373.

Modern fire records for Maine and New Hampshire and other historical evidence were investigated to infer the occurrence and distribution of fire in pre-settlement time. Between the decades of 1910-1920 and 1960-1970 fire incidence increased and average fire size decreased sharply, with the net effect being a several-fold diminution of land burned per year. Fire was unequally distributed among forest types. Pine-dominated forests in the south-coastal part of the States were bumed most frequently, with northem hardwood forests in central portions intermediate and spruce-fir forests least influenced by fire. The spruce-fir type in northern New England appears to be an exception to the generalization that coniferous forests burn more readily than hardwoods. Historical evidence suggests that in pre-Columbian time a significant potential for fire ignition existed in association with lightning and the incendiary activities of Native Americans. Because human control of fire size was lacking, the extent of prehistoric fires may have equalled that in the early 20th Century.

Ferguson, S. H., and D. J. Archibald. 2002. The 3/4 power law in forest management: How to grow dead trees. Forest Ecology and Management 169: 283-292.

Structural complexity of managed forests is proving to be vitally important for the conservation of wildlife and ecological processes. We tested for the factors most important in determining the availability of snags (dead standing trees) in fire-origin boreal forests of northwestern Ontario, Canada. The strongest correlate of snag basal area ($m^2 \cdot ha^{-1}$) was the amount of live tree basal area, which accounted for 68% of variation in the production of snags. The relationship between live and dead tree basal area followed a 3/4 power law with a slope of 0.74 for the forest community and differing slopes for forest stands and forest age. A relationship between tree mortality and metabolic rate is consistent with rate of self-thinning theory. This invariance indicates that total community biomass is likely to be insensitive to species diversity. Mixed hardwood forest types produced the greatest basal area of snags, followed by poplar, mixed conifer, jack pine and spruce stands. The percentage of stems that were dead was greatest in young forests (18% of stems in 0 to 60-year-old forests), decreased to a low percentage of 12% in 61- to 80-year-old forests, and thereafter increased with age of forests from 15 to 16% in 81-100, > 100-year-old forests, respectively. In contrast, the number of small diameter (10-22 cm dbh) snags (stems ha^{-1}) was greatest in 61- to 100-year-old forests, whereas medium diameter (22-30 cm dbh) snags and large diameter (> 30 cm dbh) snags were greatest in old-growth (> 100 years) forests. The management implications are that increased live tree density due to environmental conditions, or possibly intensive forest management practices following clear cutting, may secondarily result in greater snag production and the structural complexity that favours wildlife biodiversity. Forest management guidelines that incorporate allometric relationships are needed to ensure maintenance of biodiversity and habitat heterogeneity following timber harvesting.

Ferguson, S. H., and P. C. Elkie. 2003. Snag abundance 20, 30, and 40 years following fire and harvesting in boreal forests. Forestry Chronicle 79: 541-549.

The retention of standing dead trees (snags) has become an important conservation concern, especially when forest management efforts attempt to emulate natural

disturbance. We investigated the abundance of snags within Ontario's (Canada) boreal forest (dominated by jack pine) following 10-20, 21-30, and 31-40 years of both fire and forest harvest disturbance over a 24,000 km^2 area. Fire frequency varied considerably, with 90% of the fires in the study area occurring in the 1970s. We did not detect differences in basal area of snags ($m^2 \cdot km^{-2}$) between burned and harvested stands. However, differences occurred in dead-stem density ($number \cdot km^{-2}$); the burned stands produced more snags in the 21- to 30-year post-disturbance class and the harvested stands produced more snags in the 31- to 40-year post-disturbance class. Similarly, the distribution of diameter classes of snags differed between the burned and harvested stands. In size classes greater than 32 cm (dbh), we found more snags in the harvested forests 21-40 years following disturbance. We did not find differences in the basal area of snags between disturbance types, whether they were hardwood or softwood. However, hardwood snags occurred in greater abundance in the larger diameter classes. Our findings were limited by the changing timber harvest treatments selective harvest, clearcut, and ecological cut), the small number of disturbance events, and the variety of stand compositions.

Foster, D. R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. Canadian Journal of Botany 61: 2459-2471.

The fire history of the wilderness of southeastern Labrador is marked by a patchy distribution of large fires in time and space. During the 110-year period encompassed by this study, major fires occurred in four decades, 1870-1879, 1890-1899, 1950-1959 and 1970-1979. The regional pattern of fire activity has important phytogeographical implications. The lichen woodlands and birch forests are fire-dependent vegetation types; their distribution in the modern landscape is strongly correlated with the historical occurrence of fire during the past 110 years. In addition it is postulated that the historical absence of fire across the large plains in southeastern Labrador has contributed to the development of extensive peatlands in these areas.

Freedman, B., V. Zelazny, D. Beaudette, T. Fleming, S. Flemming, G. Forbes, J. S. Gerrow, G. Johnson, and S. Woodley. 1996. Biodiversity implications of changes in the quantity of dead organic matter in managed forests. Enviromental Reviews 4: 238-265.

Dead organic matter is an important structural and functional element in natural forests, but its quantity, quality, and spatial distribution are greatly modified by intensive harvesting and management through forestry. From the perspective of conflicts with biodiversity, the most important changes are associated with reductions in the abundance of snags, cavity trees, and coarse-woody debris, all of which are well known as critical habitat elements for a wide range of indigenous species. Changes in the depth and quality of the forest floor of managed stands are also important for some species and guilds of wildlife. Resolution of this conflict between forestry and biodiversity will require the design and implementation of management systems that accommodate the critical habitat qualities associated with dead organic matter, particularly with large-dimension deadwood and cavities. This goal may be most effectively achieved by an integrated strategy that involves basing forest-management planning on shifting-mosaic habitat models of stand harvesting and replacement, designed to ensure a continuous availability of sufficient areas of stands old enough to sustain habitat features associated with dead organic matter, along with the provision of protected areas of mature and older growth forest, associated with riparian buffers, deer yards, and non harvested ecological reserves and other kinds of protected areas. These protected areas are necessary to accommodate those elements of biodiversity that cannot tolerate the conditions of managed stands.

Frelich, L. E. 2002. Forest Dynamics and Disturbance Regimes: Studies From Temperate Evergreen-Deciduous Forests. Cambridge University Press, Cambridge, U.K.

[Natural and settlement history of the transition forest zone of the Great Lakes Region is addressed with a focus on forest disturbance regimes. Using several case studies from the region, this book illustrates the interactions between these disturbances and forest responses in structure and composition. Forest dynamics in the different forest types, ranging from deciduous to boreal, are addressed comparatively with respect to forest succession, including descriptions of various study techniques. Finally, a series of generalized principles of forest responses to disturbances are presented at stand and landscape scale and extended to conceptual models of forest stability over time and space.]

Frissell, S. S., Jr. 1973. The importance of fire as a natural ecological factor in Itasca State Park, Minnesota. Quaternary Research 3: 397-407.

During the period between 1650 and 1922 at least 32 fires occurred in Itasca State Park. Twenty-one of these fires were of major consequence. A fire occurred on the average of every 8.8 years with "major" fires every 10.3 years. Any specific location in the park was affected by fire about every 22 yr. Individual burns varied in size from [235 ha] to approximately [12,944 ha] (99% of the park). Sixteen of the 21 "major" fires resulted in the regeneration of pine forests. Management programs involving intensive fire control have resulted in a serious departure from natural conditions.

Gasaway, W. C., and S. D. Dubois. 1985. Initial responses of moose to a wildfire in interior Alaska. Canadian Field-Naturalist 99: 135-140.

The initial response of seven radio-collared moose to wildfire was investigated to determine if moose were displaced from the burned portion of their home ranges. Home ranges of these m,oose overlapped a 500-km^2 fire that burned from 3 May-20 June 1980 in interior Alaska. By comparing relocations and home ranges of animals from May-August of the two years preceding the fire to data in the year of the fire, we concluded radio-collared moose were not displaced. Moose selected primarily unburned sites within the perimeter of the fire. [This publication states that following a 50,000 ha fire, 15% was unburned].

Gluck, M. J., and R. S. Rempel. 1996. Structural characteristics of post-wildfire and clearcut-landscapes. Environmental Monitoring and Assessment 39: 435-450.

A continuing discussion in the field of ecology and forest management concerns the implications of clear felling as a functional replacement for wildfire in disturbance-driven ecosystems. At the landscape level, spatial pattern has been shown to influence many ecologically important processes. Satellite imagery allows the evaluation of structural patterns created by alternative forest management activities at broad scales. In NW Ontario, both clear felling and wildfire have occurred over large contiguous areas. Spatial characteristics, including composition, patch size, patch shape and interspersion were calculated from classified Landsat Thematic Mapper (TM) data at two thematic scales and used to compare post-wildfire and clear felled landscapes. Patches in the clear felled landscape were larger in size, and had a more irregular shape than those in the wildfire landscape. Differences in landscape structure were much more pronounced at broad scales than at fine thematic scales.

Greif, G. E., and O. W. Archibald. 2000. Standing-dead tree component of the boreal forest in central Saskatchewan. Forest Ecology and Management 131: 37-46.

The standing-dead tree component (which is important as wildlife habitat) was assessed in part of the upland forests in the mixedwood boreal forest in central Saskatchewan, Canada. Comparisons of the average number of dead trees per hectare were made between softwood stands, softwood-dominant mixedwood stands, hardwood-dominant mixedwood stands and hardwood stands. General trends in snag size and density were evaluated by comparing similar stand types of various height classes. The majority of the snags within the four forest associations were of small diameter (2-10 cm), comprising from 0.6 to 18.6% of the stems in these stands with the number of small-diameter dead trees per hectare decreasing in the older, taller stands. The density of small-diameter snags ranged from 440 ha^{-1} in 5 m softwood stands to 55 ha^{-1} in 25 m hardwood stands. The density of large diameter snags (> 21 cm dbh) rarely comprised more than 5% of a stand.

Haeussler, S., and Y. Bergeron. 2004. Range of variability in boreal aspen plant communities after wildfire and clear-cutting. Canadian Journal of Forest Research 34: 274-288.

Composition, structure, and diversity of vascular and nonvascular plant communities was compared 3 years after wildfire and clear-cutting in mesic trembling aspen forests of the southern Canadian boreal forest. We examined mean response to disturbance and variability around the mean across four to five spatial scales. Four 1997 wildfires were located near Timmins, Ontario, and

10 1996–1997 clearcuts were located adjacent to the wildfires. We randomly located plots within mesic, aspen-dominated stands selected to minimize predisturbance environmental differences. Correspondence analysis separated wildfire and clearcut samples based on community composition: wildfires had more aspen suckers, *Diervilla lonicera* Mill., and pioneering mosses; clearcuts had more under story tall shrubs, forbs, bryophytes, and lichens. Live-tree basal area averaged 1.7 $m^2 \cdot ha^{-1}$ in wildfires and 1.8 $m^2 \cdot ha^{-1}$ in clearcuts (p = 0.59), and understory community structure (the horizontal and vertical distribution of live and dead plant biomass) was not markedly different. Clearcuts had higher species richness with greater variance than wildfires across all spatial scales tested, but differences in beta and structural diversity varied with spatial scale. Generally, clearcut–wildfire differences were more evident and wildfire variability greater at larger analytical scales, suggesting that plant biodiversity monitoring should emphasize cumulative effects across landscapes and regions.

Haines, D. A., V. J. Johnson, and W. A. Main. 1975. Wildfire atlas of the northeastern and north central states. USDA Forest Service, North Central Forest Experiment Station, General Technical Report NC-16.

[This report presents data from forest fire records (number, size, and area burned) for the period of 1960-1969 from National Forests in the Great Lakes states (Minnesota, Wisconsin, and Michigan), northeastern United States (Vermont and New Hampshire), and the central United States (Missouri through Pennsylvania) in tabular and graphical form. The data are presented temporally, showing the within-year distribution of fires by month and week, and spatially in the context of 3 major cover types common to these regions (conifer, hardwood, and grassland). Over 50% of the reported fires were in hardwoods, the most common cover type. Median fire sizes in the hardwood and conifer cover types, in all but one of the eight national forests represented in the Great Lakes region, were < 0.2 ha. The detailed information in this report may assist fire management agencies in determining when and where fire-fighting resources will be required.]

Harper, K. A., C. Boudreault, L. DeGrandpre, P. Drapeau, S. Gauthier, and Y. Bergeron. 2003. Structure, composition, and diversity of old-growth black spruce boreal forest of the Clay Belt region in Quebec and Ontario. Environmental Reviews 11: S79-S98.

Old-growth black spruce boreal forest in the Clay Belt region of Ontario and Quebec is an open forest with a low canopy, quite different from what many consider to be “old-growth”. Here, we provide an overview of the characteristics of old-growth black spruce forest for three different site types on organic, clay, and coarse deposits. Our objectives were (1) to identify the extent of older forests; (2) to describe the structure, composition, and diversity in different age classes; and (3) to identify key processes in old-growth black spruce forest. We sampled canopy composition, deadwood abundance, understorey composition, and nonvascular plant species in 91 forest stands along a chronosequence that extended from 20 to more than 250 years after fire. We used a peak in tree basal area, which occurred at 100 years on clay and coarse sites and at 200 years on organic sites, as a process-based means of defining the start of old-growth forest. Old-growth forests are extensive in the Clay Belt, covering 30–50% of the forested landscape. Black spruce was dominant on all organic sites, and in all older stands. Although there were fewer understorey species and none exclusive to old-growth, these forests were structurally diverse and had greater abundance of *Sphagnum*, epiphytic lichens, and ericaceous species. Paludification, a process characteristic of old-growth forest stands on clay deposits in this region, causes decreases in tree and deadwood abundance. Old-growth black spruce forests, therefore, lack the large trees and snags that are characteristic of other old-growth forests. Small-scale disturbances such as spruce budworm and windthrow are common, creating numerous gaps. Landscape and stand level management strategies could minimize structural changes caused by harvesting, but unmanaged forest in all stages of development must be preserved in order to conserve all the attributes of old-growth black spruce forest.

Harper, K. A., D. Lesieur, Y. Bergeron, and P. Drapeau. 2004. Forest structure and composition at young fire and cut edges in black spruce boreal forest. Canadian Journal of Forest Research 34: 289-302.

We compared structure and composition at forest edges created by wildfire and clear-cutting in black spruce dominated boreal forest in northwestern Quebec. Forest structure and plant species composition were sampled along transects perpendicular to eight 3- to 4-year-old fire edges and eight 2- to 5-year-old cut edges. Significance of edge influence was assessed by comparing mean values at different distances from the edge to the range of variation in interior forest. The influence of clearcut edges was minimal, generally extending only 5 m from the edge, and included greater log density and different species composition, compared with interior forest. At fire edges, prominent responses to edge creation included increased snag density and lower moss cover, compared with interior forest, extending up to 40 m into the forest. This initial structural change was likely due to partial burning extending into the forest. Overall, fire edges had more snags and a different species composition than cut edges. Our hypothesis that edge influence is more extensive at fire edges than at cut edges was supported for overstory and understory structure, but not for species composition. We suggest that there is a need for management to consider the cumulative effect of the loss of fire edges on the landscape.

Heinselman, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research 3: 329-382.

Fire largely determined the composition and structure of the presettlement vegetation of the Boundary Waters Canoe Areas as well as the vegetation mosaic on the landscape and the habitat patterns for wildlife. It also influenced nutrient cycles, and energy pathways, and helped maintain the diversity, productivity and long-term stability of the ecosystems. Thus the whole ecosystem was fire-dependent. To restore the natural ecosystem of the Canoe Area, fire should soon be reintroduced through a program of prescribed fires and monitored lightning fires. Failing this, major unnatural, perhaps unpredictable, changes in the ecosystems will occur.

Heinselman, M. L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. Pages 7-57 *in* H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners (compilers). Proceedings of the conference - Fire Regimes and Ecosystem Properties, December 11-15, 1978, Honolulu, HI. USDA Forest Service, General Technical Report WO-26.

Most presettlement Canadian and Alaskan boreal forests and Rocky Mountain subalpine forests had lightning fire regimes of large-scale crown fires and high-intensity surface fires, causing total stand replacement on fire rotations (or cycles) of 50 to 200 years. Cycles and fire size varied with latitude, elevation, and topographic climate factors. Some areas had smaller, less intense surface fires at shorter intervals. The Great Lakes-Acadian forests had regimes of short cycle crown fires in near boreal jack pine and spruce forests, combinations of moderate intensity short interval surface fires and small scale crown fires at longer intervals in red white pine forests, and low intensity long interval fires in hardwoods. Fire maintained the structure and pattern of the forest mosaic. These regimes still prevail in the far north. Elsewhere regimes and the forest mosaic are greatly modified by logging, anathropogenic fires, and fire suppression.

Hely, C., Y. Bergeron, and M. D. Flannigan. 2000. Coarse woody debris in the southeastern Canadian boreal forest: Composition and load variations in relation to stand replacement. Canadian Journal of Forest Research 30: 674-687.

Quantities and structural characteristics of coarse woody debris (CWD) (logs and snags) were examined in relation to stand age and composition in the Canadian mixedwood boreal forest around Lake Duparquet, Quebec. Forty-eight stands originating after fire (from 32 to 236 years) were sampled on mesic clay deposits. The point-centered quadrant method was used to record canopy composition and structure (living trees and snags), and the line-intersect method was used to sample logs of all diameters. The forest was characterized by an association of *Abies balsamea*, *Picea mariana*, *Betula papyrifera*, *Picea glauca*, and *Populus tremuloides*. Total log load, mean snag density and volume per stand were similar to other boreal stands. Linear and non-linear regressions showed that time since fire and canopy composition were significant descriptors for log load changes, whereas time since fire was the only significant factor for snag changes. Coarse woody debris accumulation models through time since fire were different from the U-shaped model because the first initial decrease from residual pre-disturbance debris was missing, the involved species had rapid decay rates with no long-term accumulation, and the succession occurred from species replacement through time.

Hobson, K., and J. Schieck. 1999. Changes in bird communities in boreal mixedwood forest: Harvest and wildfire effects over 30 years. Ecological Applications 9: 849-863.

Bird communities were contrasted in 3 replicate forest stands for each of 3 age classes (1, 13 to 15-, and 22 to 28-years-old) and 2 treatment types (wildfire and harvest) in north-central Alberta, Canada, during 1996. Stands were chosen from old (> 120 years) boreal mixedwood forests with > 95% of canopy trees killed during fire, and harvested sites retaining an average of 6% of the pre-harvest canopy trees. The study area was a diverse mosaic of forest stand types and ages, including *Picea mariana*, *Picea glauca*, *Pinus banksiana*, *Populus balsamifera* and *Betula papyrifera*. For all age classes, post-harvest sites had greater bird abundance. Species composition also differed between harvested and fire damaged sites. Two-Way Indicator Species Analysis (TWINSPAN) identified 5 major ecological species groupings that differed between wildfire and harvest sites, and among stand ages. Correspondence analysis (CA) identified similar bird communities. The greatest differences between bird communities occurred immediately following disturbance, and gradual convergence of communities occurred throughout the first 28 years after disturbance. Convergence in avian communities was correlated with the loss of standing snags on post-wildfire sites. However, differences in bird communities were apparent up to 28 years following disturbance, and this lack of complete convergence has important consequences for sustainable forestry practices designed to maintain biodiversity in the boreal mixedwood forest. It is concluded that harvest designed to approximate stand-replacing fires may require the retention of more snags than is currently practised, and that new approaches to fire salvage logging are also required to ensure the adequate retention of standing dead trees on the landscape.

Hoyt, J. S. 2000. Habitat associations of black-backed *Picoides arcticus* and three-toed *P. tridactylus* woodpeckers in the northeastern boreal forest of Alberta. M.Sc. Thesis, University of Alberta, Edmonton, AB.

Black-backed and Three-toed woodpecker numbers might decrease in boreal Alberta due to fire suppression and changes in the structure and age composition of the forest. I surveyed recently burned, old-growth and mature coniferous forests and different aged burns to determine both species' habitat associations and how long they occupy post-fire forests. I also examined Black-backed woodpecker foraging habitat selection in a 3-year-old burn. Black-backs only occupied recently burned forests, which were occupied up to 8-years post-fire. They selected moderately burned, large diameter, standing, and the lower 1/3, of jack pine for foraging. Insect data collected failed to predict Black-backed foraging habitat selection or post-fire occupancy, primarily due to sampling design problems. Three-toeds occupied recently burned, old and mature forests, but associations with mature and old forests were unclear since mature sites that were occupied had vegetation characteristics that resembled old sites. Their occupancy decreased between 3 and 8-years, post-fire.

Hoyt, J. S., and S. J. Hannon. 2002. Habitat associations of black-backed and three-toed woodpeckers in the boreal forest of Alberta. Canadian Journal of Forest Research 32: 1881-1888.

Recent studies suggest that black-backed and three-toed woodpeckers might decrease in abundance because of habitat loss from fire suppression and short-rotation logging in landscapes managed for forestry. We examined black-backed and three-toed woodpecker occupancy of stands in a 2-year post-fire forest, mature and old-growth spruce and pine forests (dominated by *Picea glauca*, *P. mariana* and *Pinus banksiana*), and six post-fire coniferous forests (dominated by *Populus tremuloides*) of different ages. Three-toeds were detected in old stands and in the 2-year-old burn, and their probability of occupancy of burned forests decreased between 3 and 8 years post-fire. Within 50 km of the 2-year-old burn, black-backs were only detected in the burn and not in old-growth or mature conifer stands. However, they did occupy old coniferous stands located 75 and 150 km from the recent burn. They had a similar probability

of occupying stands in the 3-, 4-, and 8-year-old burns but were not detected in the 16-year-old burn. The persistence of three-toed woodpeckers in boreal Alberta will likely depend on the presence of both old-growth and recently burned coniferous forests or forests with old-growth structural characteristics. Black-backed woodpeckers appear to be more burn dependent than three-toeds, and their long term persistence may depend on the frequency of recently burned forests within their dispersal range.

Hunter, M. L. 1993. Natural fire regimes as spatial models for managing boreal forests. Biological Conservation 65: 115-120.

Because organisms have adapted to the natural disturbance regimes of forest ecosystems such as fires and windfalls, it has been suggested that timber harvesting systems be designed to imitate such regimes. In the case of boreal forests (shaped by crown fires that are frequent and of catastrophic intensity), this would result in very large clear fellings; in two studies, mean fire size was 12,710 ha (Labrador) and 7,764 ha (Quebec). A solution is proposed in which moderate-sized clear-felled areas are clustered into portions of land areas bounded by water bodies; these areas have an average size of 770 ha (Labrador) and 322 ha (Quebec).

Imbeau, L., J.-P. L. Savard, and R. Gagnon. 1999. Comparing bird assemblages in successional black spruce stands originating from fire and logging. Canadian Journal of Zoology 77: 1850-1860.

Comparisons of the effects of logging and fire as disturbance agents on the composition of bird assemblages in boreal ecosystems are still lacking or are limited to the short-term impacts of clear felling. In Quebec, Canada, where the boreal forest is largely dominated by black spruce stands, 140 point-count stations were surveyed in 3 post-logging and 4 post-fire development stages determined according to the height of the regenerating spruce trees. Bird species richness did not vary among forest development stages, but bird abundance was higher in recent clearcuts. Recently disturbed areas were characterized by open-land bird assemblages dominated by Neotropical migrants, which reached their highest abundance in clearcuts. Moreover, logged stands were distinguished from burned sites by the absence of cavity-nesting birds. Forest-bird assemblages reestablished themselves as soon as young spruces reached the sapling stage. However, the black-backed woodpecker, three-toed woodpecker, and brown creeper were restricted to mature stands or recent burns and are thus likely to be negatively affected by modern forestry, which involves fire suppression and short logging rotations. It is suggested that retention of larger areas of continuous mature forest might be essential to maintain these species in managed regions. [Results of this study include snag densities from young (black spruce regeneration < 2 m in height) and older post-fire and post-harvest sites.]

Johnson, E. A., and G. I. Fryer. 1987. Historical vegetation change in the Kananaskis Valley, Canadian Rockies. Canadian Journal of Botany 65: 853-858.

Data on forest vegetation from a survey in 1883 were compared with data collected in 1972 from this area in Alberta. Data on fire scars and tree ages were used to reconstruct the fire histories for 1783-1882 and 1883-1972. A transition probability matrix showed that sites occupied by lodgepole pine or Engelmann spruce in 1883 tended to support the same species in 1972. Fires were not more frequent after the beginning of European activity in 1883; average fire interval was 150 years. Fires were slightly larger during 1783-1882 than during 1883-1972. Results showed that European land use for timber, mineral and water resources allowed the topography and fire regimes to continue to determine the vegetation pattern.

Johnson, E. A., K. Miyanishi, and J. M. H. Weir. 1998. Wildfires in the western Canadian boreal forest: Landscape patterns and ecosystem management. Journal of Vegetation Science 9: 603-610.

Mimicking of natural disturbance for ecosystem management requires an understanding of the disturbance processes and the resulting landscape patterns. Since fire is the major disturbance in the boreal forest, three widely held beliefs about fire behaviour and resulting landscape patterns are examined in the light of the empirical evidence available. These beliefs are: (1) that there is a ‘natural’ fire frequency for boreal ecosystems; (2) that the landscape mosaic created by wildfire is generally one of small, younger patches embedded within a matrix of older forest; and (3) that forest flammability is largely controlled by fuel accumulation. Despite the apparently logical basis for such beliefs, they are not well

supported by empirical evidence. This discrepancy is explained by problems such as failure to appreciate the relationship between number of fires and area burned and inappropriate extrapolations or generalizations from other regions and vegetation types. The most important implications for management are that the natural disturbance processes producing landscape patterns in the boreal forest generally operate at much larger scales than management units, and that humans may have more indirect (through land use change) rather than direct (through fire suppression) effects on the frequency of wildfires.

Kachmar, M., and G. A. Sanchez-Azofeifa. 2003. Detection and analysis of post forest fire residuals using medium and high resolution satellite imagery. Sustainable Forest Management Network, University of Alberta, Edmonton, AB. Project Reports 2003/2004. http://sfm-1.biology.ualberta.ca/english/pubs/PDF/PR_200304sanchezazofeifaaunde7.pdf [date for public release: 24 January 2005].

[The goal of this project was to develop a protocol that will allow improved estimation of wildfire extent at higher resolutions and the quantification of post-fire residual areas (ie., patches of live forest within the boundaries of a burn). IKONOS and Landsat ETM+ (4- and 28.5-m spatial resolution, respectively) satellite imagery were applied in 1 of 2 recent burns (>100,000 ha) in northern Alberta, Canada. Using IKONOS imagery in the first burn (House River fire), the smallest residual class size (< 0-5 ha) contained more residual area while in the second burn (Chisholm fire) using Landsat imagery, the largest class size (> 80 ha) had the most residual area. These differences are likely reflective of the different spatial resolution of the imagery used. Many small residual patches in the Chisholm fire may have been classified as single patches using the coarser spatial resolution of the Landsat imagery.]

Kafka, V., S. Gauthier, and Y. Bergeron. 2001. Fire impacts and crowning in the boreal forest: Study of a large wildfire in western Quebec. International Journal of Wildland Fire 10: 119-127.

A spatial analysis of major wildfire was conducted to study the ecological impacts of wildland fires in the boreal forest. The fire covered nearly 500 km^2 in the northwestern part of Quebec's boreal forest, Canada (major tree species include black spruce and jack pine) during summer 1995. The spatial distribution of different fire impacts on the forest canopy was obtained using timber damage assessment maps. Fire impacts varied throughout the burned area, ranging from areas where trees had completely burned crowns (43%) to remaining patches of trees with green foliage (3%). The effects of local stand and site factors on crown fire, as assessed by the fire impacts, were evaluated using geographic information systems. Despite the large extent and high intensity of the wildfire created by extreme fire weather conditions, stepwise logistic regression and analysis by log-linear models indicated that variations in surface material, stand composition, and estimated stand age played a role in the presence or absence of crowning at the stand level. However, it appears that height and density of stand, as well as topography, did not have a significant influence. Our study presents the variability of fire impacts and its implications, and it provides a better understanding of the relationships between landscape components and fire crowning.

Kasischke, E. S., D. Williams, and D. Barry. 2002. Analysis of the patterns of large fires in the boreal forest region of Alaska. International Journal of Wildland Fire 11: 131-144.

Analyses of the patterns of fire in Alaska were carried out using 3 different data sets, including a large-fire database dating back to 1950. Analyses of annual area burned statistics illustrate the episodic nature of fire in Alaska, with most of the area burning during a limited number of high fire years. Over the past 50 years, high fire years occurred once every 4 years. Seasonal fire statistics indicated that high fire years consist of larger fire events that occur later in the growing season. On a decadal basis, average annual area burned has varied little between the 1960s and 1990s. Using a geographic information system (GIS), the spatial distribution of fires (aggregated by ecoregions) was compared with topographic, vegetation cover, and climate features of Alaska. The use of topographic data allows for a more realistic determination of fire cycle by eliminating areas where fires do not occur due to lack of vegetation above the treeline. Geographic analyses show that growing season temperature, precipitation, lightning strike frequency, elevation, aspect, and the level of forest cover interact in a complex fashion to control fire frequency.

Larivee, M. 2003. Effects of wildfire and clear-cutting on ground level spider assemblages in a boreal forest. M.Sc. Thesis, Carleton University, Ottawa, ON.

I examined how ground living spider assemblages respond to recently burned and recently cut black spruce forest stands inside the disturbed stands and at their edges in eastern Québec, Canada. My main objective was to determine if wildfire and clear-cutting affect the structure of the forest floor in different ways, resulting in different spider assemblages. Firstly, environmental variables associated with the structure of the forest floor were measured at every site and beside each trap along the edge transects. Over 9000 individuals from 124 species of spiders were identified throughout the study. Burned stands had higher shrub cover, less coarse woody debris and thicker litter and moss-lichen substrate with an overall more homogenous forest floor structure than the clear-cut stands. Correspondence analysis showed that the composition of the spider assemblages was different in all 3 types of stand. Spider abundance and alpha diversity (mean richness per site) of hunting spiders were highest in the clear-cut sites, which also had the lowest species turnover between stands. Environmental variables at the edges of wildfire and clear-cut stands did not differ in their response to the edge but a slightly more abrupt change in the ground-level spider assemblages was detected at the clear-cut edges through correspondence analyses. The depth of edge influence created by both disturbances on open and interior habitat spider guilds was approximately 30 m on each side of the edge. I discuss the implications of my results in the context of sustainable management of boreal forests. [Results of this study include snag (> 1.5 m in height) and stump (< 1.5 m) densities 2 years post-fire and post-harvest in stands dominated by black spruce with balsam fir].

Lee, P. 1998. Dynamics of snags in aspen-dominated midboreal forests. Forest Ecology and Management 105: 263-272.

Data from the Alberta Lands and Forest Service permanent sample plots (PSP) were analysed to determine densities, size distributions, input rates, falldown rates, and longevity patterns of snags (• ?10 cm dbh) within aspen-dominated boreal forests in Alberta. The mean density of snags in 20 to 39 year old stands was 18.1 snags·ha^{-1} increasing to 61.6-99.8 snags·ha^{-1} in stands up to 100+ yr old. In general, size distributions of trees and snags exhibited a reverse J-shaped size distribution. In stands < 40 yr old, size distributions of snags lagged behind trees. However, as the stand aged and self-thinning of small trees was supplemented by the death of canopy codominants, the size distribution of snags began to increasingly overlap with that of trees. Overall snag input rates varied from 0.08 to 8.2% of trees per annum, with larger values associated with older stands and/or smaller trees. Snag falldown rates varied from 9 to 21% of snags per annum depending upon stand age. Falldown rates exhibited a U-shaped pattern with rates decreasing in 60 to 79 year old stands. Snag longevity patterns exhibited a negative sigmoidal shape with an initial period of relative stability for approximately 5 years after death, and afterwards the probability of falldown increased with greatest falldown occurring between 10 and 20 years after death.

Lee, P. 2002. Forest structure after wildfire and harvesting. Pages 5-1 to 5-48 *in* S. J. Song (editor). Ecological basis for stand management: A synthesis of ecological responses to wildfire and harvesting. Alberta Research Council Inc., Vegreville, AB.

[This report chapter summarizes the results of a review of the literature spanning boreal and sub-boreal forests of North America and Fennoscandia to compare the successional development of forest structure after wildfire and timber harvest. The review discusses residual patches, large trees, standing dead trees, downed woody debris, cut block and residual edges, and riparian edges through various stages of stand development (initiation, establishment, old seral). The chapter concludes with a summary of findings, associated management implications, and knowledge gaps.]

Lee, P., and S. Crites. 1999. Early successional deadwood dynamics in wildfire and harvest stands. Pages 601-606 *in* T. S. Veeman, D. W. Smith, B. G. Purdy, F. J. Salkie, and G. A. Larkin (editors). Proceedings of the 1999 Sustainable Forest Management Network Conference, Science and Practice: Sustaining the Boreal Forest, February 14-17, 1999. Sustainable Forest Management Network, University of Alberta, Edmonton, AB.

This paper focuses on the dynamics of residual trees, snags, and downed woody materials (DWM) along a retrospective chronosequence of aspen-dominated wildfire (1 to over 120 years) and post-harvest (5-6%

residual) stands (1 to 28 years). Not surprisingly, densities/volumes and decay profiles of snags and DWM of wildfire and harvest stands exhibited their greatest differences immediately after disturbance. Consumption of the forest floor by wildfires resulted in lower amounts of DWD than in pre-burn stands. Fire-caused mortality of live trees produced a large initial pulse of snags, however, by 14 years many of these snags had fallen resulting in a pulse of DWM. In contrast, harvest stands exhibited an initial pulse of DWM produced by on-site timber processing, however, most of this pulse had declined by 28 years post-disturbance and was only being slowly replaced by residual trees and snags. Despite early successional differences, post-wildfire and post-harvest stands were converging in the densities/volumes and decay profiles of deadwood by 28 year old stands. However, significant differences still existed in the volume of DWM between wildfire and harvest stands. From a management perspective, leaving merchantable (• 10 cm DBH) and undersized non-merchantable trees at harvest were important factors in speeding the convergence of deadwood trajectories between wildfire and harvest stands.

Lee, P., C. Smyth, and S. Boutin. 2002. Large-scale planning of live treed residuals based on a natural disturbance-succession template for landscapes. Pages 13-1 to 13-21 *in* S. J. Song (editor). Ecological basis for stand management: A synthesis of ecological responses to wildfire and harvesting. Alberta Research Council Inc., Vegreville, AB.

[This report chapter discusses the difficulties of translating patterns occurring following wildfire into practical guidelines for landscape planning and presents a natural disturbance succession approach to leaving treed residuals over a post-harvest landscape. Relying on data mainly from 30 years of fire history in boreal forests in Alberta, Canada, it provides specific targets for residual area, size classes of residual area based on cut block size. Recommendations for spatial distribution of residuals are not provided due to lack of supporting information. The chapter concludes with a discussion of rationale for this approach, underlying assumptions, how to integrate the proposed templates with other conservation strategies, and supports the application of an adaptive management approach.]

Lee, P. C., S. Crites, M. Nietfeld, H. V. Nguyen, and J. B. Stelfox. 1997. Characteristics and origins of deadwood material in aspen-dominated boreal forests. Ecological Applications 7: 691-701.

This study examines the densities, physical structure, and origins of snags and downed woody material (DWM) in young (20-30 years), mature (50-65 years), and old (120 + years) stands in aspen dominated boreal forests in northeastern Alberta, Canada. Nearest neighbour and line intercept techniques were used to sample trees, snags, and DWM. Overall snag densities (• ?10 cm dbh) were greater in mature and old stands. Overall coarse DWM (• 11 cm diameter) counts were greater in young and old stands; volume of coarse DWM was greater in old stands. Analysis of spatial components of variation suggested that fires produced initially heterogeneous patterns in the densities of trees and dead woody material. The degree of spatial heterogeneity within and among stands decreased as stands developed to maturity. As a stand developed from maturity to old age, densities of trees and dead woody material retained spatial homogeneity within stands; however, they became more heterogeneous among stands. Comparisons of size distributions and decay patterns indicated that in young stands approximately 19.1 ± 13.0 snags·ha^{-1} (53.9%) and 48.5 ± 11.9 $m^3 \cdot ha^{-1}$ of coarse DWM (79.2%) were derived from the pre-fire cohort of trees. Mature stands had 3.8 ± 4.0 snags·ha^{-1} (5.8%) pre-fire snags. However, 50.4 ± 6.4 $m^3 \cdot ha^{-1}$ coarse DWM were classified as pre-fire in origin (65.7%). In old stands, snags and coarse DWM were probably generated from the post-fire cohort of trees. In general, the diversity of sizes and decay patterns of snags and DWM within stands was largely due to the mix of pre-fire materials and the post-fire materials generated by self-thinning and senescence/death of large trees. To simulate some of the conditions that occur after natural disturbances such as wildfires, timber harvest strategies should, in part, attempt to maintain the biological legacy associated with deadwood materials.

Lefort, P., S. Gauthier, and Y. Bergeron. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. Forest Science 49: 509-521.

The fire history of two adjacent regions of the boreal forest, one characterized by logging (Ontario—510,000 ha) and the other by small scale agricultural activities (Quebec —140,000 ha), was studied before and after these regions were opened up to settlement in 1916. From a review of provincial forest fire records and the assessment of the age of fire-initiated forest stands, it appears that large fire were rare but occurred during the pre-settlement period on both sides of the border. After 1916, due to slash and burn activities, the agricultural region (Quebec) had proportionally about twice the burned areas and ten times more fires than the forestry region (Ontario). Despite differences in population density, road networks, and land use, fire size class occurrence did not differ between landscapes over time. However, the occurrence of fires larger than 100 ha, in 3 development phases (1916-1939; 1940-1969; 1970-1998) decreased in both regions from settlement to the present, particularly during the late phase (1970-1998) in the agricultural region. An analysis of fluctuations in the Canadian forest Fire Weather Index system (FWI), a rating of fire danger severity, showed major climatic stresses at the beginning of the century (1916-1924), followed by a decrease in the occurrence of extreme FWI values. Combined with the impact of climate, which affected the annual area burned and the number of large fires in both landscapes, the results suggest that the landscape fragmentation, the increase in the percentage of deciduous trees over time and/or effective fire detection by residents led to a decrease in the number of fires larger than 100 ha on the agricultural side for the late phase (1970-1998).

Li, C. 2000. Fire regimes and their simulation with reference to Ontario. Pages 115-140 *in* A. H. Perera, D. L. Euler, and I. D. Thompson (editors). Ecology of a Managed Terrestrial Landscape: Patterns and Processes of Forest Landscapes in Ontario. UBC Press, Vancouver, BC.

[This book chapter provides an overview of the nature of fire disturbance and the role of fire in the development of forest landscapes. First the terminology associated with fire regimes including fire frequency, fire cycle, fire size and distribution, fire intensity and severity, is defined, followed by a summary of the ecological role of fire in boreal forests. Fire regimes in the boreal forest of Ontario, Canada are used as a basis for discussing the influence of biotic and abiotic factors on fire regimes. Methods of reconstructing natural fire regimes, such as historical or empirical reconstruction and simulation modelling, are described. A case study compares fire regimes developed using the model ON-FIRE with those from empirical data in Ontario and shows how this information can be used in policy and planning.]

Li, C. 2004. Simulating forest fire regimes in the foothills of the Canadian Rocky Mountains. Pages 98-111 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating Natural Forest Landscape Disturbances: Concepts and Applications. Columbia University Press, New York, NY.

[This book chapter provides an analysis of forest fire regimes in Alberta, Canada. Analysis results based on empirical data characterize fire patterns, including fire size, distribution, and cycle observed under fire suppression. These are compared with simulation modelling results, from analyses using SEM-LAND (Spatially Explicit Model for LANdscape Dynamics) for an area of Weldwood's forest management area in west-central Alberta, to demonstrate the model's ability to predict natural fire patterns. The model is outlined briefly and results are discussed in relation to the uses of various fire regime reconstruction methods in forest management.]

Li, C., I. G. W. Corns, and R. C. Yang. 1999. Fire frequency and size distribution under natural conditions: A new hypothesis. Landscape Ecology 14: 533-542.

Decisions for sustainable forest resource management require a better understanding of forest dynamics as a result of disturbances. Forest fires are one of the major types of natural disturbances in many forest landscapes. Existing fire regime models can be used in evaluating the influence of a fire regime on landscape dynamics, but these models require users to define fire frequency and its size distribution as separate characteristics of a fire regime before running the models. By using a theoretical long-term spatial fire regime model, the hypothesis that fire frequency and its size distribution are correlated with each other under natural conditions was tested. Input data on the annual number of fire ignition sources for the model were obtained by a stochastically simulated time series, based on analyses of temporal fire ignition sources of lightning-caused fires in Alberta and NW Ontario (Canada) that indicated a 3.3-3.6 year cyclic pattern. The results demonstrated that the hypothesis cannot be rejected and that the correlation between fire frequency and its size distribution was robust. Thus, the natural fire size distribution can be estimated when the fire return interval for a given forest landscape is known, if the natural fire size distribution can be approximated by a negative exponential probability distribution. This result simplifies the description of a fire regime from two parameters to one in some existing fire regime models. This simplification is limited to a 'let burn' scenario.

Li, C., M. Ter-Mikaelian, and A. Perera. 1997. Temporal fire disturbance patterns on a forest landscape. Ecological Modelling 99: 137-150.

Potential temporal fire disturbance patterns on a forest landscape were investigated using a fire regime model with four different fire probability functions: (1) forest age-independent; (2) hyperbolic increase with forest age; (3) sigmoidal increase with age; and (4) linear increase with age. Different combinations of parameter values for a logistic equation were used to approximate different fire probability functions. An extensive model behaviour study suggested that fire regimes similar to the observations in Ontario could result from any of the fire probability functions, but with different parameter values. Simulation results on the case study area indicated that when the fire rotation period was fixed to 200 years (corresponding to fire regimes in the southern part of northwestern Ontario), the predicted temporal disturbance patterns (average interval between two successive fires) were similar for small and intermediate fires, but different for large and severe fires. The results from the fire probability function with a sigmoid shape appeared the most appropriate among the four tested fire probability functions. The average interval between two successive fires for each size group is: small fires every 5.8 years, intermediate fires every 34.4 years, and large fires every 151.6 years. Better prediction of a temporal disturbance pattern, especially for large and severe fires, will require an explicit understanding of the quantitative relationship between fire probability and forest age.

Lyon, L. J. 1977. Attrition of lodgepole pine snags on the Sleeping Child burn, Montana. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. Research Note INT-219.

Following 2 years with little windthrow, snags on the Sleeping Child Burn fell at an annual rate of 13.4 percent. Snags < [7.6 cm] dbh fell at a rate of 27.9% and nearly all were down in 15 years. Snags larger than [7.6 cm] fell at an annual rate of 8.4%, but those larger than [20.3 cm] fell sporadically. At current rates, all snags will fall within the next 40 years; however, a few larger snags with a lower probability of windthrow will stand indefinitely.

McRae, D. J., L. C. Duchesne, B. Freedman, T. J. Lynham, and S. Woodley. 2001. Comparisons between wildfire and forest harvesting and their implications in forest management. Enviromental Reviews 9: 223-260.

Emulation silviculture is the use of silvicultural techniques that try to imitate natural disturbances such as wildfire. Emulation silviculture is becoming increasingly popular in Canada because it may help circumvent the political and environmental difficulties associated with intensive forest harvesting practices. In this review we summarize empirical evidence that illustrates disparities between forest harvesting and wildfire. As a rule, harvesting and wildfire affect biodiversity in different ways, which vary a great deal among ecosystem types, harvesting practices, and scale of disturbance. The scales of disturbance are different in that patch sizes created by logging are a small subset of the range of those of wildfire. In particular, typical forestry does not result in the large numbers of small disturbances and the small number of extremely large disturbances created by wildfires. Moreover, the frequency of timber harvesting is generally different from typical fire return intervals. The latter varies widely, with stand-replacing fires occurring in the range of 20 to 500 years in Canada. In contrast, harvest frequencies are dictated primarily by the rotational age at merchantable size, which typically ranges from 40 to 100 years. Forest harvesting does not maintain the natural stand age distributions associated with wildfire in many regions, especially in the oldest age classes. The occurrence of fire on the landscape is largely a function of stand age and flammability, slope, aspect, valley orientation, and the location of a timely ignition event. These factors result in a complex mosaic of stand types and ages on the landscape. Timber harvesting does not generally emulate these ecological influences. The shape of cut blocks does not follow the general ellipse pattern of wind driven fires, nor do harvested stands have the ragged edges and unburned patches typically found in stand-replacing fires. Wildfire also leaves large numbers of snags and abundant coarse woody debris, while some types of harvesting typically leave few standing trees and not much large debris. Successional pathways following logging and fire often differ. Harvesting tends to favour angiosperm trees and results in less dominance by conifers. Also, understory species richness and cover do not always recover to the preharvest condition during the rotation periods used in typical logging, especially in eastern Canada and in old-growth forests. As well, animal species that depend on conifers or old-growth forests are affected negatively by forest harvesting in ways that may not occur after wildfire. The road networks developed for timber extraction cause erosion, reduce the areas available for reforestation, fragment the landscape for some species and ecological functions, and allow easier access by humans, whereas there is no such equivalency in a fire-disturbed forest.

Miyanishi, K., and E. A. Johnson. 2001. Comment - A re-examination of the effects of fire suppression in the boreal forest. Canadian Journal of Forest Research 31: 1462-1466.

A report by P. C. Ward and A. G. Tithecott (Ontario Ministry of Natural Resources, Aviation, Flood and Fire Management Branch, Publ. 305, 1993) is frequently cited in the literature as providing evidence of the effects of fire suppression on the boreal forest. The study is based on 15 years of fire and stand age data from Ontario, Canada. A re-examination of this report reveals serious flaws that invalidate the conclusions regarding effects of fire suppression on fire size and fire frequency. The fire-size data from the unprotected zone are censored in the small size classes because of detection resolution, thus invalidating comparisons of shapes of the distributions between the protected and unprotected zones. Use of different plotting scales gives the false appearance of large differences in the number of large fires between the two zones. Stand age data are used to show a change in fire frequency in the 20th Century, and this change is attributed to fire suppression. However, no evidence is presented to support the conclusion that this change in fire frequency is attributable to fire suppression, and not to climate change. The estimate of the current fire cycle is based on too short a record to give a reliable estimate, given the variation in annual area burned. Therefore, this report does not present sound evidence of fire suppression effects and should not be cited as such.

Morissette, J. L., T. P. Cobb, R. M. Brigham, and P. C. James. 2002. The response of boreal forest songbird communities to fire and post-fire harvesting. Canadian Journal of Forest Research 32: 2169-2183.

Post-fire timber harvesting (salvage logging) is becoming more prevalent as logging companies try to recover some of the economic losses caused by fire. Because salvaging is a relatively new practice and because of the common perception that burned areas are of little value to wildlife, few guidelines exist for salvaging operations. We surveyed birds in unburned and burned stands of jack pine, mixedwood, and trembling aspen to characterize the post-fire bird community in commercially important forest types. The effects of salvage logging were examined in mixedwood and jack pine. Using fixed-radius point counts, a total of 1,430 individuals representing 51 species were detected during this study. Community analysis revealed that burned forests supported a distinct species assemblage of songbirds relative to unburned forests and that salvage logging significantly altered this community. An examination of guild composition showed that resident species, canopy and cavity nesters, and insectivores were the least likely to be detected in salvaged areas. Species less sensitive to salvage logging tended to be habitat generalists, omnivores, and species that nest on the ground or in shrubs. We suggest alternative management strategies that may help reduce the impact of salvage logging on the boreal forest songbird community. [Results of this study include percent cover of downed woody material 3 years post-fire in burned mixedwood and jack pine sites.]

Nakamura, N., P. M. Woodard, and L. Bach. 2003. Splitting in fire-killed trees in the boreal forest of Alberta. Northern Journal of Applied Forestry 20: 167-174.

Tree boles in the boreal forests of Alberta, Canada, will split once killed by a stand-replacing crown fire. A total of 1485 fire-killed trees were sampled, 1 year after burning, in 23 plots in 14 widely separated stands within a 370,000 ha fire. Sampling occurred in the Upper and Lower Foothills natural subregions. The frequency of splitting varied by species but averaged 41% for all species. The order in the frequency of splitting was balsam fir > black spruce > white spruce > lodgepole pine. The type of splitting (straight, spiral, or multiple) varied by species, as did the position of the split on the tree bole. Aspect or solar angle was not statistically related to the type or occurrence of splitting. [Results of this study include an average and range of fire-killed tree densities in severely burned stands 1 year after fire].

Nappi, A., P. Drapeau, J.-F. Giroux, and J.-P. L. Savard. 2003. Snag use by foraging black-backed woodpeckers (*Picoides arcticus*) in a recently burned eastern boreal forest. Auk 120: 505-511.

We studied snag use for foraging by Black-backed woodpeckers one year after a fire in an eastern black spruce boreal forest in Quebec, Canada. We searched for signs of foraging (bark flaking and excavation holes) by Black-backed Woodpeckers on 6,536 snags sampled in 56 plots located in portions of the burned forest that had not been salvage logged. A logistic regression model was developed based on the presence or absence of foraging signs. Results showed that Black-backed woodpeckers used larger snags that were less deteriorated by fire (qualified as high-quality snags). Direct field observations of individuals foraging on 119 snags also indicated that used snags corresponded to those of high predicted quality. Finally, we assessed the relationship between food availability and snag characteristics by measuring the density of wood-boring beetle larvae holes on 30 snags of different size and deterioration classes. High-quality snags contained higher prey densities (wood-boring beetle holes) than smaller and more deteriorated snags. We recommend that forest blocks characterized by large and less deteriorated trees be preserved from salvage logging in recently burned boreal forests in northeastern North America. [Results of this study include the total number of snags present within plots approximately 1 year following a 12,540 ha burn].

Nappi, A., P. Drapeau, and J.-P. L. Savard. 2004. Salvage logging after wildfire in the boreal forest: Is it becoming a hot issue for wildlife? Forestry Chronicle 80: 67-74.

In recent years, the increase in wood demand, the reduction in the availability of timber resources and the northern expansion of timber harvesting along with the general perception that wildfires create ecological disasters, have favoured an increase in salvage logging in burned boreal forests. Concurrently, pioneer studies have shown that these post-fire forests may represent important habitats for several wildlife species and that intensive salvage logging, by removing standing snags, has several impacts on wildlife. However, the effects of salvage logging on biodiversity have yet to be considered in post-fire management plans. We examine the issue of salvage logging for wildlife in the boreal forest, with particular reference to Quebec as an example. We describe our current state of knowledge on the use of burned forests by some wildlife and on the impacts of salvage logging on these habitats. We conclude that snag retention at multiple spatial and temporal scales in recent burns, which will be salvage-logged, is a prescription that must be implemented to meet the principles of sustainable forest management and the maintenance of biodiversity in the boreal forest.

NSDEL. 2003. Preliminary assessment of the ecological impacts of the Wallace Lake Fire on Tobeatic Wilderness Area. Nova Scotia Environment and Labour, Environmental and Natural Areas Management Division, Protected Areas Branch, Halifax, NS. NSDEL Technical Note 0301.

In May 2003, a human-caused wildfire burned almost 600 ha of the Tobeatic Wilderness Area. The greatest ecological impact is at the landscape scale, where the fire has reduced the total area of the landscapes two largest forest patches, thus diminishing forest interior habitats. The fire also decreased connectivity and increased fragmentation of large contiguous forest patches in an already highly fragmented landscape. Local-level impacts are greatest in the high intensity burn areas. High-intensity areas and some moderately burned areas have greatly altered the maturity class structure and species composition of the forest. Local-level ecological processes and biodiversity are also affected by the fire.

OMNR. 1997. Forest management guidelines for the emulation of fire disturbance patterns - analysis results. Ontario Ministry of Natural Resources, Forest Management Branch, Sault Ste. Marie, ON. Unpublished Report.

[This report provides fire size frequency distribution's for Site Regions in Ontario's Boreal and Great Lakes-St. Lawrence (GLSL) forest regions, distances between fires (fire centre to centre) in the Boreal and GLSL forest regions, and post-fire residual area (insular and peninsular denotations) from fires in the Boreal forest region. The time period and number of fires from which analyses were conducted are provided.]

Payette, S., C. Morneau, L. Sirois, and M. Desponts. 1989. Recent fire history of the northern Quebec biomes. Ecology 70: 656-673.

The fire history of 54,000 km^2 of northern Quebec biomes (including (a) northern boreal forest, (b) southern and (c) northern forest-tundra, and (d) shrub tundra) was documented by examining size and dates of 20th Century wildfires using tree ring techniques. Results showed that pronounced south-north differences in fire properties existed, corresponding to climate and vegetation gradients. Fire frequency per biome decreased south-north from closed forest (0.7 $fire \cdot yr^{-1}$) to shrub tundra (0.4 $fire \cdot yr^{-1}$). Average fire size decreased south-north by 100-fold from approx. 8,000 ha in (a) to 80 ha in (d) while modal fire size was < 50 ha in each of the four biomes. Most fires (> 80%) in (c) and (d) were < 100 ha, and fires > 100,000 ha occurred only in (a) and (b). Less than 35% of all mapped fires in (a) were < 50 ha, but > 30% were > 1,000 ha. From south to north, the fire-free interval per biome was, respectively, approx. 2.6, 0.6, 0.6, and 2.2 year, data for (a) being overestimated. The largest burned areas were recorded in the 1950s throughout the biomes, probably associated with long-lasting drier and warmer conditions. The fire rotation period per biome, based on the percentage of burned areas during the 1920-84 period (or 1930-84 in tundra), increased south-north by 100-fold from 100 year in (a) to 9320 year in (d). The fire rotation period around the treeline was estimated to be >7800 year. Biome boundaries have developed and are maintained in response to fire by the ability of black spruce to seed and regenerate. Stability of northernmost conifer sites is maintained by the inability of patchy shrub and conifer cover in (c) and (d) to carry fire and the failure of trees to produce viable seeds in these two biomes. Present data suggest that the area is characterized by a much higher fire frequency than expected from the fire weather index and from calculated frequencies typical of vegetation-type studies. It is concluded that size of the study area is a key element in the determination of regional fire regimes. The ecological significance of natural fire rotation and post-fire regeneration in northern environments is discussed in a palaeoecological perspective.

Pedlar, J. H., J. L. Pierce, L. A. Venier, and D. W. McKenney. 2002. Coarse woody debris in relation to disturbance and forest type in boreal Canada. Forest Ecology and Management 158: 189-194.

We measured volume of coarse woody debris (CWD) in 3 mature forest types (conifer, mixed, and deciduous), and 2 disturbance types (burns and clearcuts, both formerly mixed forests) in a boreal landscape in northwestern Ontario, Canada. The main tree species in the study area are *Picea mariana*, *Pinus banksiana*, *Populus tremuloides*, *Abies balsamea*, *Betula papyrifera*, *Larix laricina* and *Thuja occidentalis*. The CWD levels in mixed (160.80 ± 15.43 $m^3 \cdot ha^{-1}$) and deciduous (105.29±14.05 $m^3 \cdot ha^{-1}$) forests were significantly higher than those measured in coniferous forests (17.81±4.64 $m^3 \cdot ha^{-1}$). Deadwood in these mature forests was predominantly downed material (i.e. logs) from a range of sizes and decay states. One-year-old burns, previously of mixedwood composition, had significantly more CWD (342.61 ± 60.60 $m^3 \cdot ha^{-1}$) than mature mixed forests (160.80 ± 15.43 $m^3 \cdot ha^{-1}$) and recent clearcuts (111.97 ± 35.14 $m^3 \cdot ha^{-1}$). The CWD in burns was primarily standing deadwood in the early stages of decay, while the bulk of CWD in clearcuts was made up of small pieces of recently downed material. Our findings underline the differences between burns and clearcuts with respect to CWD dynamics. We note the implications of this for boreal wildlife.

Perera, A. H., and D. J. B. Baldwin. 2000. Spatial patterns in the managed forest landscape of Ontario. Pages 74-99 *in* A. H. Perera, D. L. Euler, and I. D. Thompson (editors). Ecology of a Managed Terrestrial Landscape: Patterns and Processes of Forest Landscapes in Ontario. UBC Press, Vancouver, BC.

[This chapter examines Ontario's forest cover patterns from several spatial scales, as well as over a 45-year period. The main source of information is Landsat TM imagery and an extensive spatial database of forest fire and harvest. The spatial analyses were conducted using a 10 km x 10 km grid cell template, covering over 500,000 km^2. It reports that eco-regions of Ontario differ in their dominant forest cover types, in the proportion of young forest resulting from harvest, and spatial patterns of forest patches, but not in forest cover composition and diversity. In comparison to heavily urbanized southern Ontario, the managed forest zone in northern Ontario is not fragmented, or patchy. However, the amount of harvested area has increased from 1950s to mid-1990s, the area doubling every decade, while the total area burned by forest fires during the same decades remained constant. The amount of forest edge has increased almost exponentially during the 1980s and 1990s as a result of forest harvest. This trend is attributed to the move towards many clearcut blocks, increased road network, and other associated clearings. It cautions, however, that without adequate null models and benchmarks, trajectories and spatial patterns of land cover change cannot be interpreted completely.]

Perera, A. H., D. Yemshanov, F. Schnekenburger, D. J. B. Baldwin, D. Boychuk, and K. Weaver. 2004. Spatial simulation of broad-scale fire regimes as a tool for emulating natural forest landscape disturbance. Pages 112-122 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating Natural Forest Landscape Disturbances: Concepts and Applications. Columbia University Press, NY.

[The goal of this paper is to illustrate the use of a spatial simulation modelling method to characterize broad-scale fire disturbance regimes in boreal forests, as a null model for forest management purposes. Using BFOLDS (Boreal Forest Landscape Dynamics Simulator), which includes a process-based fire simulation sub-model and an empirical Markov-chain forest succession sub-model, a 200-yr fire regime was simulated in north-central Ontario over 2 M ha at a 1 ha spatial resolution. The simulations produced an average annual burn rate of 1.45 ± 0.03% (n=20); average fire size of 2,815 ± 42.6 ha; an average fire cycle of 69 years; and a fire size-class distribution that was negative exponential. Probability distributions constructed using simulation results showed that 60% fires were < 1000 ha, but accounted for only 1.6% of the burn area. Other reported results on fire regime include mean interval between fires, spatial distribution of fire probabilities, and probabilities of canopy and site aging. It contains a long discussion on applications of the simulated fire regime information in designing emulation strategies though forest management, also focusing on the sources of variability in fire regimes.]

Perron, N. 2003. Peut-on et doit-on s'inspirer de la variabilité naturelle des feux pour élaborer une stratégie écosystémique de répartition des coupes à l'échelle du paysage? Le cas de la pessière noire à mousses de l'ouest au Lac-Saint-Jean. [Is it possible and advisable to use models of natural fire variability to develop an ecosystem strategy for the distribution of clear cuts across the landscape? The case of a western spruce-moss stand in the Lac-Saint-Jean area]. [Ph.D. Thesis, Université Laval, Quebec, QC].

[Original in French. The study defines the background for an ecosystem strategy for the distribution of cuts in the western spruce-moss stands of the Lac-Saint-Jean area. A landscape-level analysis was used to develop a representation of recent disturbances, as well as to define the residual forest found there. Regionally, logging was the main cause of disturbance between 1973 and 1997, affecting 413,054 ha, compared to 205,635 ha attributed to fires. A large number of adjacent cutting areas resulted in vast clusters. Most cutting areas (74%) were between 501 and 9 296 ha, while most burned areas (79%) were between 39,122 and 44,750 ha. Cutting blocks were often adjacent while large fire areas were at least 10 to 55 kilometres apart. Spatial analyses using FRAGSTATS with Landsat images revealed several similarities among the disturbances. There was a similar proportion of residual forest among fire-based landscapes (7-37%)

and cutting-based landscapes (9-44%). Few residual forests were isolated within the fire-based landscape (0-8%) and cutting-based landscapes (0-14%). However, residual forests found in the cutting-based landscape was less fragmented and showed a more complex pattern than in the fire-based landscapes. Based on these observations, an ecosystem strategy for scattered clusters of cutting areas (SÉCAD) was developed to maintain the mosaic developed within the limits of natural variability. It focuses on the residual forest that should be maintained and it predicts the disappearance of forest blocks. It makes possible the creation of regeneration areas but restricts their size and increases their distribution over the land. As large regeneration areas are generally not well received by the public, mitigation measures have been planned. They aim mainly to improve the visual aspect to make these areas more socially acceptable. Finally, the implementation of SÉCAD plus will not be easy as it could conflict with legislation and lessen forestry opportunities.]

Romme, W. H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecological Monographs 52: 199-221.

Fire scar analysis in the 73 km^2 Little Firehole River catchment area showed evidence of 15 fires since 1600, of which 7 were major fires that burned > 4 ha, destroyed the existing forest and initiated secondary succession. Most of the upland forest area was burnt by large destructive fires in the middle and late 1700s. Fires since then have been small and infrequent. The subalpine plateaux of Yellowstone National Park appear to have a natural fire cycle of 300-400 years, in which large areas burn during a short period that is followed by a long relatively fire free period during which a highly flammable fuel complex redevelops. The study site appeared to be midway between major fires. The sequence of vegetation mosaics during the last 200 yr was reconstructed from fire history data. Indices of landscape diversity were computed, treating forest types and successional stages as taxa and incorporating components of richness, evenness and patchiness. Landscape diversity was greatest in the early 1800s, then declined during 70 years without major fires as even aged *Pinus contorta* forests developed. Two small fires and the effects of *Dendroctonus ponderosae* have increased landscape diversity during the last 50 years. These reconstructions suggest that the area has a nonsteady state ecosystem characterized by long-term cyclic changes in landscape composition and diversity. A simulation model showed that management policies of total fire exclusion or selective fire control would reduce the richness and patchiness of vegetation but would increase the evenness and reduce the magnitude of periodic fluctuations in overall diversity.

Rupp, T. S., A. M. Starfield, F. S. Chapin, III, and P. Duffy. 2002. Modeling the impact of black spruce on the fire regime of Alaskan boreal forest. Climatic Change 55: 213-233.

In the boreal biome, fire is the major disturbance agent affecting ecosystem change, and fire dynamics will likely change in response to climatic warming. We modified a spatially explicit model of Alaskan subarctic treeline dynamics (ALFRESCO) to simulate boreal vegetation dynamics in interior Alaska, USA. The model is used to investigate the role of black spruce ecosystems in the fire regime of interior Alaska boreal forest. Model simulations revealed that vegetation shifts caused substantial changes to the fire regime. The number of fires and the total area burned increased as black spruce forest became an increasingly dominant component of the landscape. The most significant impact of adding black spruce to the model was an increase in the frequency and magnitude of large-scale burning events (i.e., time steps in which total area burned far exceeded the normal distribution of area burned). Early successional deciduous forest vegetation burned more frequently when black spruce was added to the model, considerably decreasing the fire return interval of deciduous vegetation. Ecosystem flammability accounted for the majority of the differences in the distribution of the average area burned. These simulated vegetation effects and fire regime dynamics have important implications for global models of vegetation dynamics and potential biotic feedbacks to regional climate.

Sander, B. 2003. Post-fire structure and decomposition dynamics of coarse woody material in the western Canadian continental boreal forest. Ph.D. Thesis, University of Alberta, Edmonton, AB.

In the western Canadian continental boreal forest the structural properties and coarse woody material (CWM) fuel loads of different stages of early stand development (defined as tree seedling, tree sapling and young tree) were compared in aspen, jack pine and black spruce stands using a chronosequence approach.

Stand ages ranged from 8 to 57 years. Decomposition of the fire-originated CWM was measured as changes in wood density over time. Aspen sites had the highest average CWM fuel load of 21.4 $Mg \cdot ha^{-1}$. Jack pine had the lowest average fuel load of 2.65 $Mg \cdot ha^{-1}$. Black spruce stands had an average fuel load of 3.01 $Mg \cdot ha^{-1}$. Weighted, nonlinear regression was used to estimate parameter values for linear, exponential and sigmoidal decomposition functions of CWM wood density. The performances of the functions were compared using a secondary Akaike Information Criterion (AICc). Post-fire standing dead trees did not decompose significantly. For aspen CWM the sigmoidal function had the best fit as indicated by the lowest AICc (-8.395), followed by the linear and the exponential function. For jack pine CWM the AIC c of the linear and sigmoidal function were very similar (-10.978 and 10.551) and the exponential function had the highest value and the poorest fit. For black spruce CWM all equations performed poorly; the linear and exponential function had similar values of AICc (-20.732 and -19.876) whereas the sigmoidal function had the highest value. Variables influencing the moisture content of CWM like distance of the CWM from the ground and an estimated climate moisture index affected decomposition dynamics differently: CWM close to the ground decomposed faster than CWM elevated > 5 cm off the ground, the effect of the climate moisture index was most pronounced in jack pine increasing the lag-term for decomposition. Proposed conceptual decomposition models identify the need for more quantitative data to improve breakdown functions of snags and the vertical distribution of CWM during the first decades after fire.

Schaeffer, J. A., and J. W. O. Pruitt. 1991. Fire and woodland caribou in southeastern Manitoba. Wildlife Monographs No. 116.

The effects of fire on the Aikens Lake population of woodland caribou were studied for 2 years. Quantity, quality and accessibility of forages were determined in areas burned 5, 37 and 90-160 years earlier. These measures were correlated with patterns of habitat use during winter. Principal components analysis showed that original floristic distinctions between jack pine and mixed forest communities persisted after fire. Compared with old-growth (90 years) stands, most burned upland habitats had enhanced productivity of summer forages, but reduced quality and accessibility of winter forages. Adaptations of caribou behaviour to the fire regime, which is probably necessary to maintain lichen resources, are discussed. [This monograph provides a reference to unpublished data (J. A. Schaeffer, p. 21) stating the fall rate of fire-killed trees 5.5 (49%) and 9.5 years (90%) following fire. The number of deadfalls·m^{-1} in burned areas of different ages are also provided.]

Schroeder, D., and A. H. Perera. 2002. A comparison of large-scale spatial vegetation patterns following clearcuts and fires in Ontario's boreal forests. Forest Ecology and Management 159: 217-230.

The role of wildfires as the most significant source of disturbance in boreal forests has been equaled by clearcuts during the past five decades. Post-disturbance revegetation patterns are important because they have a direct influence on many ecological processes. However, the knowledge of post-disturbance changes in spatial patterns of forest cover is scarce, especially at large scales. We examined spatial patterns of forest cover in a four-decade series of post-fire and post-clearcut landscapes in boreal forests in Ontario, Canada. Dense forest cover types consist of conifer, deciduous and mixedwood forests. A suite of indices was used to quantify spatial patterns of post-disturbance vegetation, based on Landsat TM imagery, and edaphic factors such as soil parent material, soil texture (includes sand, gravel, loam, silt and clay) and soil moisture. Indices were grouped in terms of patch geometry, contagion and composition. We used a general linear model to compare the effects of disturbance type, time since disturbance, edaphic conditions, and their interactions on these indices. Clearcuts produced more heterogeneous landscapes after disturbances in comparison to fires. Time since disturbance also had a significant effect on spatial patterns of vegetation: the older disturbances had more landcover types with higher interspersion. Edaphic conditions also significantly affected spatial patterns of vegetation. Landscapes with complex spatial patterns of edaphic conditions also had complex spatial patterns of vegetation.

Schulte, L. A., and D. J. Mladenoff. (In press). Severe wind and fire regimes in northern Wisconsin (USA) forests: Historical variability at the regional scale. Ecology (accepted).

We studied the spatial patterns of wind and fire disturbance regimes for the pre-Euroamerican settlement period (ca. 1850) in the northern Wisconsin, USA using the U.S. General Land Office original Public Land Survey (PLS) records. Heavy windthrow was generally more prevalent in these presettlement forests than fire disturbance, and was characterized by predominantly small (93-340 ha) patches that were complex in shape. Very large areas of severe blowdown did occur (~ 4,400 ha), and given the heterogeneous nature of windstorms in the region, multiple patches of windthrow were likely attributable to single windstorm events. In comparison, patches of stand-replacing fires were larger (144-587 ha), simpler in shape, and generally isolated to a few sub-areas of northern Wisconsin. Although the original PLS records represent only a single slice in time, their extensive nature provides a powerful baseline for addressing changes in forest conditions and disturbance regimes associated with climate and land use for both the present and more distant past. Such baselines are informative in discussions of historical variability and restoration silviculture.

Schulte, L. A., and G. J. Niemi. 1998. Bird communities of early-successional burned and logged forest. Journal of Wildlife Management 62: 1418-1429.

In studies near Tower, Minnesota, early-successional boreal forests created by fire or logging were surveyed for birds species and their habitat during the 1994 and 1995 breeding seasons. The overall bird species richness and number of individuals (territorial males·ha^{-1}) were higher in burned forests than in logged forests, but some individual species were more abundant in either logged or burned forests. The differences in bird presence and abundance were related to vegetation differences in the burned and logged habitat types. Burned areas had higher densities of dead trees, wider size ranges of dead trees, and greater heterogeneity in the shrub layer. Logged areas had higher densities of live trees, more live tree species, and a wider size range of live trees. Red maple was the live tree species found in greatest abundance in logged areas, while balsam fir was most abundant on burned areas. Management objectives for simulating natural fire regimes are suggested.

Serrouya, R., and R. D'Eon. 2004. Variable retention forest harvesting: Research synthesis and implementation guidelines. Sustainable Forest Management Network, University of Alberta, Edmonton, AB.

[This report provides an overview of variable retention forest harvesting including a synthesis of supporting experimental research and implementation guidelines. Rationale for variable retention is outlined followed by a brief discussion of post-fire residual patch size and a summary of responses of various ecosystem components including birds, small mammals, gastropods, and insects documented in Canadian boreal forests, mainly in three studies in British Columbia and one in Alberta. Future research to confirm the findings is recommended.]

Simard, A. J., and R. W. Blank. 1982. Fire history of a Michigan jack pine forest. Michigan Academician 15: 59-71.

Fire has always been part of jack pine ecosystems. Jack pine is reported to have developed cone serotiny several million years ago (Yeatman 1967). Examination of lake silt in the Boundary Waters Canoe Area (BWCA) in Minnesota disclosed high charcoal levels associated with a predominance of jack and red pine between 6,000 and 9,000 years ago (Swain 1972). The sediments indicate gradually decreasing charcoal levels associated with the transition to the present day Great Lakes and boreal forest communities. Swain (1972), when examining sediments accumulated over the past 1,000 years, found charcoal maxima in the BWCA at 1300 and 1400 AD, an 80-year peak between 1670 and 1750, and a subsequent decline to present day low levels. From this, Heinselman (1973) concluded that "fire was a major factor in northern Minnesota's forest ecosystems long before the arrival of European man." There is every reason to believe that the same holds true for the northern half of the Lower Michigan peninsula. [This publication presents the size frequency distribution of 692 fires (1960-1977) in an 189,000 ha area dominated by jack pine in the northern Lower Peninsula of Michigan.]

Simon, N. P. P., F. E. Schwab, and R. D. Otto. 2002a. Songbird abundance in clear-cut and burned stands: A comparison of natural disturbance and forest management. Canadian Journal of Forest Research 32: 1343-1350.

To evaluate the efficacy of forest management to emulate natural disturbance, we compared bird abundances among burned and clear-cut, former black spruce sites in Labrador, Newfoundland, Canada, after 5, 14, and 27 years of succession. Total bird density was lower in the clear-cut sites resulting from fewer hermit thrushes, yellow warblers, Swainson's thrushes, and fox sparrows. Hermit thrushes were positively correlated with snag density while yellow warblers and Swainson's thrushes were positively associated with deciduous tree cover and negatively correlated with conifer cover. Only yellow-rumped warblers had higher densities on clear-cut sites, likely due to greater conifer cover. Bird densities and species richness peaked in the 14-year-old burns and exceeded that of mature forests reported for Labrador. This demonstrates the importance of natural early successional forests for birds. Although logged areas support several species found in natural young burns, logging does not precisely mimic fire. This suggests that forest managers should allow some forests to burn naturally. [Results of this study include snag and live tree densities 5, 14, and 27 years post-fire.]

Simon, N. P. P., C. B. Stratton, G. J. Forbes, and F. E. Schwab. 2002b. Similarity of small mammal abundance in post-fire and clearcut forests. Forest Ecology and Management 165: 163-172.

To test the assumption that forest harvesting can maintain wildlife through emulating natural disturbance, we compared small mammal abundance between seven post-fire and nine clearcut plots representing three ages since disturbance (4, 14 and 27 years). On each site, two Victor snap traps were placed at 100 stations on 10 x 10 grids spaced 20 m apart. *Clethrionomys gapperi* were more abundant in clearcut plots, likely due to abundant coarse woody debris. This difference decreased through time. No other species differed between disturbance types. In both burned and clearcut plots, the abundance of *C. gapperi* was lowest on 14-year-old sites while *Microtus pennsylvanicus* and *Sorex cinereus* peaked at 14 years. At the meso-scale (plot-level), grass, herbs, and coarse woody debris explained 53% of the variation in small mammal abundance. At the micro-scale (individual trapsite), several variables showed statistical significance, yet only 13% of the variation in small mammals was explained. This was reduced to 4% when the spatial component of ecological variation was controlled. This suggests that our small mammals are coarse-grained foragers and fine-scale vegetation descriptions have little ability to explain small mammal abundance. We conclude that the coarse-filter approach to forest management by emulating natural disturbances can maintain small mammal communities in central Labrador. [Results of this study include percent cover of coarse woody debris 5, 14, and 27 years post-fire.]

Smyth, C. L. 1999. Overstory composition of live residuals in fire affected landscapes of northern Alberta. M.Sc. Thesis, University of Alberta, Edmonton, AB.

Natural disturbance processes, such as wildfire, are influenced by pre-disturbance landscape pattern, therefore pre-disturbance landscape information can be used to explain post-disturbance landscape pattern. This study investigates the relationship between pre-fire vegetation and the distribution of unburned residuals within twenty fire affected landscapes of the boreal forest of northern Alberta. Over one-third of the residuals included in the study contained a significantly greater proportion of deciduous, mixedwood, white spruce, or muskeg-dominated vegetation type than would be expected from random. The influence of vegetation on residuals varied between fires, ranging from 0 to 100% of the residuals associated with one of the four vegetation types considered. The percentage of residuals with a significantly greater proportion of deciduous, mixedwood, white spruce, or muskeg vegetation within a fire was positively correlated to fire size. The percentage of residuals associated with one of the four vegetation types was not correlated with annual area burned.

Stocks, B. J. 1991. The extent and impact of forest fires in northern circumpolar countries. Pages 197-202 *in* J. S. Levine (editor). Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, Cambridge, MA.

[This book chapter describes the extent of forest fires across the circumpolar region in the form of annual fire statistics presented in figures. Fire size class distributions are provided for Ontario by decade from 1920 through 1989. There has been a trend towards an increase in smaller fires (< 0.1 ha) and a decline in larger fires (4.1-40.0 ha, 40.1-200 ha, and > 200 ha). Fire size class distribution for Canada as a whole are provided (1970-85) and show that only 2-3 % of fires are > 200 ha but account for 97-98 % of the total area burned. Across the boreal forest there is much fluctuation in the annual area burned mostly due to extreme fire weather events.]

Stuart-Smith, K., and R. Hendry. 1998. Residual trees left by fire: Final report. BC Ministry of Forests, Invermere Forest District, Invermere, BC. Enhanced Forest Management Pilot Project Report No. 7.

[This report presents results of an analysis of post-fire residual area (live tree clumps, insulars, and skipped areas) from 10 fires (87 -2,909 ha size; 37-63 age) in the East Kootenays of southeastern British Columbia. Clumps were generally < 2 ha while insulars and skips were > 2 ha. Most skips would be considered peninsular as they were extensions into the burns from the surrounding contiguous forest. Insular residuals ranged in size from 2-100 ha overall, and averaged 10.4 ha (SD 6.1) in 7 of the fires (ESSFdk and MSdk biogeoclimatic zones). Peninsular residuals in 7 of the fires averaged 13.5 ha (SD 7.7).]

Stuart-Smith, K., I. T. Adams, and K. W. Larsen. 2002. Songbird communities in a pyrogenic habitat mosaic. International Journal of Wildland Fire 11: 75-84.

Wildfires play a key role in shaping the boreal forest landscape, yet the response of wildlife to the patchy mosaics they create is poorly understood. We studied songbirds 5-6 years post-fire in a large burn (9,600 ha) in the boreal mixedwood forest of north-eastern Alberta. In the spring of 1995 and 1996 we estimated abundance of songbirds in four areas, each with four replicate sites: unburned patches within the fire (Isolates); burned patches (Burns); patches that had been clear-cut prior to burning by wildfire (Cut-Burns); and the unburned, continuous forest adjacent to the burn (Peripherals). We also sampled shrub-based arthropods with sweep-nets at each site. To investigate the role of Isolates, we compared them to Peripherals and to Burns. We compared Cut-Burns to Burns to examine the effect of logging prior to burning. In general, Isolates supported higher numbers of species and individuals than Peripherals, mainly due to higher numbers of aerial-foraging birds. Isolates and Burns had similar species richness and abundance, but Burns supported more aerial foragers while Isolates had more foliage gleaners. Cut-Burns generally supported fewer individuals than Burns, in particular fewer shrub-nesters, aerial foragers, and neotropical migrants. More bird species reached their highest densities in Burns than in any other area. Songbird species richness and abundance were positively related to dry arthropod biomass, with Burns and Isolates having the highest arthropod biomass. These patterns indicated that, 5-6 years post-burn, the patchy mosaic created by this wildfire supported more species than the mature forest surrounding the fire. Clear-cut logging prior to burning resulted in a diminished songbird community compared to that found in burned stands.

Tinker, D. B., and D. H. Knight. 2000. Coarse woody debris following fire and logging in Wyoming lodgepole pine forests. Ecosystems 3: 472-483.

The accumulation and decomposition of coarse woody debris (CWD) are processes that affect habitat, soil structure and organic matter inputs, and energy and nutrient flows in forest ecosystems. Natural disturbances such as fires typically produce large quantities of CWD as trees fall and break, whereas human disturbances such as timber harvesting remove much of the CWD. Our objective was to compare the amount of CWD removed and left behind after clear felling to the amount consumed and left behind after natural fires in Rocky Mountains lodgepole pine. The masses of fallen logs, dead-standing trees, stumps, and root crowns more than 7.5 cm in diameter were estimated in clear felled and intact lodgepole pine forests in Wyoming, USA and compared to estimates made in burned and unburned stands in Yellowstone National Park (YNP), where no timber harvesting has occurred. Estimates of downed CWD consumed or converted to charcoal during an intense crown fire were also made in YNP. No significant differences in biomass of downed CWD more than 7.5 cm in diameter were detected between burned stands and those following a single clear felling. However, the total mass of downed CWD plus the mass of snags that will become CWD was nearly twice as high in burned stands than in clear felled. In YNP, approximately 8% of the downed CWD was consumed by fire and an additional 8% was converted to charcoal, for an estimated loss of about 16%. In contrast, approximately four times more wood (70%) was removed by clear felling. Considering all CWD more than 7.5 cm in diameter that was either still present in the stand or removed by harvesting, slash treatment, or burning, clear felled stands lost an average of 80 tonnes·ha^{-1} whereas stands that burned gained an average of 95 tonnes·ha^{-1}. Some CWD remains as slash and stumps left behind after harvesting, but stands subjected to repeated harvesting will have forest floor and surface soil characteristics that are beyond the historic range of variability of naturally developing stands.

Tinker, D. B., and D. H. Knight. 2001. Temporal and spatial dynamics of coarse woody debris in harvested and unharvested lodgepole pine forests. Ecological Modelling 141: 125-149.

Coarse woody debris (CWD) biomass was measured and mapped in burned, clear-felled, and intact lodgepole pine forests in two areas of the Rocky Mountains of Wyoming, USA: the Medicine Bow National Forest (MBNF) and Yellowstone National Park (YNP). In addition, the amount of CWD consumed or converted to charcoal by fire was estimated in a recently burned stand in YNP. A spatially explicit simulation model (DEADWOOD) was then created to simulate the effects of various clear felling and fire regimes on CWD over a 1,000-year period. Approximately 8% of downed CWD were consumed during a single fire and an additional 8% was converted to charcoal. After 1,000 years of simulation, 100-year fire-return intervals produced CWD that occupied more of the forest litter than did 200- or 300-year intervals. The time required for 100% occupancy of the forest litter by CWD was 1,125, 1,350, and 1,300 years for 100-, 200-, and 300-year fire-return intervals, respectively. Simulations suggest that current harvest and post-harvest slash treatment regimes will require at least four centuries longer for 100% of the forest litter to be occupied by CWD (1,800-3,600 years) than under fire regimes. This may have important effects on soil characteristics. Only when post-harvest CWD slash was doubled over the current amounts did clear felling leave sufficient CWD to maintain forest litter CWD within the historic range of variability for naturally developing post-fire stands.

Turner, M. G., and W. H. Romme. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9: 59-77.

Crown fires create broad-scale patterns in vegetation by producing a patch mosaic of stand age classes, but spread and behaviour of crown fires also may be constrained by spatial patterns in terrain and fuels across the landscape. In this review, implications of landscape heterogeneity for crown fire behaviour and the ecological effects of crown fires over large areas are discussed. Fine-scale mechanisms of fire spread can be extrapolated to make broad-scale predictions of landscape pattern by coupling knowledge obtained from mechanistic and empirical fire behaviour models with spatially-explicit probabilistic models of fire spread. Climatic conditions exert a dominant control over crown fire behaviour and spread, but topographic and physiographic features in the landscape and spatial arrangement and types of fuels have a strong influence on fire spread, especially when burning conditions (e.g. fuel moisture and wind) are not extreme. General trends in crown fire regimes and stand age class distributions can be observed across continental, latitudinal, and altitudinal gradients. Crown fires are more frequent in regions having more frequent and/or severe droughts, and younger stands tend to dominate these landscapes. Landscapes dominated by crown fires appear to be non-equilibrium systems. This non-equilibrium condition presents a significant challenge to land managers, particularly when implications of potential changes in global climate are considered. Potential changes in global climate may alter not only frequency of crown fires but also severity. Crown fires rarely consume the entire forest, and spatial heterogeneity of burn severity patterns creates a wide range of local effects and is likely to influence plant reestablishment as well as many other ecological processes. Increased knowledge of ecological processes at regional scales and effects of landscape pattern on fire dynamics should provide insight into understanding behaviour and consequences of crown fires.

Turner, M. G., W. W. Hargrove, R. H. Gardner, and W. H. Romme. 1994. Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. Journal of Vegetation Science 5: 731-742.

A map of burn severity resulting from the 1988 fires that occurred in Yellowstone National Park (YNP) was derived from Landsat Thematic Mapper (TM) imagery and used to assess the isolation of burned areas, the heterogeneity that resulted from fires burning under moderate and severe burning conditions, and the relationship between heterogeneity and fire size. About 80% of the park is covered with coniferous forests dominated by lodgepole pine. Most severely burned areas were close (50-200 m) to unburned or lightly burned areas, suggesting that few burned sites are very far from potential sources of propagules for plant re-establishment. Fires that occurred under moderate burning conditions early during the 1988 fire season resulted in a lower proportion of crown fire than fires that occurred under severe burning conditions later in the season. Increased dominance and contagion of burn severity classes and decreases in the edge:area ratio for later fires indicated a slightly more aggregated burn pattern compared to early fires. The proportion of burned area in different burn severity classes varied as a function of daily fire size. When daily area burned was relatively low, the proportion of burned area in each burn severity class varied widely. When daily burned area exceeded 1,250 ha, the burned area contained about 50% crown fire, 30% severe surface burn, and 20% light surface burn. Understanding the effect of fire on landscape heterogeneity is important because the kinds, amounts, and spatial distribution of burned and unburned areas may influence the reestablishment of plant species on burned sites.

Ward, P. C., and A. G. Tithecott. 1993. The impact of fire management on the boreal landscape of Ontario. Ontario Ministry of Natural Resources, Aviation, Flood and Fire Management Branch, Sault Ste. Marie, ON. Publication No. 305.

Fire is the primary natural process that takes boreal ecosystems from one state to another. It is the process that determines the structure of the forest, the size of stands, and, ultimately, forest-level diversity. Our perspective on fire effects has been shaped by our reaction to the impact of fire on a site or local area; elements of forest fuels, weather, and topography become the stage for a dramatic event with dramatic results. The great fires of the early part of this century brought Ontario into the modern age of fire suppression and, later, fire management. Indeed, our reaction to fires as devastating events catalyzed the beginnings of many forest management agencies including the Ontario Ministry of Natural Resources (OMNR). Often we become focused on these fire or stand level impacts and lose sight of the role of fire in the landscape; from the end of the last ice age until well into this century, fire was the dominant agent of change in the boreal landscape. Fire controlled the distribution of species in the boreal forest, favouring the existence of pioneer communities that are well adapted to fire. Jack pine, black spruce, and aspen are classic examples of disturbance-dependent species; they require no survivors for their successful regeneration after fire. It is from this landscape perspective that we must review the role of fire in shaping the distribution of species, stands, and forest communities. It is also from this perspective that we must evaluate the impact of efforts to manage fire in the landscape.

Ward, P. C., A. G. Tithecott, and B. M. Wotton. 2001. Reply - A re-examination of the effects of fire suppression in the boreal forest. Canadian Journal of Forest Research 31: 1467-1480.

P. C. Ward and A. G. Tithecott (Ontario Ministry of Natural Resources, Aviation, Flood and Fire Management Branch, Publ. (1993) 305) presented data that indicated that fire suppression activities in Ontario, Canada, led to reductions in average annual area burned and greater numbers of small fires, compared with what would have been observed in the absence of suppression. K. Miyanishi and E. A. Johnson (Can. J. For. Res. (2001) 31, 1462-1466) have questioned aspects of that report, suggesting that the evidence does not demonstrate that suppression influences fire size or frequency. Fire-history studies in Ontario's forests and recent fire disturbance records do show that the fire-return interval has lengthened considerably in Ontario's protected forest since pre-suppression times. Analysis of forest inventory age-class distributions also reflect a reduction in overall forest disturbance rates in the past 40 years. Average annual burn fractions (ABF) calculated for protected and unprotected forests in northwestern Ontario for the period 1976-2000 show an ABF of 1.11% in the unprotected forest and only 0.34% in the protected forest. There is clear evidence that fire suppression in Ontario contains many fires at small sizes that would have otherwise grown to larger sizes, and reduces the overall average annual area burned in the protected forest.

Wei, X., J. P. Kimmins, K. Peel, and O. Steen. 1997. Mass and nutrients in woody debris in harvested and wildfire-killed lodgepole pine forests in the central interior of British Columbia. Canadian Journal of Forest Research 27: 148-155.

Mass and nutrients in woody debris, including coarse (>2.5 cm diameter) and fine (< 2.5 cm diameter) woody debris, and wood decomposition rates were compared in harvested and wildfire-killed lodgepole pine forests in the central interior of British Columbia. The aim of the study was to address the concern that intensive timber harvesting may be having on long-term site productivity, in contrast to the effects of more natural disturbances such as fire. There were significant differences in the mass of above-ground coarse woody debris and total woody debris between harvested and wildfire-killed sites. However, there were no significant differences in these two variables between stem-only harvested and whole-tree harvested sites. Whole-tree harvesting removed more N and P (about 2-fold) than stem-only harvesting. Below-ground woody debris may be nutritionally important for stands growing on low-fertility sites because of its important contribution to the total woody debris and relatively high asymbiotic nitrogen fixation rates. Because of differences in size and position, coarse woody debris on the harvested sites decays more rapidly and persists for less time than that on the fire-killed sites. The nutrient removals caused by harvesting were within the estimated range of nutrient removals caused by wildfire.

Wein, R. W., and J. M. Moore. 1977. Fire history and rotations in the New Brunswick Acadian Forest. Canadian Journal of Forest Research 7: 285-294.

The number and size of fires, their causes, the distribution of fires through the year, fire rotations and the distribution of fires in different vegetation types were analysed from records for 1920-1975. The mean size of fires during the period has decreased from about 20 ha to 4 ha, whereas the number of fires has increased since 1960. Recreation activities caused 25% of fires; lightning accounted for only 7% and no large fires were caused by lightning in the higher parts of the province. The greatest number of fires occurred in May, particularly toward the end of the month. Mean and medium annual burns were 12,000 and 2,500 ha respectively. The most extensively burned vegetation type, red spruce/hemlock/pine, had a fire rotation of 230 years. Hardwood and high-altitude coniferous types had rotations of over 1,000 years.

Wein, R. W., and J. M. Moore. 1979. Fire history and recent fire rotation periods in the Nova Scotia Acadian Forest. Canadian Journal of Forest Research 9: 166-178.

Descriptive records of wildfires since the earliest writings and quantitative provincial fire records since 1915 have been used to produce a synthesis of fire history for the province of Nova Scotia, Canada. Large annual burns were common up to the mid-1930's. Annual burns totalling over 15,000 ha occurred in each of the years 1918, 1920, 1921, 1930, 1934, 1944, and annual burns totalling over 30,000 ha occurred in each of the years 1920 and 1921. Lightning has accounted for 1% of the number of fires (three per year). Thirty percent of the fires have occurred in the month of May; however, fires have been recorded for all months. Fire rotation periods for the province as a whole were 1,000 or 2,500 years, using the mean annual burn or median annual burn, respectively, for all burns in the years 1915 to 1975. In contrast, calculations of burned area on maps produced at the turn of the century gave pre-suppression fire rotation periods of just over 200 years. Vegetation types have had widely varying fire rotation periods. The vegetation of Cape Breton Island has been subjected to almost no fires over 20 ha, whereas the vegetation type with the shortest fire rotation period (in the interior of western Nova Scotia) has been subjected to fire rotation periods as low as 65 years at the turn of the century, to about 2,000 years for the years 1958 to 1975. A summary of fire rotation periods for the Boreal, Great Lakes-St. Lawrence, and Acadian Forest Regions found in the literature is presented for comparison with the Nova Scotia data, and more detailed comparisons are made between the fire rotation periods of the similar vegetation types in New Brunswick and Nova Scotia.

Weir, J. M. H. 1996. Fire frequency and age mosaic of a mixedwood boreal forest. M.Sc. Thesis, University of Calgary, Calgary, AB.

The mixedwood boreal forest is composed of a mosaic of different aged stands, produced by large infrequent fires that account for most of the area burned. This study uses a 3,461 km^2 time-since-fire map that resolves age patches as small as 5 ha to investigate the spatial pattern of the age patch mosaic and fire frequency of a mixedwood boreal forest in central Saskatchewan, Canada. The age patch mosaic is comprised of large, young, oblong patches that lie adjacent to one another and small, old, circular patches of remnant forest that are contained within more recent burns. The oldest patch in the study area last burned in 1760. From 1760 to 1890, the entire study area had a fire cycle of 25 years (95% CI: 15-40 years). However, between 1890 and 1945 the fire cycle of the north region increased to 75 years (95% CI: 45-140 years) while that of the south region remained 25 years. From 1945 to 1995 the fire cycle of the entire area increased to 645 years (95% CI: 200-4,270 years).

Zhang, Q., K. S. Pregitzer, and D. D. Reed. 1999. Catastrophic disturbance in the presettlement forests of the Upper Peninsula of Michigan. Canadian Journal of Forest Research 29: 106-114.

The General Land Office (GLO) survey notes (1840-56) were used to examine the interaction among natural disturbance, vegetation type, and topography in the presettlement forests of the Luce District, an ecological unit of approximately 902 000 ha in the Upper Peninsula of Michigan, USA. The surveyors recorded 104 fire and 126 windthrow incidences covering 3.1 and 2.8% of the total length of the surveyed lines, respectively. The rotation periods over the entire landscape were 480 years for fire and 541 years for windthrow, but these varied with vegetation type and topographic position. Fire occurred more frequently on southerly aspects and at elevations where pinelands were concentrated. The density of windthrow events increased with elevation and slope, with the highest occurrence on westerly aspects. Based on the estimated rotation periods, it was calculated that 7.5, 24.4, and 68.1% of the presettlement forest were in the stand initiation, stem exclusion, and old forest (including both understorey reinitiation and old-growth) stages, respectively. Pinelands and mixed conifers were the major components in both the stand initiation (34.5 and 31.1%) and the stem exclusion stage (20.9 and 39.8%), while mixed conifers (39.3%) and northern hardwoods (34.7%) were the major old-forest cover types. The diverse mosaic of various successional stages generated by natural disturbance suggests a 'shifting-mosaic' landscape in this region.

Appendix I.

List of contacts and responses from survey of ongoing studies related to NDPE Guide directions

A request for information about ongoing natural fire regime studies in boreal and Great Lakes forests was sent via e-mail and posted to listserv discussion groups.

a) Individuals contacted directly (*denotes email request sent twice, **bold** indicates respondents)

Andison, David (Bandaloop Landscape-Ecosystem Services, Belcarra, BC)

Baker, Jim (Ontario Ministry of Natural Resources (OMNR), Ontario Forest Research Institute, Sault Ste. Marie, ON)

*Baker, William (University of Wyoming, Laramie, WY)

*Barry, Dave (McGregor Model Forest, Prince George, BC)

Bergeron, Yves (University of Quebec, Montreal, PQ)

*Boutin, Stan (University of Alberta, Edmonton, AB)

Buchanan-Mappin, J. (Kananaskis Field Stations, c/o University of Calgary, Calgary, AB)

*Cumming, Steve (Boreal Ecosystems Research Ltd., Edmonton, AB)

*DeLong, Craig (BC Ministry of Forests, Prince George, BC)

Ehnes, James (Ecostem Ltd., Winnipeg, MB)

Elkie, Phil (OMNR, Thunder Bay Science and Technology Unit, Thunder Bay, ON)

*Flannigan, Mike (Natural Resources Canada, Great Lakes Forestry Centre, Sault Ste. Marie, ON)

Gauthier, Sylvie (Natural Resources Canada, Laurentian Forestry Centre, Sainte-Foy, PQ)

Glenn, Susan (University of BC, Vancouver, BC)

Gustafson, Eric (USDA Forest Service, Rhinelander, WI)

Hall, Ron (Natural Resources Canada, Northern Forestry Centre, Edmonton, AB)

Harvey, Brian (University of Quebec at Abitibi-Temiscaming, PQ)

Hawkes, Brad (Canadian Forest Service, Pacific Forestry Centre, Victoria, BC)

Hayes, Jane (USDA Forest Sevice, Pacific Northwest Research Station, Portland, OR)

*Hessburg, Paul (USDA Forest Service, Pacific Northwest Research Station, Portland, OR)

Hirsch, Kelvin (Natural Resources Canada, Northern Forestry Centre, Edmonton, AB)

*Johnson, Edward (University of Calgary, Calgary, AB)

Johnston, Mark (Saskatchewan Environment and Resource Management, Prince Albert, SK)

Kafka, Victor (Parks Canada, Hull, PQ)

Kayahara, Gordon (OMNR, Northeast Science and Technology Unit, South Porcupine, ON)

*Li, Chao (Natural Resources Canada, Northern Forestry Centre, Edmonton, AB)

*Lytle, David (USDA Forest Service, North Central Research Station, Grand Rapids, MN)

***MacLean, David (University of New Brunswick, Fredericton, NB)**

***Marshall, Peter (University of BC, Vancouver, BC)**

*Martell, David (University of Toronto, Toronto, ON)

McAlpine, Rob (OMNR, Aviation and Forest Fire Management Branch, Sault Ste. Marie, ON)

*Messier, Christian (University of Quebec at Montreal, Montreal, PQ)

*Miller, Carol (USDA Forest Service, Missoula, MT)

Mladenoff, David (University of Wisconsin, Madison, WI)

Naylor, Brian (OMNR, North Bay District Office, North Bay, ON)

Palik, Brian (USDA Forest Service, North Central Research Station, Grand Rapids, MN)

*Parisien, Marc-Andre (Canadian Forest Service, Northern Forestry Centre, Edmonton, AB)

*Parminter, John (BC Ministry of Forests, Victoria, BC)

Pinto, Fred (OMNR, North Bay District Office, North Bay, ON)

*Prince Albert Model Forest (Prince Albert, SK)

***Rempel, Rob (Lakehead University, Thunder Bay, ON)**

*Romme, William (Colorado State University, Fort Collins, CO)

Runesson, Ulf (Lakehead University, Thunder Bay, ON)

*Schmiegelow, Fiona (University of Alberta, Edmonton, AB)

Sickley, Ted (University of Wisconsin, Madison, WI)

*Spence, John (University of Alberta, Edmonton, AB)

*Spies, Thomas (USDA Forest Sevice, Pacific Northwest Research Station, Portland, OR)

***Stelfox, Harry (Alberta Sustainable Resource Development, Edmonton, AB) — Cordy Tymstra (Forest Protection Division, Dept. of Sustainable Res. Dev., Edmonton, AB) responded on his behalf**

Tithecott, Al (OMNR, Aviation and Forest Fire Management Branch, Sault Ste. Marie, ON)

Turner, Monica (University of Wisconsin, Madison, WI)

*Waldram, Mike (Manitoba Model Forest, Pine Falls, MB)

Watt, Bob (OMNR, Northeast Science and Technology Unit, South Porcupine, ON)

*Weetman, Gordon (University of BC, Vancouver, BC)

*Wein, Ross (University of Alberta, Edmonton, AB)

*Wotton, Mike (Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON)

Zasada, John (USDA Forest Service, North Central Research Station, Grand Rapids, MN)

b) Respondents from listserv discussion groups

Berg, Ed (US Fish and Wildlife Service, Soldotna, AK)

Carlson, Daren (Minnesota Department of Natural Resources, St. Paul, MN)

DiBari, John (Western Carolina University, Cullowhee, NC)

Johnstone, Jill (Yukon College, Whitehorse, YT)

Milne, David (Wildland Fire Management, Community Services, Whitehorse, YT)

Schneller, Robert (University of Wisconsin, Madison, WI)

Appendix II.

List of citations for literature related to natural fire disturbances in boreal and near-boreal forests in North America.

This list of citations contains the literature on boreal forest fire regimes. Of the 284 publications listed here, 104 have information relevant to NDPE Guide directions. Each citation includes a numerical notation in square brackets to indicate the specific guide criteria it addresses: [1] = fire size; [2] = spacing; [3] = residual area; and [4] = residual structure. Of these, the 48 in bold font are those containing original experimental evidence directly related to NDPE guide. The remaining 180 citations are fire regime-related literature not relevant to the NDPE Guide directions. Each includes a numerical notation in square brackets to indicate the general topical area it addresses: [A] = fire cycle, fire interval, fire frequency, fire history; [B] = forest age structure and succession as related to time-since-fire; [C] = climate change (effects on fire regimes); [D] = fire behaviour, fire growth modelling, and causal factors of fire growth; and [E] = detecting and mapping techniques of fire scars and modelling of fire occurrence.

Alexander, M. E. 1980. Forest fire history research in Ontario: A problem analysis. Pages 96-110 *in* M. A. Stokes and J. H. Dieterich (Technical Coordinators). Proceedings of the Fire History Workshop. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. General Technical Report RM-81. [A]

Alexander, M. E., J. A. Mason, and B. J. Stocks. 1977. Two and a half centuries of recorded forest fire history. Forestry Canada, Great Lakes Forest Research Centre, Sault Ste. Marie, ON. Leaflet. [A]

Amiro, B. D., and J. M. Chen. 2003. Forest fire scar aging using SPOT VEGETATION for Canadian ecoregions. Canadian Journal of Forest Research 33: 1116-1125. [D]

Anderson, K. R., D. L. Martell, M. D. Flannigan, and D. Wang. 2000. Modelling of fire occurrence in the boreal forest region of Canada. Pages 357-367 *in* E. S. Kasischke and B. J. Stocks (editors). Fire, Climate Change, and Carbon Cycling in the Boreal Forest. Springer-Verlag, New York, NY. [E]

Anderson, K. R., and D. X. Viegas. 2002. Fire growth modelling at multiple scales. Page 105 *in* Proceedings of the IV International Conference on Forest Fire Research, Wildland Fire Safety Summit, 18-23 November, Luso, Coimbra, Portugal. [D]

Andison, D. W. 1996. Managing for landscape patterns in the sub-boreal forests of British Columbia. Ph.D. Thesis, University of British Columbia, Vancouver, BC. [1]

Andison, D. W. 1998. Temporal patterns of age-class distributions of foothills landscapes in Alberta. Ecography 21: 543-550. [B]

Andison, D. W. 1999. Assessing forest age data in foothills and mountain landscapes of Alberta: Laying the groundwork for natural disturbance research. Bandaloop Landscape-Ecosystem Services, Coal Creek Canyon, CO. Alberta foothills disturbance ecology research series: Report No. 1. [B]

Andison, D. W. 2003a. Patch and event sizes on foothills and mountain landscapes of Alberta. Bandaloop Landscape-Ecosystem Services, Belcarra, BC. Alberta foothills disturbance ecology research series: Report No. 4. [1] [3]

Andison, D. W. 2003b. Disturbance events on foothills and mountain landscapes of Alberta: Part I. Bandaloop Landscape-Ecosystem Services, Belcarra, BC. Alberta foothills disturbance ecology research series: Report No. 5. [3]

Andison, D. W. 2003c. Surviving as an island remnant. Bandaloop Landscape Ecosystem Services, Belcarra, BC. Natural Disturbance Program Quicknote No. 18. [3]

Andison, D. W. 2003d. Surviving as a matrix remnant. Bandaloop Landscape Ecosystem Services, Belcarra, BC. Natural Disturbance Program Quicknote No. 22. [3]

Andison, D. W., and P. L. Marshall. 1999. Simulating the impact of landscape-level biodiversity guidelines: A case study. Forestry Chronicle 75: 655-665. [1]

Apfelbaum, S. I., and A. Haney. 1981. Bird populations before and after wildfire in a Great Lakes pine forest. Condor 83: 347-354. [4]

Apfelbaum, S. I., and A. Haney. 1986. Changes in bird populations during succession following fire in the northern Great Lakes wilderness. Pages 10-16 *in* Proceedings - National Wilderness Research Conference: Current Research. USDA Forest Service, Intermountain Research Station, Ogden, UT. General Technical Report INT-212. [4]

Armstrong, G. W. 1999. A stochastic characterisation of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. Canadian Journal of Forest Research 29: 424-433. [B]

Armstrong, G. W., W. L. Adamowicz, J. A. Beck, Jr., S. G. Cumming, and F. K. A. Schmiegelow. 2003. Coarse filter ecosystem management in a nonequilibrating forest. Forest Science 49: 209-223. [B]

Baker, W. L. 1989a. Effect of scale and spatial heterogeneity on fire-interval distributions. Canadian Journal of Forest Research 19: 700-706. [A]

Baker, W. L. 1989b. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. Ecology 70: 23-35. [1]

Baker, W. L. 1992. Effects of settlement and fire suppression on landscape structure. Ecology 73: 1879-1887. [1]

Baker, W. L. 1995. Long-term response of disturbance landscapes to human intervention and global change. Landscape Ecology 10: 143-159. [C]

Beall, H. W. 1946. Forest fires and fire-hazard records in the mid-west national parks. Forestry Chronicle 22: 135-137. [D]

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992. [1]

Bergeron, Y. 2000. Species and stand dynamics in the mixed woods of Quebec's southern boreal forest. Ecology 81: 1500-1516. [B]

Bergeron, Y., and D. Gagnon. 1987. Age structure of red pine (*Pinus resinosa* Ait.) at its northern limit in Quebec. Canadian Journal of Forest Research 17: 129-137. [B]

Bergeron, Y., and J. Brisson. 1990. Fire regime in red pine stands at the northern limit of the species' range. Ecology 71: 1352-1364. [D]

Bergeron, Y., and S. Archambault. 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the 'Little Ice Age'. Holocene 3: 255-259. [C]

Bergeron, Y., and P.-R. Dansereau. 1993. Predicting the composition of Canadian southern boreal forest in different fire cycles. Journal of Vegetation Science 4: 827-832. [A]

Bergeron, Y., and M. D. Flannigan. 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water, Air, and Soil Pollution 82:437-444. [C]

Bergeron, Y., and A. Leduc. 1998. Relationships between change in fire frequency and mortality due to spruce budworm outbreak in the southeastern Canadian boreal forest. Journal of Vegetation Science 9: 492-500. [A]

Bergeron, Y., S. Gauthier, V. Kafka, P. Lefort, and D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: Consequences for sustainable forestry. Canadian Journal of Forest Research 31: 384-391. [A]

Bergeron, Y., B. Denneler, D. Charron, and M. P. Girardin. 2002a. Using dendrochronology to reconstruct disturbance and forest dynamics around Lake Duparquet, northwestern Quebec. Dendrochronologia 20: 175-189. [A]

Bergeron, Y., A. Leduc, B. D. Harvey, and S. Gauthier. 2002b. Natural fire regime: A guide for sustainable management of the Canadian boreal forest. Silva Fennica 36: 81-95. [1] [3]

Bergeron, Y., S. Gauthier, M. Flannigan, and V. Kafka. In press. Fire regimes at the transition between mixedwood and coniferous boreal forest in Northwestern Quebec. Ecology (accepted). [1]

Bessie, W. C., and E. A. Johnson. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76: 747-762. [D]

Beverly, J. L. 1998. Management and history of fire in Wabakimi Provincial Park, northwestern Ontario. M.Sc. Thesis, University of Toronto, Toronto, ON. [A]

Bonan, G. B., and H. H. Shugart. 1989. Environmental factors and ecological processes in boreal forests. Annual Review of Ecology and Systematics 20: 1-28. [A]

Bonar, R. L., H. Lougheed, and D. W. Andison. 2003. Natural disturbance and old-forest management in the Alberta Foothills. Forestry Chronicle 79: 455-461. [B]

Bormann, F. H., and G. E. Likens. 1979. Catastrophic disturbance and the steady state in northern hardwood forests. American Scientist 67: 660-669. [A]

Bourgeau-Chavez, L. L., E. S. Kasischke, S. Brunzell, J. P. Mudd, and M. Tukman. 2002. Mapping fire scars in global boreal forests using imaging radar data. International Journal of Remote Sensing 23: 4211-4234. [E]

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