Disturbance Events on Foothills and Mountain Landscapes of Alberta

Part I

Alberta Foothills Disturbance Ecology Research Series
Report No. 5

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DISCLAIMER

foothills MODEL FOREST
research growing into practice.

Foothills Model Forest is one of eleven Model Forests that make up the Canadian Model Forest Network. As such, Foothills Model Forest is a non-profit organization representing a wide array of industrial, academic, government and non-government partners, and is located in Hinton, Alberta. The three principal partners representing the agencies with vested management authority for the lands that comprise the Foothills Model Forest, include Weldwood of Canada Ltd. (Hinton Division), Alberta Sustainable Resource Development and Jasper National Park. These lands encompass a combined area of more than 2.75 million hectares under active resource management.

The Canadian Forest Service of Natural Resources Canada is also a principal partner in each of the eleven Model Forest organizations and provides the primary funding and administrative support to Canada's Model Forest Program.

The Foothills Model Forest mission: We are a unique partnership dedicated to providing practical solutions for stewardship and sustainability on Alberta forestlands. What we learn will be:

- reflected in on-the-ground practice throughout Alberta and elsewhere in Canada, where applicable
- incorporated in forest and environmental policy and changes;
- widely disseminated to and understood by a broad spectrum of society.

This will be the result of a solid, credible, recognized program of science, technology, demonstration and outreach.

ACKNOWLEDGEMENTS

This research was possible only through the hard work and dedication of many individuals. First and foremost, Weldwood of Canada Ltd. (Hinton Division), Jasper National Park, the Canadian Forest Service, Alberta Newsprint Company, Weyerhaeuser Company Ltd., Alberta Sustainable Resource Development, and the Alberta Forest Products Association generously supported the natural disturbance research presented in this report.

The Foothills Model Forest (FtMF) Natural Disturbance Program was the vision of two individuals: Hugh Lougheed from Weldwood of Canada Ltd., and Dan Farr, then with the Foothills Model Forest. Since then, the unflagging support of the FtMF Natural Disturbance activity team is reflected in the thoroughness of the research, and quality of the data. I would like to thank Dan, Hugh, Gord Stenhouse (then with Weldwood), George Mercer, Al Westhaver and Dave Smith from Jasper National Park, Don Harrison, Herman Stegehuis, and Bob Anderson from Alberta Sustainable Resource Development, Greg Branton from Alberta Newsprint Company, and Rick Blackwood, Mark Storie and Don Podlubny from the Foothills Model Forest for their perpetual faith and support. Also, many thanks to the FtMF Board of Directors, and in particular Bob Udell, for their unrelenting belief in the Natural Disturbance Program.

The FtMF Natural Disturbance Program was fortunate to inherit some exceptional raw age data thanks mostly to the vision and efforts of Jack Wright, formerly of Weldwood of Canada Ltd, and Gerald Tande, who did his graduate work in Jasper National Park. These data were complimented by the meticulous work of MP Rogeau who coordinated all of our outstanding stand-origin sampling and mapping. Kim MacLean was instrumental in putting together the island remnants database and some preliminary analysis. Christian Weik of the FtMF has also been instrumental in providing any and all forms of GIS support to our research program in general, and these data in particular.

To the numerous field crews who tirelessly cut and cored trees across the FtMF, and sanded and counted rings on those rainy days, thank you for your efforts. Also, thanks to Kris McCleary for constructive input and assistance throughout the process, and Dr. Bill Baker for providing valuable input during the early stages of these projects.

EXECUTIVE SUMMARY

This fifth report in the FtMF 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

Using an extensive and highly detailed set of data collected, mapped, and digitized over several years on historical fires, this report poses and answers a series of nine fundamental questions:

1) A small number of very large fires account for most of the area disturbed on a given landscape. The exact proportions of fires of different size-classes vary by natural sub-region.
2) The shape complexity of events generally increases as events become larger. However, in general, events are quite simple in shape, largely because the rules used to define an event tend to smooth out boundaries, and completely eliminate interior gaps.
3) The actual area burnt 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.
4) About 35% of all events have only a single disturbance patch. Another 26% have between two and five disturbance patches, and another 15% have between six and ten disturbance patches. Generally, as the size of the disturbance increases, the number of disturbance patches increases.
5) 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.
6) Disturbance patches are more convoluted in shape than events, and their complexity increases with increasing size.
7) The number of undisturbed remnant patches over five hectares in size within an event is about 1/3 of the total number of disturbed patches.
8) Single large undisturbed patches are uncommon in disturbance events. Undisturbed remnant patches tend to be more evenly distributed by size within events.
9) Corridor matrix remnants are not only more dominant that bay matrix remnants, but they tend to be the largest residual patches within a given disturbance event.

These nine outcomes represent significant new insight into the patterns of natural disturbances at intermediate or meso scales, and this new knowledge can be easily integrated into either forest management planning or monitoring systems. 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.

INTRODUCTION AND REPORT OVERVIEW

This report is divided into several related parts:

Part 1 is a general overview of the FtMF Natural Disturbance Program, and is common to all reports in this series.

Part 2 includes a detailed description of an event, and any new terminology, analysis results presented in response to a series of nine related questions about disturbance events and general conclusions.

Appendix A provides all of the equations used within figures in the report.

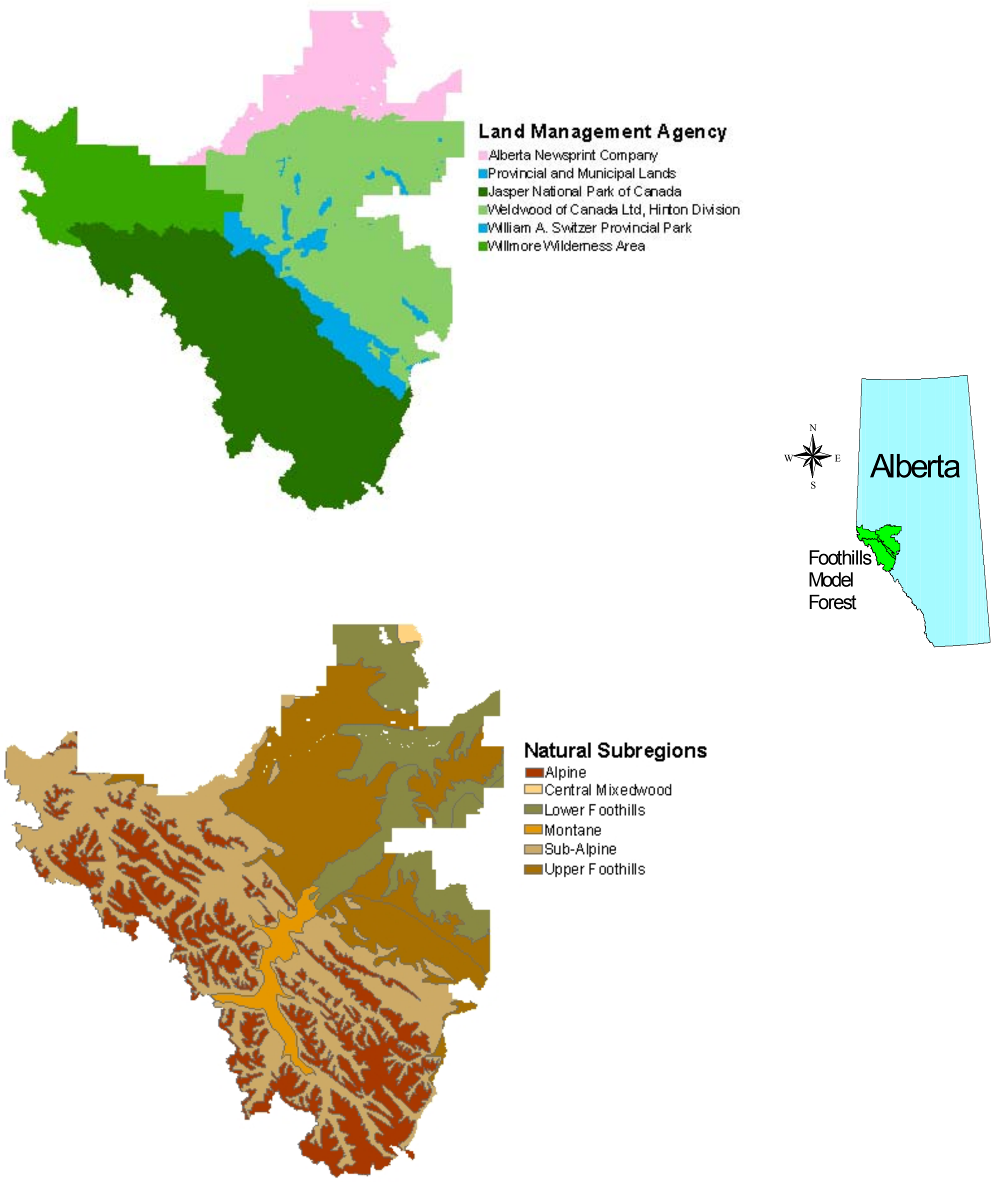
A glossary defines all of the technical terms used in this report.

Note that this report contains no methodological details. The data collected and methods used for this report have already been summarized in detail in:

MacLean, K., D. Farr, D.W. Andison and K. McCleary. 2003. Island remnants on foothills and mountain landscapes of Alberta: Methods. Alberta Foothills Disturbance Ecology Methodology Series, Report No. 1, November 2003. Foothills Model Forest, Hinton, Alberta.

Part 1: THE FtMF NATURAL DISTURBANCE PROGRAM

In 1995, the Foothills Model Forest (FtMF) in Hinton, Alberta initiated a research program to describe natural and cultural disturbance patterns across over 2.75 million hectares of foothills and mountain landscapes (Figures 1 and 2). The main purpose of the research is to provide FtMF partners and co-operators with a complete picture of how natural and cultural disturbances have historically shaped these landscapes. Ultimately, each partner intends to use this information to help guide policy and management towards developing more ecologically sustainable land management practices.



Figures 1 and 2. Foothills Model Forest administrative areas and ecological zones.

The Foothills Model Forest Natural Disturbance Program is a co-operative venture, led by a team of representatives from the Foothills Model Forest, Weldwood of Canada, Hinton Division, Alberta Sustainable Resource Development (SRD), Jasper National Park (JNP), and Alberta Newsprint Company (ANC). The comprehensive research program is partitioned into over 40 inter-related projects, each of which address a single disturbance question at a single scale. All projects are linked through a long-term research plan which includes details of the purpose and methods for each project and how they link together to form a complete picture of natural disturbance patterns. It also defines ground-rules for conducting the research to maintain focus, assess progress, respond to new information, and effect the timely completion of the work. These self-imposed ground-rules are as follows:

1) The main assumption driving this research program is: ***In the absence of information on alternatives, using natural disturbance patterns to guide management is one of the best possible means of achieving ecological sustainability.*** Therefore, our main research focus is on patterns, and the disturbance processes responsible for those patterns. This is not to say that the ecological responses to those patterns are not important, but they are secondary issues/questions for which more basic knowledge and extensive research is required.

2) Since both natural and cultural disturbances affect pattern, the program implicitly considers all types of disturbances. The danger of the deliberate isolation and study of different types of disturbance agents is the assumption of pre-conceived, and possibly incorrect, relationships between pattern and process.

3) The research is driven by operational needs, and the results are designed to be readily interpreted. This means that the research must consider translations of results to management practices. This is being accomplished in two ways. First, direct linkages have been sought to monitoring programs through the description of pattern(s). Although the output of this research is non-species specific, it is highly quantitative, and it is possible in many cases to define "natural baselines", making it ideally suited to monitoring. The second means of developing operational translations is through experimentation and demonstration. This allows for the evaluation of operational changes in terms of a) the success of creating the desired pattern(s), b) the biological responses of species and processes not part of the original research, c) practicality, and d) socio-economic impacts.

4) Finally, internalizing the research is to be avoided. High-quality research must be conducted by professionals, openly peer-reviewed, presented at public meetings, conferences and tours, and published in FtMF NDP Quicknotes, internal reports, news updates, posters, and refereed journals. A communications plan has been developed for the FtMF Natural Disturbance Program to guide the dissemination and integration of the research.

SOME DEFINITIONS

The term "landscape" has many meanings at many different scales. As a research document, a "landscape" in this report refers to ***an ecosystem large enough to allow observation and understanding of the interaction of disturbance, geomorphology, and topography with the biota***. In other words, a large collection of forest stands, whose common link is their dynamic relationship of disturbance to the land features (Forman and Godron 1986). In the foothills of Alberta, a landscape may be anywhere from 100,000 to 1,000,000 hectares. Like any ecological definition, this one is arguable, but it does allow some convenient scale distinctions to be made:

1) **Regional**

Several landscapes spatially related and commonly influenced by regional climatic patterns. The FtMF study area is a region in which several large landscapes have been identified with unique topographic, biotic, and pattern (disturbance) features. Beyond a region is a biome.

2) **Landscape**

Ecosystems that share common disturbance and land associations, as well as the resulting arboreal (tree) relationships with disturbance and land features. The ecologically based natural subregions have proven useful in defining landscapes (which include the Lower Foothills, Upper Foothills, Subalpine East, Subalpine JNP, and the Montane – see Figure 2).

3) **Sub-landscape**

Sections of one or more landscapes that exhibit a combination of ecological, social, and economic characteristics. Sub-landscapes can be defined in different ways depending upon management needs. For example, in our research, sub-landscapes are arbitrarily chosen blocks within landscapes in which more detailed analysis will be completed at higher levels of resolution.

4) **Event / Meso**

Areas within or between landscapes that at some point in time are commonly affected by a single disturbance such as a forest fire. Events include one or more disturbance patches, and may cross landscape boundaries. They may also include both forested and non-forested patches.

5) **Patch**

Contiguous areas of land that share common physical or biological characteristics. Age patches share year or year-range of origin (such as Old Forest), type patches depict areas of common tree species combinations, and Alberta Vegetation Inventory Patches define complex combinations of age, tree species, density and height, other vegetation, and other site factors. Relevant to this report, there are also *disturbance patches*, which have been affected similarly by a disturbance event, and *remnant patches*, which are any areas that have not been disturbed within a disturbance event.

6) **Island**

One type of remnant patch within a disturbance patch. There are no size limits on islands at this point, but they tend to be small. Islands may also be any combination of age, type and may be operable or inoperable.

7) **Matrix**

All undisturbed land outside the boundaries of disturbance events. Thus, any part of a landscape that is not within an event is matrix. *Matrix remnants* are undisturbed residual land within an event that are physically attached to the surrounding matrix.

The geographical terminology used in this document is as follows. The FtMF consists of two major land areas divided by the foothills of the Rocky Mountains (see Figure 1). To the west of the foothills lies approximately 1.1 million hectares of Jasper National Park. To the east of the mountains is an area of approximately the same size, which covers the Weldwood Forest Management Area (FMA) but also includes William A. Switzer Provincial Park, the town site of Hinton, a large coal mine, and a strip of land under the management of Alberta SRD. Outside the boundary of the FtMF, but still in our study area is approximately 370,000 hectares representing the ANC FMA (Figure 1). The area to the west of the foothills is all Jasper National Park, and will be referred to as such. Since the area to the east of the mountains is a mixture of tenure, it will simply be referred to as the "Foothills East".

Although the Willmore Wilderness Area is a part of the FtMF, it will not be discussed in this report as little data exists for this area.

Within Jasper National Park, three natural subregions exist: the Montane, Subalpine, and the Alpine. In the Foothills East there are also three main natural subregions: Lower Foothills, Upper Foothills, and Subalpine (Figure 2). To avoid confusing the two subalpine areas, they will be referred to as the "Subalpine JNP" and "Subalpine East".

THE DISTURBANCE ECOLOGY RESEARCH SERIES

This research report is the fifthin a series published by the Foothills Model Forest on natural disturbance dynamics on foothills and mountain landscapes in Alberta.

For more information on the FtMF Natural Disturbance Program, or the Foothills Model Forest, please contact the Foothills Model Forest in Hinton, Alberta at (780) 865-8330, or visit our website at: http://www.fmf.ab.ca. Copies of reports and Quicknotes are available on the website in Adobe Reader® format.

Reports available in the research series:

Andison, D.W. 1999. Assessing forest age data in foothills and mountain landscapes in Alberta. Alberta Foothills Disturbance Ecology Research Series, Report No. 1, December, 1999. Foothills Model Forest, Hinton, Alberta.

Andison, D.W. 2000. Landscape-level fire activity on foothills and mountain landscapes in Alberta. Alberta Foothills Disturbance Ecology Research Series, Report No. 2, July, 2000. Foothills Model Forest, Hinton, Alberta.

Andison, D.W., and K. McCleary 2002. Disturbance in riparian zones in foothills and mountain landscapes of Alberta. Alberta Foothills Disturbance Ecology Research Series, Report No. 3, February, 2002. Foothills Model Forest, Hinton, Alberta.

Andison, D.W. 2003. Patch and event sizes on foothills and mountain landscapes of Alberta. Alberta Foothills Disturbance Ecology Research Series, Report No. 4, March, 2003. Foothills Model Forest, Hinton, Alberta.

Reports available in the methodology series:

MacLean, K., D. Farr, D.W. Andison and K. McCleary. 2003. Island remnants on foothills and mountain landscapes of Alberta: methods. Alberta Foothills Disturbance Ecology Methodology Series, Report No. 1, November 2003. Foothills Model Forest, Hinton, Alberta.

PART 2: DISTURBANCE EVENTS

BACKGROUND

Spatial patterns of natural disturbance most recognizable to humans are individual disturbance events. Information and data about the size and severity of forest fires, wind and ice storms, floods, and insect outbreaks dominate the media, and thus form the basis of our most basic level of understanding of such phenomena. The fact that the disturbance event is the most comprehensible aspect of natural disturbance for most people makes it that much more important to get this part right.

Our understanding about the patterns of fire within a single event may be accurate on a general level, but much of it is based on subjective observation and opinion. Studies that specifically quantify how, what, and where forest fires burn are surprisingly rare. For example, residual island remnants in the boreal forest have been discussed by Delong and Tanner (1996), Eberhart and Woodard (1987), and more recently Alberta Research Council (2001). However, none deal with residuals as a component of an entire event, but rather of individual disturbance patches.

Indeed, we have little empirical information on the patterns of burning within a forest fire. This represents a critical gap in information available for use in emulating disturbance - we cannot emulate that which we have not quantified. Because we lack such information, we may be oversimplifying the nature of natural disturbance regimes. We tend to skip directly from patterns and sizes of patches right to fire cycles and return intervals. The potential implications of this gap in understanding include:

1) the total amount of undisturbed residual areas being grossly underestimated,
2) misrepresentation of the sizes, composition, structure and physical arrangement of disturbance residuals,
3) assuming that a patch-size distribution is the equivalent to a disturbance size distribution and,
4) missing altogether the fact that disturbance patches tend to be clustered in space.

While all classification systems are artificial ones, it seems that we may be missing a critical scale, and thus some essential natural patterns, by not recognizing events as discreet, physical entities. Thus, a lack of knowledge leads to a critical gap in our concept of what a natural pattern emulation strategy may involve.

This emphasizes the need for a thorough investigation and description of natural disturbance events as spatial entities. These analyses have been completed at the FtMF using a variety of datasets and the total amount of information generated is extensive. To break the information into manageable parts, the results will be presented in a series of related but distinct reports.

This is the first of two reports that will be completed by the FtMF ND Program on disturbance event patterns. This one will focus on more general questions of composition and structure. The second report to follow will discuss more specific spatial issues such as topographic and biological influences.

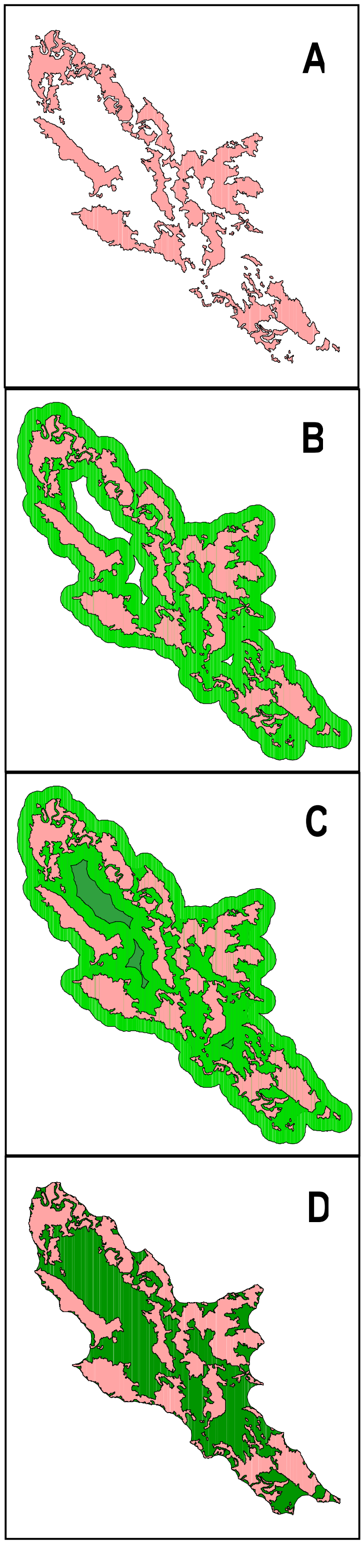
DEFINITIONS: THE DISTURBANCE "EVENT"

One of the keys to the successful integration of natural disturbance patterns into sustainable forest management is the ability to relate terms used in describing natural patterns directly into practice. The concept of a "disturbance event" as an individual disturbance episode of a forest fire, wind storm, flood, or insect outbreak, is intuitively straightforward. However, it is far more challenging to define an event in universal, concise, and spatial terms. In fact, no such definition exists in the literature. Thus, before delving into the nature of disturbance event patterns, it is necessary to first define exactly what is meant by an event in this, and future, reports.

The dominant natural disturbance agent on most forested landscapes of Alberta is forest fires. A single episode of fire is universally understood since it occurs over a relatively short period of time and is usually the result of a single source of ignition. While fires are normally described by simply mapping the outer boundaries, there is considerable subjectivity involved in even this task. Forest fires are particularly difficult to define as spatial entities because they tend to result in more than one disturbance patch, no doubt a result of fire behaviour known as "skips". In fact, in the FtMF data, there are several hundred disturbance patches in 24 fires. Thus, choosing the "outer boundaries" of a fire becomes an arbitrary choice. Rather, what we need is a system for defining events that can be applied universally and easily to any data, by anyone.

The requirements for the delineation of a disturbance event are as follows. First, it must fit logically with the concept of an event, and be easy to understand and communicate. It must also be simple enough to apply both manually and digitally. Although the digital environment is fast becoming the standard, we should not assume it is universal. It should also maximize the probability of identifying all of the patches within a single event, but at the same time minimize the chances of including patches from other events. It is expected that any such algorithm will be used to identify disturbance events that are far less obvious than are fires. And finally, the process must produce a spatial entity that can be used as the basis for spatial summaries. Questions of what amount, type, and configuration of residual undisturbed areas are prominent issues. Thus, ideally, the event entity should be as simple as possible in terms of shape and composition to allow such analyses to focus on more important questions. In the end, we have to keep in mind that *any* definition of an event that we choose is arbitrary and artificial, designed solely for the purposes of our understanding and communication.

Figure 3. An Example of How Events are Defined.



HOW TO DEFINE AN EVENT:

Based on extensive exploratory analyses, I chose the following rules for defining a disturbance event. First, identify the outer boundaries of all *potentially eligible* disturbed areas. Internal structure such as residual islands is ignored at this point. Frame A in Figure 3 shows the burnt patches of one of the fires in the foothills dataset.

Next, identify the patches that are spatially related by applying a 250m exterior buffer to all patches. This is also the first step in defining the contiguous area of the event. Frame B of Figure 3 shows the outcome of a 250m exterior buffer applied to all disturbance patches in ARCVIEW. All patches less than 500m apart (250m in two directions) will be identified as being spatially related.

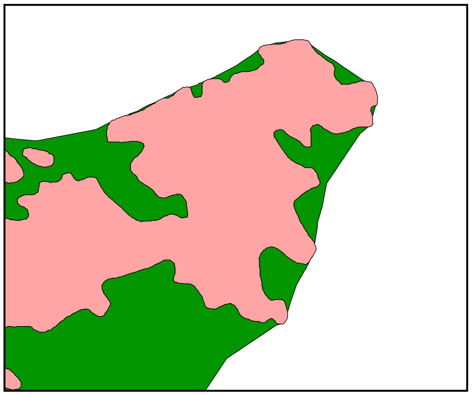
The next step is to eliminate all interior holes or “donuts” that may have been left in the buffer layer. Often, 250m may not be adequate to completely cover interior areas such as the blank spaces shown in Frame B of Figure 3. All such donuts must be eliminated. For example, the original buffer area (shown in light green in Frame C adjacent) plus the donut area (shown in dark green in Frame C) now combine to form a single polygon.

The last step is define the final event area by applying a 250m buffer on the *inside* of the combined (buffer + donuts) polygon boundary, as shown in Frame D of Figure 3. This new polygon is the final event area. Note that the event area more or less follows the outer boundaries of the disturbance patches.

This 4 step process successfully identifies a local area influenced by a fire event that can (and will) now be used to perform various summaries in this report. It satisfies all of the requirements outlined above.

It is important to realize that one of the by-products of any method that simplifies shapes is a large number of polygons on the outside of the disturbance polygon – some of them quite small. Buffers will always simplify shapes because they will eliminate smaller gaps or bays in boundaries, and truncate larger ones. The larger the buffer, the greater the smoothing effect. Furthermore, imposing an interior buffer after the fact does not reverse this simplification since the original edge detail is lost information. For example, Figure 4 is a detailed image of the north-eastern tip of the disturbance from Figure 3, with the original disturbance shown in red, and the final event area in green. All exterior bays smaller than 500m wide have been completely eliminated, as have almost all of the small “dents” in the perimeter. The analogue equivalent to this GIS smoothing process would be to simply draw lines between the outer most points of the original disturbance shape, keeping in mind the 250m limit (imposed in two directions).

Figure 4. An Example of the Smoothing Effect of the 2-Step Buffering Process.

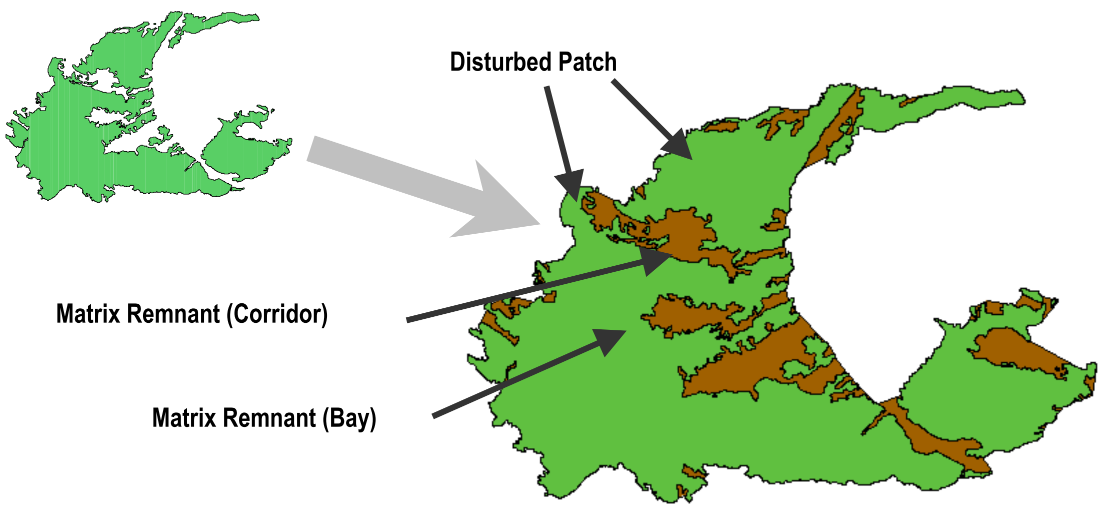


An event thus includes more than one type of spatial element. For the purposes of clarity, the following terms will be used to describe those spatial elements in this report:

Disturbed Patches are the individual, contiguous polygons that are disturbed. Disturbed patches are represented in green in Figure 5.

Matrix Remnants are the undisturbed areas separating disturbance patches within an event. In Figure 5, two types of matrix remnants are identified; "corridor" and "bay", depending on whether the undisturbed area physically separates two disturbance patches (as a "corridor"), or just fills in the area between two peninsulas of a single disturbed patch (as a "bay").

Figure 5. Defining the Spatial Entities Used in This Report.



ALTERNATIVES TO THE DEFINITION:

As discussed, the rules for defining a disturbance event outlined above are subjective, but I found that these met the basic requirements. I tested, and rejected other options. For example, instead of applying buffers, patches within the same event could be identified using "nearest neighbour" analysis. Although this would result in the same collection of patches, it would not delineate a spatial entity, which is necessary for any analysis of event composition and structure.

Different buffer distances could be used as well. The 250m level that I chose was largely based on trial and error using available natural and cultural data. It is important to note that a 250m buffer was insufficient to aggregate all disturbance patches within all of the fires into single events. The rules generated multiple events for three out of 24 fires, and one of those fires had only two events. The other two fires generated a total of 26 events. However, these are the two largest fires in the dataset, both of which demonstrate a highly dispersed burning pattern. The buffer distances required to capture each of these fires into a single event would be at least double the 250m distance adopted. However, buffers of that magnitude start to combine disturbance patches from different fires. More importantly, buffer distances beyond 250m tend to aggregate significantly greater numbers of cut blocks into very large contiguous events when applied to a culturally modified landscape. This is a reflection of the pattern of the historical fragmented harvesting patterns commonly applied on working land bases. Keep in mind that a 250m buffer aggregates all patches less than 500m apart.

Buffer distances less than 250m were found to be far less able to combine natural disturbance patches into single events. Of the 24 fires in our dataset, the set of rules outlined above created multiple events in three fires. When the buffer was reduced to just 200m, the number of multiple-event fires increased to eight. In addition, the shape of the events became much more complex, as many more "bays" persisted, whereas the 250m buffer closed them off as interior donuts.

The decision to eliminate interior holes in the buffer polygon after the initial 250m buffering goes directly to the need for simplicity and logical consistency. Conceptually, one could think of all parts of the event area as having more or less an equal chance of being impacted by the fire. From an analysis standpoint, it would be difficult to justify having interior gaps within a disturbance event. The spatial analysis is the means by which we can understand how and where fires burnt, and by what mechanisms the fire burnt where it did. Such an analysis may be compromised by artificially removing an interior portion of the fire area. Interior gaps would also be very difficult to deal with from an operational perspective (comparing these data to existing or proposed cultural events). Overall, it is just simpler to not allow interior holes.

Finally, the decision to impose an interior buffer of 250m as the last step does nothing more than reduce the final size of the event. This step could have been skipped altogether. The advantage of leaving a buffer on the event is that it would be useful analytically (e.g., it would allow one to consider where, and perhaps why, fires stopped where they did). The disadvantage of leaving a buffer on events is that it artificially inflates the area of an event, and introduces another type of residual (*i.e.*, "buffer remnants"). It also imposes an artificial assumption about the spacing of events. Natural disturbance events can overlap each other, or they can be hundreds of kilometers apart. The 250m buffer rule is meant here only as a means of aggregating patches, and not for evaluating event spacing. In the end, I decided it was simpler, and more intuitive to look at event patterns without an exterior buffer.

RESULTS

The data, methods, and assumptions used to generate these results are highly detailed, and are not discussed here. A detailed account of the raw data and methods are presented in a separate report (see MacLean et al. 2003). However, there are a few things to keep in mind regarding the data while considering the results. First, the data represent highly detailed post-fire patterns from fires that occurred between 1950 and 1970. In the vast majority of cases, photos at scales of at least 1:15,000 were used to identify patches and islands down to 0.001 ha in resolution. However, in the interests of minimizing noise due to human error and allowing for differences in photo scale, I wanted to standardize minimum resolution. Thus, individual polygons less than $200m^2$ or .02 ha, and all events less than 1 ha in size were eliminated from the dataset. Third, of the 25 original fires in the raw data, one was eliminated because of data problems (#1499). Fourth, although this project is a part of the FtMF ND program, the data used for these analyses covers a significantly larger area to the south, east, and north of the FtMF (see MacLean et al. 2003 for details). Finally, there was no indication that events generated from the same fire were in any way correlated to each other in terms of any patterns. In other words, events were independent samples.

Question 1: How large are disturbance events?

This question has already been addressed in detail in report #4 in this series (see Andison 2003b). Briefly, a small number of very large fires account for most of the area disturbed over a given time period. However, this relationship varied considerably by natural subregion. More precisely, *"Over 2/3 of the disturbed area in the Upper Foothills landscape is associated with disturbance events larger than 10,000 hectares. The Subalpine JNP landscape has the next highest proportion of disturbances over 10,000 ha (58%), followed by Subalpine East (42%) and the Lower Foothills (17%). Individual disturbance events larger than 5,000 ha were not found in the Montane landscape*" (from Andison 2003b). This report also found that proportions of very small fires were landscape specific, and not necessarily inversely related to the proportions of very large disturbances. Lastly, Andison (2003b) found that contemporary disturbance sizes differed significantly from historical ones, but once again in different ways in each of the five natural subregions. Please see report #4 for details on these and other patch size results.

When referring to this work, keep in mind that the event definition had not yet been developed, so report #4 technically refers to the "disturbed area" of events, and not event areas as described here. The analysis to follow will explore the relationship between these two variables.

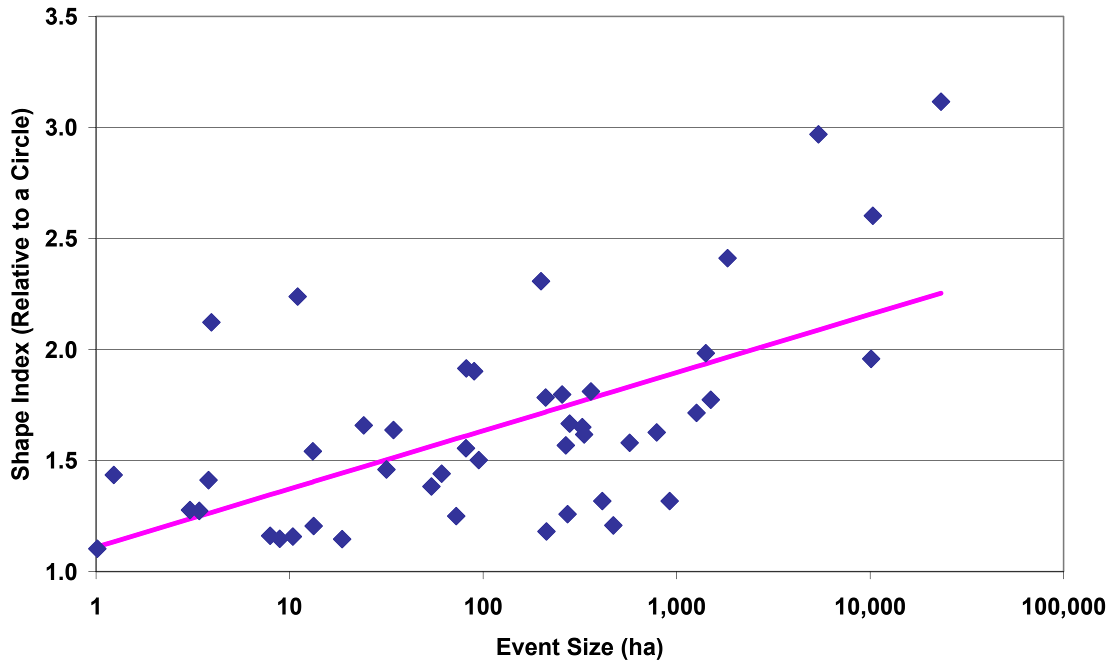
Question 2: What are the shapes of disturbance events?

Shape is a useful pattern metric because it gives a sense of the complexity of the outer boundary of an event. There are two indicators for complexity of shape; a ratio of the actual perimeter to the perimeter of the simplest possible shape for the same sized area, and the percent of interior or "core" area. Both are presented here.

Figure 6 shows the "shape index" for all events larger than one hectare. A shape index is the ratio of the actual outside perimeter of a polygon, to the outside perimeter of that area if it were a perfect circle. A circle represents the least perimeter for a given area, and so a shape index of one represents a perfect circle. As the polygon shape becomes less circular, the index increases. A shape index of two means that the actual length of a polygon perimeter is exactly twice as long as it would be for a circular polygon of the same area.

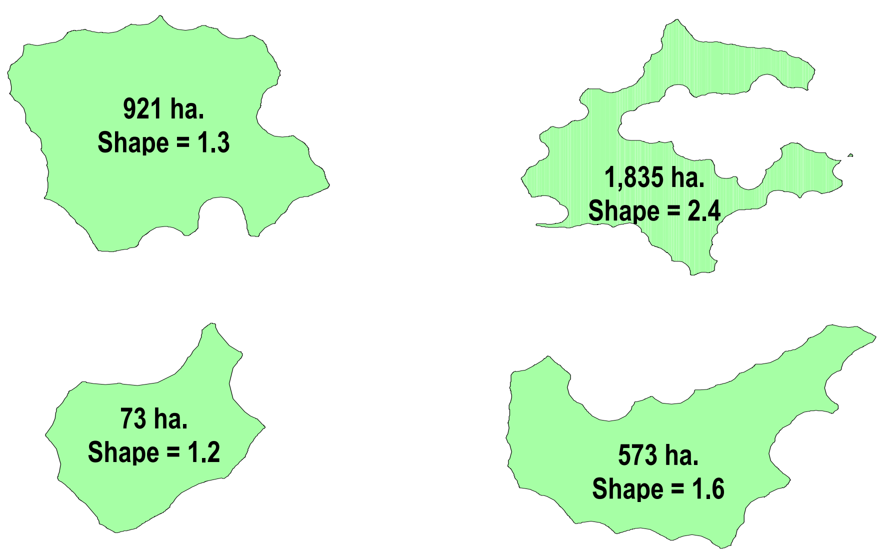
The shape indices for the event data range from 1.1 to 3.1 (Figure 6). However, the average shape is only 1.6, and the majority are less than 2.0. Shape index generally increases as events become larger. Only events several thousands of hectares in size have shape indexes greater than 2.5. A best-fit linear relationship is shown in Figure 6 (see Appendix A for equation details).

Figure 6. Event Shapes



While there are no helpful conversion rules for shape indices, it is safe to say that these shapes are quite simple, particularly given the sizes of some of the events. It is only the very largest events that become even moderately convoluted. As shown in Figure 7, for events less than 5,000 ha, shapes are fairly constant, and very simple.

Figure 7. Four Examples of Event Shapes



The second way of assessing the shape of polygons is to use “core area”, or “interior area”. The core area estimates in Figure 8 were calculated as the percentage of each event that would be interior or “core” using a 100m interior buffer, as illustrated in Figure 9. I also calculated and included on the graph the maximum possible value of the core area estimate (in red) – again based on the simplest shape of a circle. For example, a 100m interior buffer on a 100 ha circle would account for about 33 ha, leaving 67 ha, or 67% of the polygon as “interior” (so if you follow 100 ha up from the X-axis to the top red line, it will meet up with 67% on the y-axis in Figure 8). So if all of the events were perfect circles, their core area percentages would fall on the red line.

Figure 8. Core Areas of Events

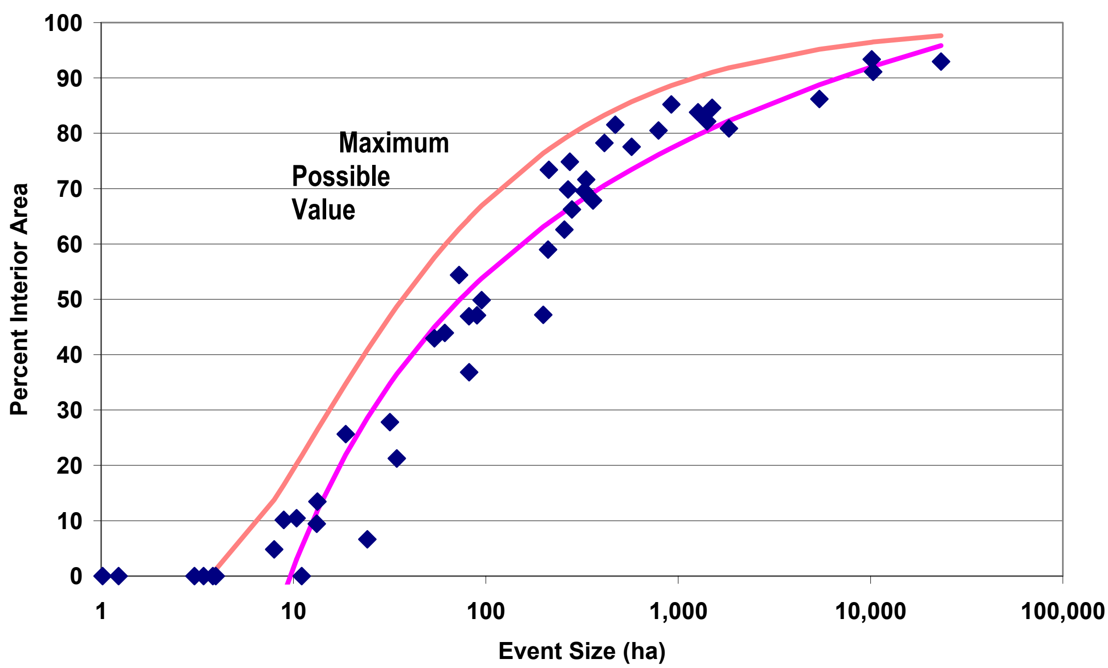
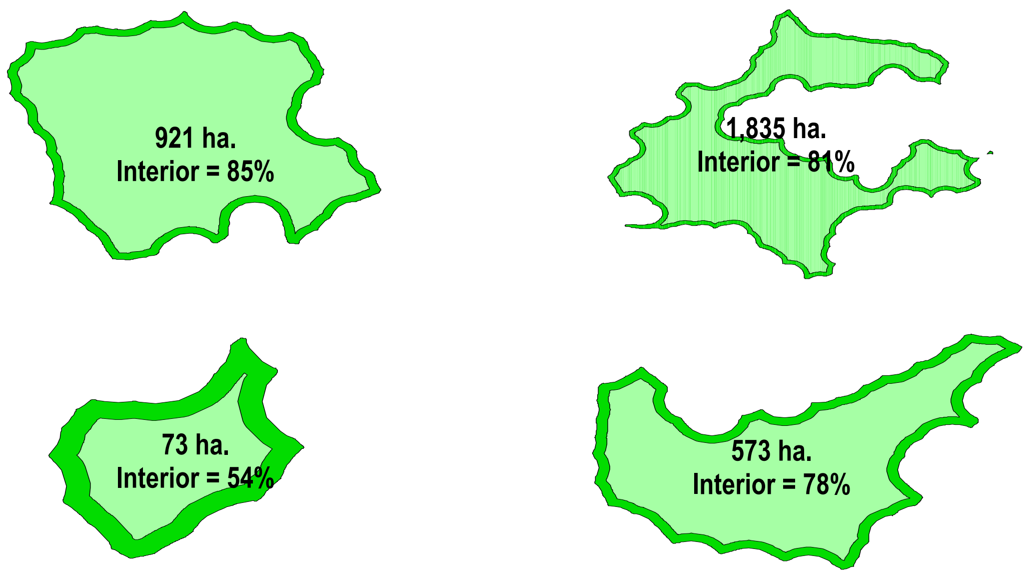


Figure 9. Four Examples of Event Interior Areas



The core areas for events generated in Alberta confirm that event shapes are very simple (see Figure 9 for examples). The largest events have the highest percentage of interior forest, in many cases very close to the maximum possible values. Interior area percentages for smaller events are comparatively lower, but the low values from the shape indices in Figure 6 suggest that many of these are just ovals. If the short axis of an oval is only 200m (which is very possible for shapes 10-20 ha in size), it will create a simple shape, but with no interior forest using a 100m buffer rule.

The knowledge that events are simply shaped with high levels of core area is not only valuable natural pattern information, but it also demonstrates one of the advantages of applying universal rules for defining events. If the general outline of disturbance events can be represented by simple shapes, they can more easily be translated into understandable terms.

Question 3: How much of an event is actually disturbed?

By definition, virtually all disturbance events will have undisturbed areas within the boundaries either as bays or corridors (see Figure 5). This is the difference between the *fire size* results from report #4, and actual disturbance *event sizes* as defined above. Using the event boundaries, the proportion of the disturbed area for events, and the ratio between disturbed area and event area, can be easily calculated.

The percent of disturbance events that are actually disturbed ranges between 44-95%, and averages about 69% (Figure 10). This means that on average, the event area is about 1 ½ times the size of the actual area disturbed, although the variation is considerable.

The percent of an event that is disturbed appears to be unrelated to event size. There was no significant relationship between these two parameters; statistical tests in this case failed to prove that the proportion of the area disturbed either increased or decreased with event size.

On the other hand, it should be noted that the variation is not only fairly broad, but well defined within the range. In fact, the raw data are distributed fairly evenly between 40 and 100 percent. Figure 11 rearranges the same data from Figure 10 into a frequency distribution, and illustrates that there is no central tendency towards an average or median. In other words, it is just as likely to find 45% of an event area in matrix remnants as it is 65% or 95%. The "natural range of variation" in this case is truly represented by the 40-100% range.

Figure 10. Total Percent of Event Areas that are Disturbed

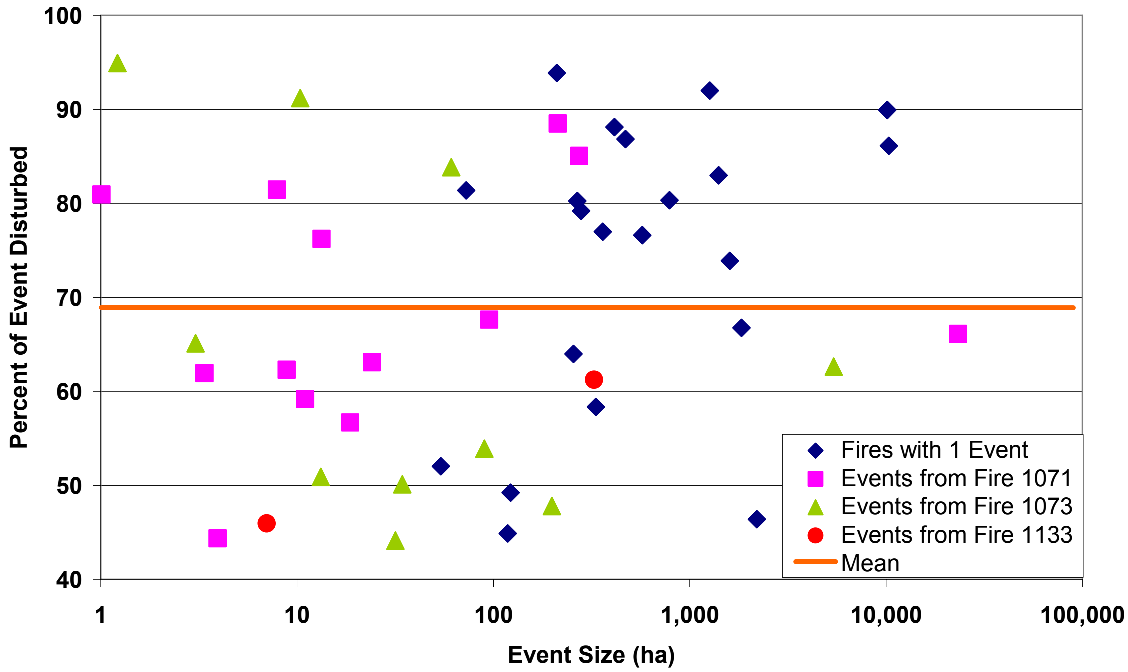
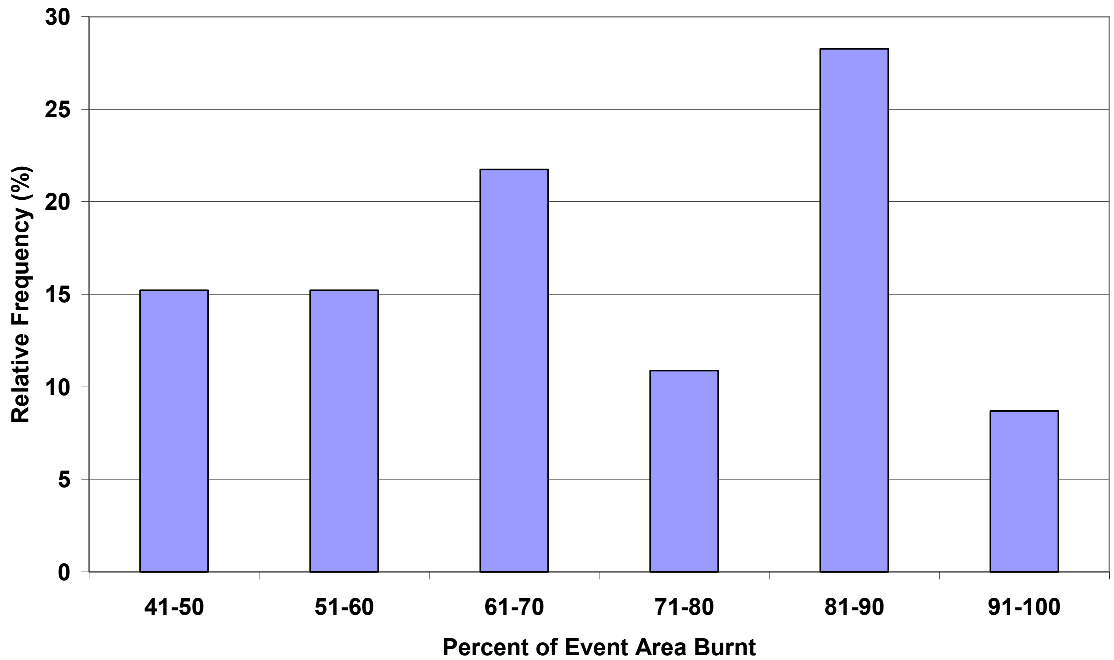


Figure 11. Disturbed Area as a Percentage of Event Area



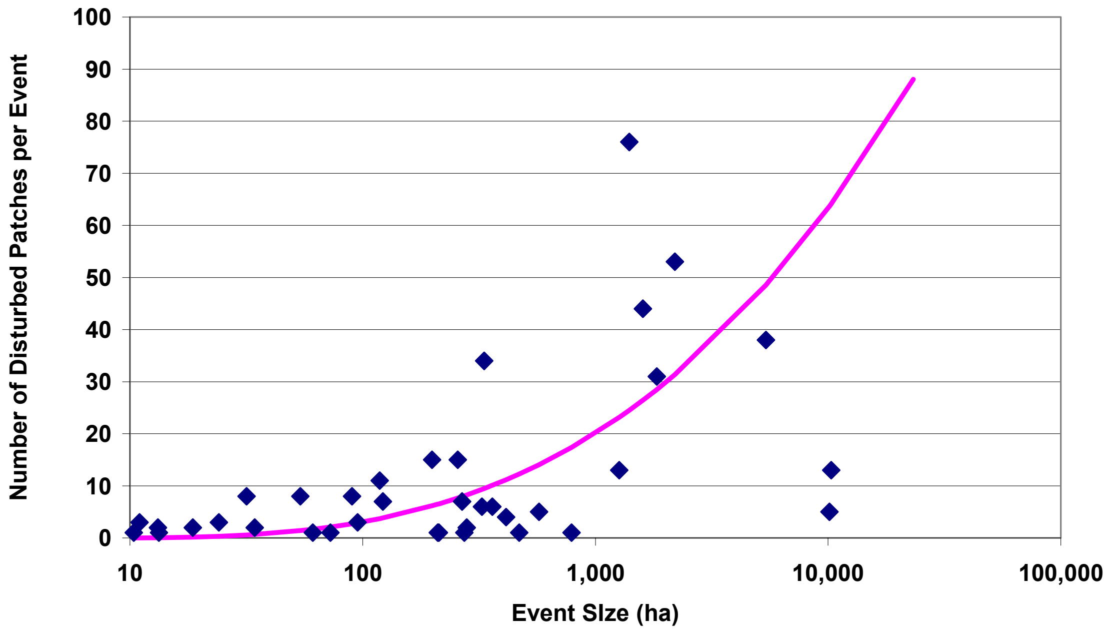
Note also that the data points in Figure 10 are identified according to the fire number. Of the 24 fires in the dataset, three had multiple events, and two of those (fires 1071 and 1073) were responsible for 26 events. The reason I showed these detailed data in Figure 10 was to demonstrate that there was no bias associated with the events from individual fires. It can be clearly seen that the percent of event disturbed from the events from both fires 1071 and 1073 represent almost the entire range of the data from the single-event fires.

Question 4: How many disturbed patches are in a disturbance event?

Of the 46 disturbance events in the sample, 16, or 35%, have only a single disturbance patch. Another 12, or 26%, have between two and five disturbance patches, and another 15% have between six and ten disturbance patches. The greatest number of disturbance patches is 236.

The number of disturbed patches increases with event size. As shown in Figure 12, although the data are highly variable, there is a definite relationship between event size and the number of disturbance patches. The average number of disturbance patches for events less than 10 ha in size is only 1.5, for events 11-100 ha. 3.3, for events 101-1,000 ha it is 7.3, and for events 1,001 to 10,000 ha, the average number of disturbed patches is over 42. This trend can also be seen in the best-fit function in Figure 12 (see Appendix A for the equation details).

Figure 12. Number of Disturbed Patches Relative to Event Area



Keep in mind that this equation, like all others in the report, captures only the *average* relationship. There is a significant amount of variation around such an average, which can been seen in the raw data in Figure 12. Furthermore, whether or not the large number of disturbance patches (236) in the largest event (23,267 ha) is unusual is unknown. It is by far the largest event in the dataset, and thus it may provide important information on the relationship between patches and large events, or it may merely be a geographical or fire behaviour artefact. To be conservative, I would suggest that based on this data, that the relationship between numbers of disturbance patches and event size is reliable only for events smaller than 10,000 ha.

Question 5: How big are the disturbance patches within events?

Once the total area disturbed and the number of disturbance patches within an event have been evaluated, the next logical question is how that area is distributed in patches of different sizes? As it turns out, there are some general rules of thumb that apply to most fire patterns.

Most natural fire events are dominated by a single large disturbance patch. About 35% of the time (or 16 out of 46 events), there is only one disturbance patch for each event. Of the remaining events with multiple disturbance patches, most are dominated by one large patch that accounts for an average of 73% of the net disturbed area (of an event). However, there is considerable variation in this figure. More specifically, at least half the time, the largest patch accounts for at least 80% of the total disturbed area of events (with multiple patches). Much less frequently, the largest patch can be less than 40% of the total area disturbed. The frequency distribution of the proportional area of the largest disturbance patch is shown in Figure 13, and demonstrates this “skewed” distribution.

Another notable pattern is that there is no relationship between the proportional area of the largest patch, and the total size of the disturbance. It is just as likely that a very large fire will have a dominant patch as it is that a small fire will have a single dominant patch.

Disturbed events of almost any size almost always contain a number of smaller disturbance patches as well. Furthermore, as the area disturbed within an event increases, the number of disturbance patches in each size-class increases. Although highly variable, the general trend of the number of disturbance patches of different size-classes is summarized by a series of five best-fit equations in Figure 14.

Figure 13. Size of the Largest Disturbance Patch as a Percentage of Net Disturbed Area in Multi-Patch Events

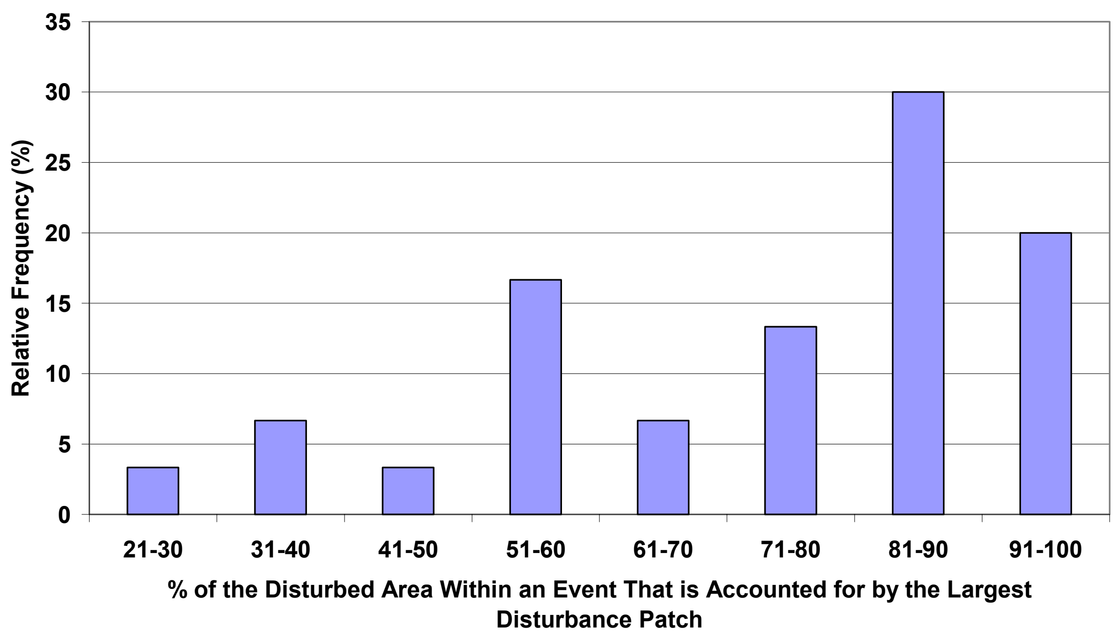
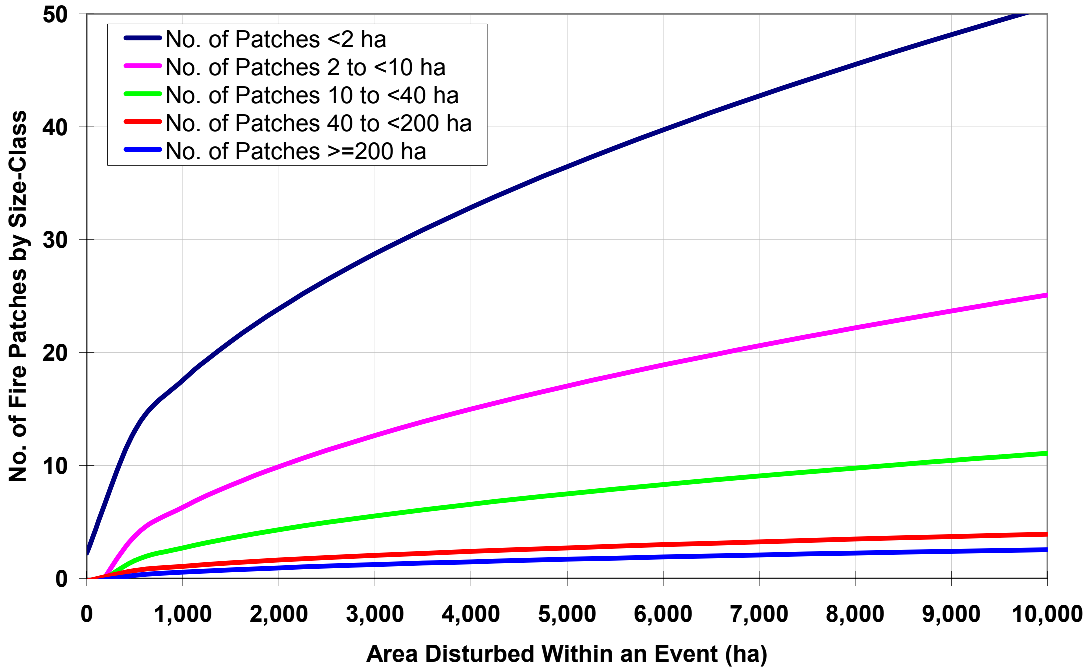


Figure 14. Relationship Between Event Size and Disturbance Patch Sizes

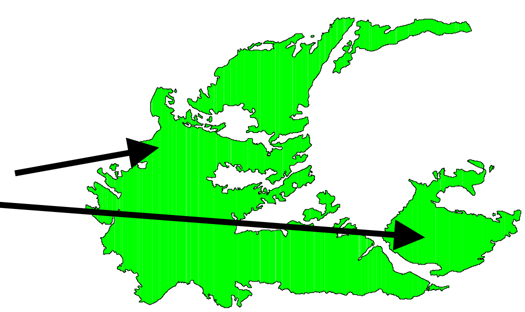


The results in this section can now be combined with the results in previous sections to begin assembling an *average* event of a given size. For example, 1,000 ha of actual disturbed area within an event will have a single large patch about (1,000 x 73%) = 730 ha (from above). From Figure 14, the 1,000 ha area will be composed of about 12-20 patches less than 2 ha, 3-8 patches between 2 and 10 ha, 1-5 patches between 11 and 40 ha, and none or one patch between 40 and 200 ha – *on average*. Variation about these averages is considerable (see Figure 15 for an example of an actual event), so these should in no way be considered to be stable relationships.

Figure 15. An Event With Multiple Disturbance Patches

8,887 ha burnt

Largest patch = 7,130 ha (80%)
1 patch 1,294 ha
1 patch 335 ha
1 patch 76 ha
1 patch 13 ha
5 patches <10 ha

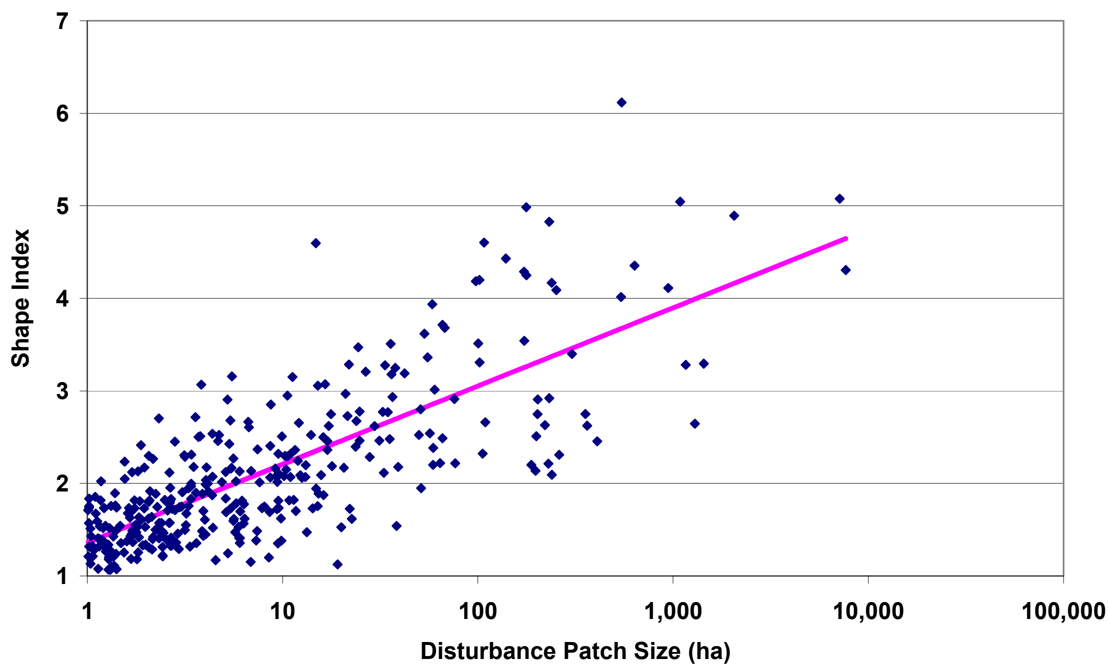


Question 6: What is the shape of disturbed patches?

Disturbance patch shape was explored in exactly the same manner as event shapes from Question 2 above.

The shape of disturbed patches is more complex than that of events. For example, a 1,000 ha event has an average shape of about 1.9 (Figure 6), while the shape of a 1,000 ha disturbance patch averages 3.9 (Figure 16). In other words, there is over twice as much edge or perimeter in a 1,000 ha disturbance patch relative to a 1,000 ha event. This discrepancy is due entirely to the edge-smoothing effect of the even-defining rules, and is magnified for larger patches. For example, 5,000 ha events average a shape index of 2.1, but 5,000 ha disturbance patches have an average shape of 4.9. Figure 16 shows the shapes of all disturbance patches in the dataset larger than one hectare, and the best-fit linear equation that represents these data (see Appendix A for equation details).

Figure 16. Disturbance Patch Shapes

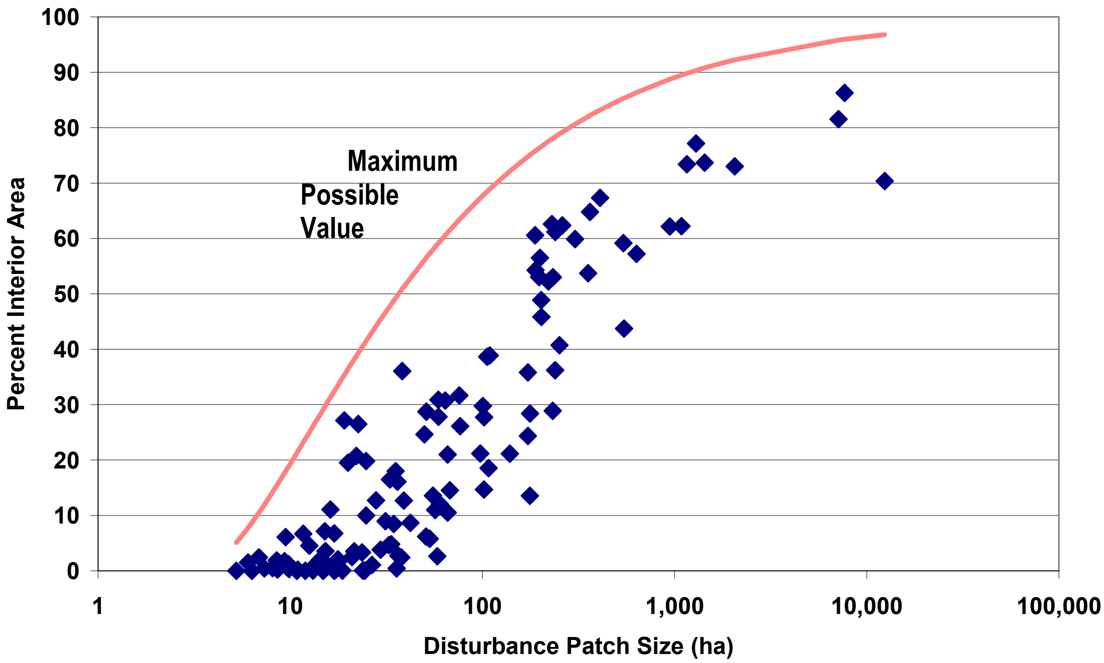


Disturbance patches predictably contain less core area than do events of similar size. Core area is particularly low for smaller disturbance patches when compared against the maximum values. For example, disturbance patches between 50-100 hectares average only 18% core area (Figure 17) compared to an average maximum of 60%. Larger disturbance patches have much more core area, but still far less than event areas of the same size. For example, disturbance patches 1-2,000 ha in size average 72% core area, and events 1-2,000 ha in size average 83% core area. This translates into a difference of 110-220 hectares of core area.

It is important to keep in mind that more interior forest is not necessarily always better. I only contrast the shapes of events and disturbance patches here to gain a sense of relative levels of polygon complexity.

The point is that disturbance patches are more convoluted than are events, and thus by association, they have less core area.

Figure 17. Core Areas of Disturbance Patches

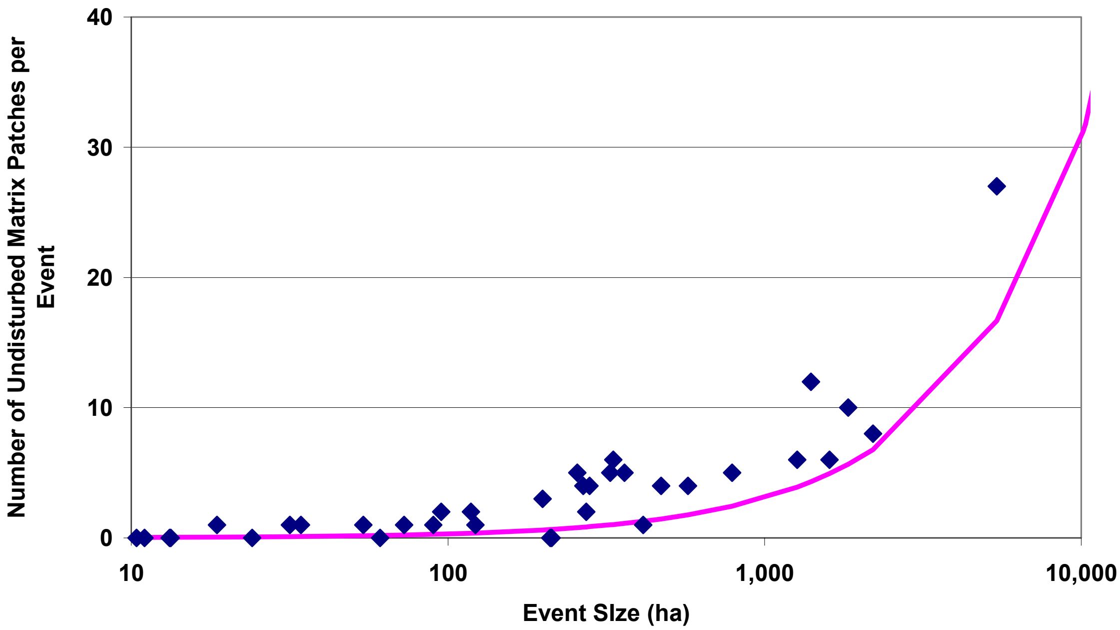


Question 7: How many undisturbed patches are in a disturbance event?

The undisturbed or remnant patches of matrix within an event are technically all artefacts since they are a product of the rules or algorithm applied to define the event. In this case, we already know there are a large number of very small remnant matrix polygons that are small "bays" on the exterior of the disturbance patches (see Figure 4). We also know that by applying a different set of rules, such as a 200m buffer instead of 250m, the number and size of those bays will change. In an effort to eliminate the majority of the artefacts related to different event-defining rules, I limited the minimum size of a remnant undisturbed patch within an event to five hectares. Virtually any set of event-defining rules would create similar undisturbed patch-size distributions with a five hectare minimum.

As with disturbed patches, undisturbed patch density increases with larger events (Figure 18). However, for a given event, there are generally far more disturbed patches than there are undisturbed matrix patches over five hectares. For example, a 1,000 ha event would have an average of 20 disturbed patches (Figure 12) and only eight undisturbed patches over five hectares (Figure 18).

Figure 18. Number of Undisturbed Patches Relative to Event Area

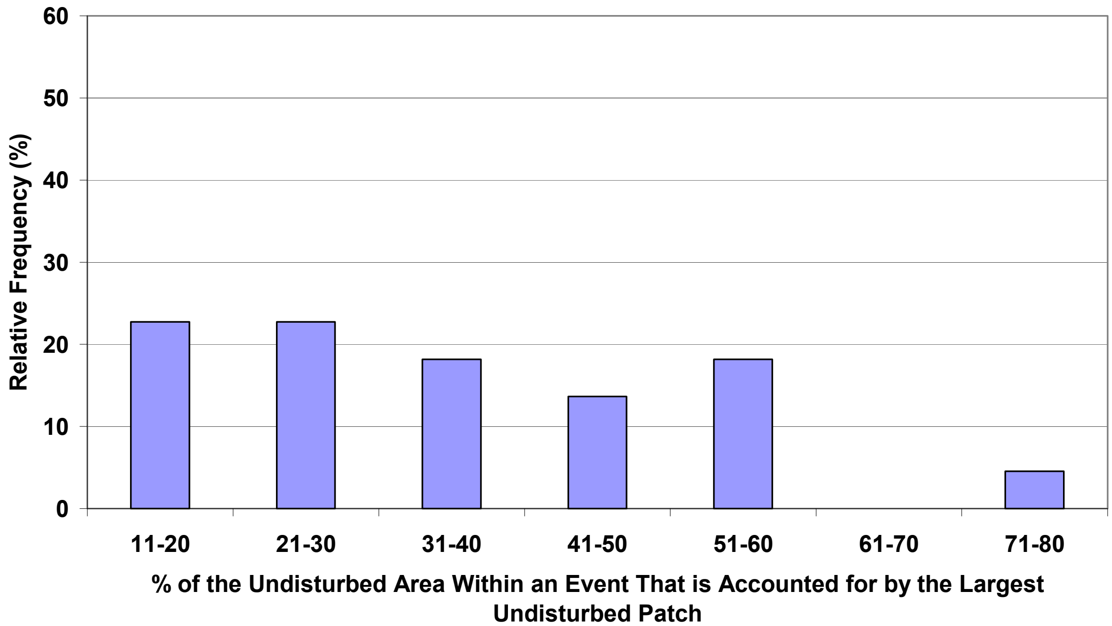


Question 8: How large are the undisturbed patches within events?

Most undisturbed patches are small. Of the 46 events, 16, or 35% had no undisturbed patches larger than five hectares. Almost all of those are in events less than about 60 hectares. Of the remaining events, another eight had only one undisturbed patch larger than five hectares, and almost all of those are in events less than about 90 hectares.

For those events with more than one undisturbed patch larger than five hectares, the undisturbed area is distributed much more evenly throughout the remaining patches. The largest undisturbed patch only accounts for an average of 36% of the total undisturbed area on an event. The frequency distribution of the proportion of area accounted for by the largest undisturbed patch is given in Figure 19. Recall that the average area of the largest disturbed patch in an event accounts for about 73% of the total disturbed area.

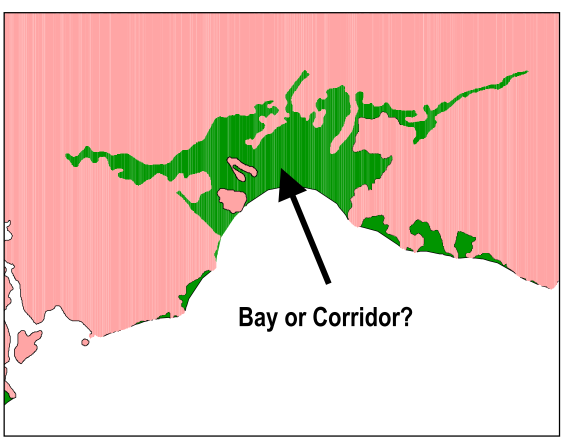
Figure 19. Size of the Largest Undisturbed Patch as a Percentage of Net Disturbed Area in Multi-Patch Events



Question 9: Are the undisturbed patches within events "bays" or "corridors"?

This is a logical question given the multi-patch nature of disturbance events since it helps understand whether matrix remnants tend to occur between, or within, disturbance patches. It is unfortunately a difficult question to answer because of the challenge in clearly differentiating between a bay and a corridor. The simplest definition of a corridor is the area between two disturbance patches of the same event. Thus it would be physically possible to use a corridor to pass between two disturbance patches within undisturbed forest. A bay is formed where the edges of the same patch turns back on itself to form a constricted area. Bays have only one entrance / exit to the surrounding matrix.

Figure 20. Two Different Types of Matrix Residuals.



The problem is that these attributes are often found together. Consider the remnant area in Figure 20 resulting from the event-forming rules (in green). Clearly, part of this remnant patch exists because of the convoluted nature of the largest disturbance patch (in red). But, it is also clear that this same remnant patch spans between this single large disturbance patch, and two smaller disturbance patches (to the left of the arrow). This duplicity complicates any precise differentiation of remnant matrix types. However, some general trends are evident.

If we count any remnant patch that separates two or more disturbance patches as being "corridor" – regardless of whether or not it functions also as a "bay" – 73% of the matrix remnant area in this study is associated with corridors. If we remove the dual-function remnant patches, the vast majority of matrix remnant area is still in corridors. Furthermore, most of the largest remnant matrix patches are corridors, and most of the small remnants are bays. Of the largest 10 remnant matrix patches in this study, nine of them are corridors, and only one is a bay. Of the 50 largest remnant matrix patches, 38 are corridors, 12 are bays.

In a way, the delineation of remnant matrix as being either a bay or a corridor is redundant information. The number, size, and shape of the disturbance patches, plus the ratio of disturbed to undisturbed area, will largely determine not only the total area of remnant matrix, but how much of that area is corridor and how much is bay. However, in general terms, this analysis is valuable to confirm that 1) different types of matrix remnants naturally exist, and 2) corridors are an event-scale natural pattern.

DISCUSSION and CONCLUSIONS

This report serves as an introduction to the concept and description of a disturbance "event". While many questions remain unanswered, it has provided some important new quantitative and qualitative knowledge on the patterns of natural disturbance events.

Normally, a research report discussion would include comparisons with findings from similar studies in Alberta and elsewhere. Unfortunately, there is no comparative analysis available in the literature. This is the first such work that even defines a disturbance event, let alone describes their patterns. This work does offer a reference point for future studies, and does so in a logical sequence of questions. Consider that we now know:

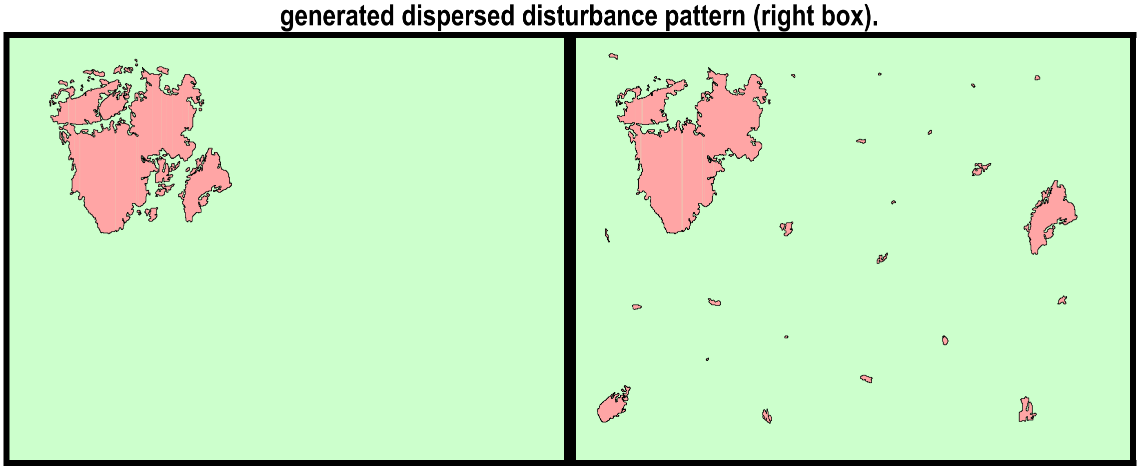
1) A small number of very large fires account for most of the area disturbed on a given landscape. The exact proportions of fires of different size-classes vary by natural sub-region.
2) The shape complexity of events generally increases as events become larger. However, in general, events are quite simple in shape, largely because the rules used to define an event tend to simply boundaries, and completely eliminate interior gaps.
3) The actual area burnt 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".
4) About 35% of all events have only a single disturbance patch. Another 26% have between two and five disturbance patches, and another 15% have between six and ten disturbance patches. Generally, as the size of the disturbance increases, the number of disturbance patches increases.
5) Events tend to be dominated by a single large disturbance patch, which accounts for an average of 73% of the disturbed area. The numbers of smaller disturbance patches of different sizes can be roughly predicted.
6) Disturbance patches are more convoluted in shape than events, and their complexity increases with increasing size.
7) The number of undisturbed remnant patches over five hectares within an event is about 1/3 of the total number of disturbed patches.
8) Single large remnant patches are uncommon in disturbance events. Undisturbed remnant patches tend to be more evenly distributed by size within events.
9) Corridor matrix remnants are not only more dominant than bay matrix remnants, but they tend to be the largest residual patches within an event.

Using this information, we can now understand the basic components of a natural disturbance event. It is possible to use the new definitions plus the analysis output to help design and/or evaluate past or planned cultural disturbance events. Once again I would caution readers to not interpret the derived relationships from the equations too literally. Their purpose was mainly to demonstrate the type and degree of the relationship(s), not to provide a series of deterministic "rules" for disturbance event design. In reality, the frequency distributions are the most "natural" results.

The advantage of having answers to this series of interrelated questions is that they can be applied in any order. It is not necessary, or necessarily desirable, to start with the general outline of an event and work down to the finer scales and questions. Existing landscape patterns, resource allocation, and other values will often restrict the design of an event. These restrictions may be better applied at finer scales, which will allow more creative design of a more general-scale event.

On a more conceptual level, the results presented here lead to several important conclusions of practical value. The most important of these is that forest fires often create more than one disturbance patch. Thus, disturbance patches are generally clustered in space. By not accounting for this clustering, (for example, doing a simple summary of disturbance patch-size distributions), we are not fully capturing natural disturbance patterns. Nor is it simply a matter of semantics. Consider the Tony Creek Burn (1950) below. The original pattern of the 921 ha fire is on the left, and on the right I have distributed the larger disturbance patches uniformly across an area of about 10,000 hectares. The disturbance patch size distribution – even a very reliable one – could result in both patterns, but only the clustered one best represents the natural pattern.

Figure 20. Original, clustered disturbance pattern (left box) and an artificially generated dispersed disturbance pattern (right box).



The other reason for considering entire events as opposed to individual patches is that doing so reveals critical information on what *else* is not disturbed. Until now, our focus has been on understanding and accounting only for "island" remnants within the disturbance patches, and that suggests that these are the only, or at least the most dominant, natural disturbance remnants. In fact, all we know at this point is that they are the easiest to identify and measure. At the very least, we now understand that there are at least two other types of remnants associated disturbance events; matrix corridors and matrix bays. Furthermore, this starts to give the concept of "connectivity" some well-needed scale-specific context.

Overall, capturing the spatial arrangement of disturbance patches may actually be one of the more relevant natural patterns for planning purposes. It successfully captures patterns of multiple disturbance patches, which has been one of the more challenging scales of observation. It is not difficult to see how this new knowledge could be used to evaluate current or future patterns of intermediate-sized "operating areas".

WHAT IS NEXT?

The analysis in this report is limited to non-spatial descriptions of the coarse-scale contents of a disturbance event. The next report will follow this same outline and describe the patterns of island remnants, including any new definitions and terms. These two reports will address questions of *what* is a disturbance event. The report following that one will deal with the *where* and *why* details of disturbance events. It will use both events and island data, and explore questions of location such as: where do matrix and island remnants tend to form? Do event boundaries correspond to other abiotic or biotic landscape features? Is the amount of disturbed area related to stand type or age? These and many other similar questions will be the focus of the second to next report, and it will be more efficient to use both island and event data to do so since it is reasonable to hypothesize that the processes responsible for the formation of disturbed patches and matrix remnants are the same ones responsible for island remnants.

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GLOSSARY OF TERMS

The following is a list of technical terms used in this document that are either uncommonly technical, or are used ambiguously. We do not claim these to be the "right" definitions, but rather the definitions used in these reports.

Biodiversity - a qualitative feature of natural systems describing the numbers and types of different biological elements at different scales. Not the same thing as diversity.

Burn fraction – a relative measure of flammability, or probability of burning for different parts of a forest landscape. Normally expressed as the average percentage burnt, per type, per year.

Crown fire - fire actively or passively reaches into the crowns of trees. Crown fires are virtually always associated with surface fires, but mortality can vary widely.

Cultural disturbance – Disturbances from anthropogenic sources only (*e.g.*, harvesting, prescribed burning, road building).

Disturbance - any abrupt event that results in the destruction or damage of any part of the biota. Disturbances can occur at any scale.

Disturbance frequency - the probability that a specific area is disturbed in a given time period. Reciprocal of "return interval".

Disturbance patch – Contiguous area affected by a single disturbance event. Disturbance Patches combine to form Disturbance Events.

Disturbance rate - the percentage of area affected by disturbance over a given period. Sometimes the reciprocal of fire cycle when expressed on an annual basis.

Disturbance regime - types, frequencies, periodicity, severity, and sizes of disturbances.

Diversity - the number (and sometimes the relative amounts) of different types of elements. Diversity is *one* element of biodiversity.

Ecological rotation – The number of years that forest stand-types generally survive intact before being disturbed from natural sources, or otherwise change form or function.

Event (or Disturbance event) – An area of land that is affected by the same disturbance. Events can be composed of multiple disturbance patches, as well as non-disturbed patches of forest and non-forest land.

Fire behaviour - how, how fast, where, and what an individual fire burns. Contrast with Landscape Fire behaviour below.

Fire cycle - the average number of years required to burn an area equivalent in size to the study area / landscape.

Fire intensity - the actual temperature at which a fire burns - as opposed to fire severity.

Fire refugia - a small area which has survived more than one fire event, and therefore tends to be much older than surrounding areas of forest.

Fire return interval - the average return time of fire at a specific location. For example, north-facing slopes may have longer fire return intervals than south-facing slopes.

Fire severity - the amount of mortality caused by a fire. Not necessarily related to fire intensity.

Island remnant – A patch or clump of trees that survived the last stand-replacing disturbance event in whole or part, located within a disturbed patch.

Landscape - a mosaic of stands large enough to have identifiable large-scale (fire) behaviour emerge. The natural subregions are referred to as landscapes in this document.

Landscape fire behaviour - how, how often, where, and what fires burn – on average - over decades or centuries.

Meso-scale - the scale of an individual fire event. Between stand and landscape scales.

Natural disturbance – Disturbances that originate from natural, non-anthropogenic sources. In this report, "natural" is usually used together with "historical" to describe disturbance processes, this allows for the inclusion of unknown levels of historical aboriginal activity.

Natural range of variability / variation – (NRV) Structural, compositional, and functional variation of an ecological system, at any spatial or temporal scale, predominantly (but not wholly) caused by natural disturbance regimes.

Non-forested – any area of a landscape that is void of tree growth, including water, meadow, brush, rock outcrop, swamp and bog.

Non-operating – term adopted for this report, but synonymous with the Alberta government term "non-productive forest land" and defined as: land not capable of meeting the specific productive and potentially productive growth time lines.

Patch - a contiguous area of the same type (defined by age, composition, structure, or other feature).

Pattern - any behaviour (spatial or temporal) that is not random.

Riparian zone – terrestrial area immediately adjacent to water bodies, creeks, rivers, or streams.

Seral-stage – Stand development categories that relate to structure and composition, but are often simply associated with broad age-classes. In this report we use four seral-stages; Young, Pole, Mature, and Old.

Surface fire - fires that burn along the ground, only occasionally "torching" individual trees. Tree crowns are usually unaffected.

Stand-origin map – map showing the year of the origin of the stand, or the date of the last stand-replacing disturbance event. Also often referred to as a time-since-fire map.

Veteran – An individual tree that survived the last disturbance event.

Appendix A – Equations Used in This Report

Figure 6: Only those events larger than 1 ha were used.
$EventShape = 1.11 + 0.262\log(EventArea)$ n=46, R^2 = 0.35, SE = 0.38

Figure 7: Only those events larger than 10 ha were used.
$\%CoreArea = 182.9 - 180.9\sqrt{1/\log(EventArea)}$, n=41, R^2 = 0.93, SE = 7.78

Figure 10: Only those events larger than 10 ha were used.
$No.ofDisturbedPatches = \left(-1.075 + 1.265 \times \log(EventArea)\right)^3$
N=37 (ie, only those events larger than 10 ha), n=38, R^2 =0.41, SE = 0.86

Figure 11: Only those events larger than 1 ha with more than one disturbance patch were used.
$\#DisturbedPatches < 2ha = 2.237 + 0.438\sqrt{EventArea}$ n=29, R^2=0.34, SE=20.9.
$\#DisturbedPatches(2-10)ha = -2.399 + 0.275\sqrt{EventArea}$ n=29, R^2=0.43, SE=9.9
$\#DisturbedPatches(11-40)ha = -1.166 + 0.122\sqrt{EventArea}$ n=29, R^2=0.48, SE=4.0
$\#DisturbedPatches(41-200)ha = -0.237 + 0.042\sqrt{EventArea}$ n=29, R^2=0.42, SE=1.5
$\#DisturbedPatches(> 200)ha = -0.379 + 0.029\sqrt{EventArea}$ n=29, R^2=0.74, SE=0.54

Figure 16: Only those events larger than 1 ha, and less than 10,000 ha were used.
$DisturbedPatchShape = 1.36 + 0.846\log(EventArea)$ n=346, R^2 = 0.60, SE = 0.53

Figure 18: Only those events larger than 1 ha with more than one disturbance patch were used.
$\#UndisturbedPatches = 0.0762(EventArea)^{2/3}$ n=29, R^2=0.98, SE=2.0