CSIRO PUBLISHING

International Journal of Wildland Fire **2008**, *17*, 234–244 www.publish.csiro.au/journals/ijwf

What do we know about forest fire size distribution, and why is this knowledge useful for forest management?

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Abstract. Forest fire size distribution (FSD) is one of the suite of indicators of forest fire regimes. It is applied in forest fire management, particularly for planning and evaluating suppression efforts. It is also used in forest management in the context of emulating natural fire disturbances. Given the recent growth in research and applied interest in this topic, we review and synthesise the state of knowledge on FSD, and identify sources of knowledge uncertainties and future research directions. Based on literature, it is common for forest fires to follow the power law probability distribution, particularly the truncated subtype, under a variety of forest types and forest and fire management practices. Other types of FSD are also observed, but under specific circumstances. Although there is evidence that observed FSDs vary both over space and time, the knowledge is too fragmented to generalise the cause–effect relationships for such variation. As well, it is not clear how the various methods of studying FSD and their spatio-temporal scales influence derivations of FSDs. We suggest that a hypothetico-deductive research approach, combining empirical studies with process-based simulations is an effective means to advance the knowledge of FSD. We suggest caution in the use of FSD in forest management because applying different distributions or even different parameters for the same distribution may result in great fire size class differences and thus different implications for forest management.

Additional keywords: emulating forest disturbances, fire management, number of fires, power law, self-organisation.

Introduction

Forest fire regimes are typically characterised by the frequency or return interval, magnitude, and severity of collective fire events. However, none of these indicators reflect the fire sizes that occurred: for example, the total area burned in a region could result from many small fires or a few large fires but indicate the same fire frequency–return interval, total area burned, and severity. Information about fire sizes illustrates an important aspect of a fire regime and is a useful indicator. Forest fire size distribution (FSD) is the probability of distribution of individual fire sizes that describes the quantitative relationship between fire size and its corresponding number of occurrences in a forest landscape or region over a certain period.

Over the past decade, global interest in using FSD as an aspatial indicator or parameter in the analysis of forest fire regimes has increased: in boreal North America (Alvarado *et al.* 1998; Weber and Stocks 1998; Li *et al.* 1999; Cumming 2000; Li 2000; Ward *et al.* 2001; Lefort *et al.* 2003; Bergeron *et al.* 2004; Parisien *et al.* 2004), non-boreal North America (Heyerdahl *et al.* 2001; DiBari 2003), southern Europe (Moreno *et al.* 1998; Pereira *et al.* 2004), and Australia (Gill *et al.* 2003). The insight gained from FSD complements other common indicators of forest fire regimes. As well, interest in FSD among researchers has extended beyond theoretical inquiries of fire regimes to applications in forest management and forest fire management.

In the present article, our goal is to review and synthesise the published literature about FSD, with the intent of generalising the state of knowledge and its utility in forest management. First we focus on various definitions and methods of determining FSD, the spatial and temporal variability of FSD, and the factors that determine and influence FSD. Subsequently, we explore the applications of FSD in forest management and forest fire management, with a brief discussion on the uncertainties in FSD knowledge and future research directions needed to address those concerns.

Knowledge of forest fire size distributions

The increased interest by researchers in various aspects of FSD is reflected by the rapid growth in the number of publications on that topic, especially during the last 10 years (Fig. 1). Although most are qualitative descriptions of FSD properties, the net number of publications that focus on quantifying properties of FSD has increased (Fig. 1).

The present body of published knowledge of FSD stems from a variety of investigations, each with different objectives. Some information on FSD is from studies of fire regimes (Li *et al.* 1999; Parisien *et al.* 2004). Others have studied temporal variations in FSD (Robertson 1972; Schoenberg *et al.* 2003) or factors that influence FSD, especially the effects of fire management (Minnich 1983; Ward and Tithecott 1993; Minnich and Chou 1997; Li *et al.* 1999; Turcotte *et al.* 1999; Rollins *et al.* 2001; Ward *et al.* 2001; Song *et al.* 2002; Cumming 2005). Many have focussed on deriving FSDs in general (Strauss *et al.* 1989; Malamud *et al.* 1998, 2005*b*; Li *et al.* 1999; Ricotta

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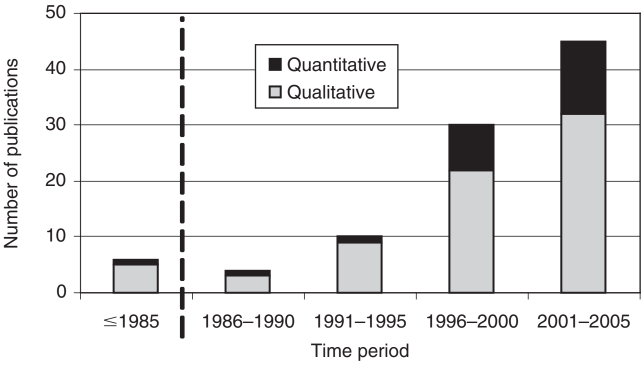

Fig. 1. Temporal trend in publications that address forest fire size distributions based on a keyword-based literature search for 1950–2005. Quantitative, publications that quantify properties of FSD; Qualitative, publications that describe FSD textually.

et al. 1999, 2001; Schenk *et al*. 2000; Cumming 2001; Reed and McKelvey 2002; Song *et al*. 2002; Schoenberg *et al*. 2003; Pereira *et al*. 2004) or for specific instances such as large fire sizes (Moritz 1997; Alvarado *et al*. 1998). These publications belong to two major methodological categories. The more popular approach has been to collect fire occurrence–fire size data from historical records and derive empirical relationships (Robertson 1972; Strauss *et al*. 1989; Chou *et al*. 1993; Moritz 1997; Alvarado *et al*. 1998; Weber and Stocks 1998; Ricotta *et al*. 1999, 2001; Burroughs and Tebbens 2001; Cumming 2001; Ward *et al*. 2001; Schoenberg *et al*. 2003; Díaz-Delgado *et al*. 2004; Holmes *et al*. 2004; Pereira *et al*. 2004). Other researchers used a variety of simulation models to estimate FSDs (Malamud *et al*. 1998, 2005*a*; Li *et al*. 1999; Malamud and Turcotte 1999; Turcotte *et al*. 1999; Cumming 2000; Schenk *et al*. 2000; Song *et al*. 2001; Reed and McKelvey 2002; Gill *et al*. 2003).

Furthermore, the general concept of FSD is referred to by many different terms based on specific objectives and methods employed: wildfire size distribution (Li *et al*. 1999; Cumming 2000, 2001; Schenk *et al*. 2000; Ward *et al*. 2001; Reed and McKelvey 2002; Schoenberg *et al*. 2003; Díaz-Delgado *et al*. 2004; Pereira *et al*. 2004), fire size frequency distribution (Chou *et al*. 1993; Holmes *et al*. 2004), number–size distribution of forest fire areas (Burroughs and Tebbens 2001), probability distribution that describes fire-size population (Moritz 1997; Alvarado *et al*. 1998), distribution of fire size (Robertson 1972), frequency–area (or frequency–size) distribution of fires (Malamud *et al*. 1998, 2005*a*, 2005*b*; Malamud and Turcotte 1999; Turcotte *et al*. 1999; Ricotta *et al*. 2001; Song *et al*. 2002).

The differences in specific objectives, approaches, and terminology notwithstanding, all FSDs are described using the same basic elements: the number of fire occurrences and their corresponding sizes, both in a defined spatial extent, and over a specified time period. In these descriptions, fire size is typically defined as the area burned within the fire perimeter including unburned patches, also known as fire residuals or skips (Hunter 1993; Cumming 2001; Heyerdahl *et al*. 2001; Rollins *et al*. 2001). In addition to fire sizes and their corresponding numbers of occurrences, the spatial extent or the size of the study areas within which fires have been observed (Boychuk *et al*. 1997; Schenk *et al*. 2000; Heyerdahl *et al*. 2001) and the temporal period or number of years over which fires have been observed (Ricotta *et al*. 2001; Rollins *et al*. 2001; Ward *et al*. 2001; Li 2004) are essential to describe FSD. As we will discuss in later sections, the size of area and the length of observation period affect the sample size (total number of fire occurrences) and especially the number of large fires, and lead to greater errors in empirical formulation of FSDs. In special situations, descriptors of FSD may include the minimum and maximum fire sizes when the derivations are limited to a size range of fires.

Forest fire size distributions reported in literature

Most of the published literature on FSD is from studies of the North American boreal forest and most generalisations in that knowledge are derived from that literature. For example, it is widely known that in North American boreal forests, most fires that occur in a given large forest landscape over a sufficiently long period are small, but a small number of large fires account for most of the area burned (Payette *et al*. 1989; Bergeron 1991; Hunter 1993; Ward and Tithecott 1993; Hawkes *et al*. 1997*a*, 1997*b*; Johnson *et al*. 1998, 2001; Weber and Stocks 1998; Cardille and Ventura 2001; McRae *et al*. 2001; Bergeron *et al*. 2002, 2004; Ryan 2002; Andison 2003*a*, 2003*b*; Lefort *et al*. 2003; Li 2004; Parisien *et al*. 2004). This holds true for forests in other regions of the world as well, for example in the north-western United States (Cramer 1959; Heyerdahl *et al*. 2001); south-western United States (Davis 1965; Minnich 1983; Strauss *et al*. 1989; Chou *et al*. 1993; Minnich and Chou 1997); Rocky mountains (Rollins *et al*. 2001); Australia (Haydon *et al*. 2000); and Spain (Moreno *et al*. 1998; Vazquez and Moreno 2001; Díaz-Delgado *et al*. 2004). Once this generality is quantified, forest fire sizes are most likely to follow the probability distributions of the power law family, which include power law, negative exponential, and Pareto, as well as truncated versions of those distributions.

Power law family of forest fire size distributions

The probability distribution function of a power law distribution can be expressed as:

$$P(X = A) \sim A^{-b} \tag{1}$$

where $P(X = A)$ is the probability distribution function, X is a random variable, A is a given fire size, and b is the constant (slope).

Fig. 2 is an example of power law distribution. The slope value b is the most important parameter of the power law distribution of fire sizes. When $b > 1$, small fires account for more total area burned than large fires; when $b < 1$, large fires account for more total area burned than small fires; and when $b = 1$, all fires sizes have equal contribution to the total area burned. It is important to remember that the fire size and its number are in log scale, and therefore, effect of changes in slope values on fire sizes and number is not linear.

The truncated power law distribution is used when the data do not fit over the whole range of forest fire sizes. Truncations are applied for very small and very large fire sizes. Generally truncation is applied to improve the fit of the FSD. This is discussed in more detail in later sections.

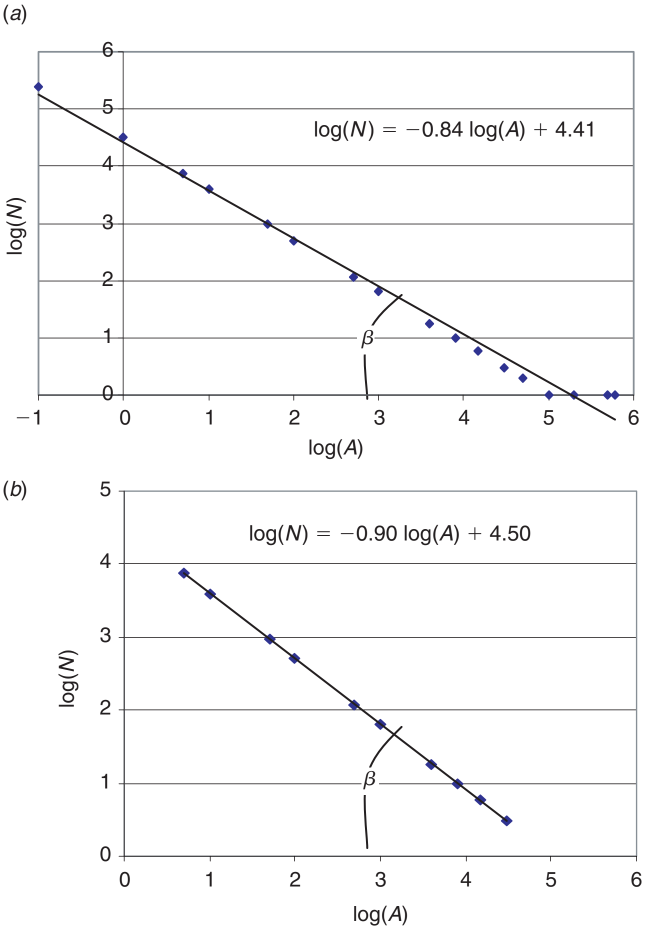

Fig. 2. An illustration of power law distribution of forest fire sizes: (*a*) power law distribution with a slope value (*b*) of 0.84; and (*b*) truncated power law distribution with a slope value (*b*) of 0.90 (N is the number of fires at a given size A, β is the slope angle, and the slope value $b = \tan\beta$).

Malamud *et al.* (1998) were the first to provide quantified empirical evidence that forest fires follow power law distribution. They found that FSD from a range of forest types, varying from Alaska to the western United States to Australia, followed power law distribution, albeit with different slope values. In their study, Alaskan boreal forests followed a power law distribution with a slope of 1.43; forests in the western United States had slope ranges from 1.31 to 1.34; and the Australian Capital Territory had slope ranges from 1.43 to 1.49. Ward *et al.* (2001) reported a wide range of fire sizes (4 to 20 000 ha) over a 34-year period in boreal Ontario, Canada, also followed the power law distribution. However, they reported that the specific slope values varied with the intensity of the degree of fire suppression: the slope value was lower (1.127) in the fire management zone where all fires were aggressively suppressed than the slope value (1.254) in the zone where fire suppression was less aggressive. There is evidence for power law behaviour in FSD from China (Song *et al.* 2001) as well, with slopes ranging from 1.25 to 1.30. Malamud *et al.* (2005*b*) reported that all forest fire sizes (even fires exceeding 100 000 ha) in each ecoregion in the mainland United States also fit power law behaviour in their FSD, with slopes ranging from 1.1 to 1.8. In addition to these empirical studies of fire sizes, power law behaviour in FSD is also reported from simulation modelling studies that investigated self-organisation characteristics of forest fires (Malamud *et al.* 1998; Turcotte *et al.* 1999; Schenk *et al.* 2000). It is now almost generalised that 'both real and modelled fire-prone landscapes exhibit roughly power law statistics in fire size *v.* frequency' (Moritz *et al.* 2005).

A few studies have also fitted the negative exponential distribution to FSD, all from the Canadian boreal region (Weber and Stocks 1998; Li *et al.* 1999; Cumming 2000). The negative exponential distribution is expressed as:

$$P(X = A) \sim e^{-bA} \quad A > 0, b > 0 \tag{2}$$

where $P(X = A)$ is the probability of a fire of size A, X is a random variable, and b is the shape parameter for the negative exponential probability distribution.

There are many reports of truncated versions of the power law distribution as well, where the FSD is fitted only for a preselected range of fire sizes. For example, Ricotta *et al.* (1999, 2001) reported that the power law distribution was applicable only to fire size classes from 30 to 3000 ha in the Mediterranean region, where forest fires can exceed 100 000 ha. A similar report from Australia (Burroughs and Tebbens 2001) indicates that the power law distribution is applicable only to fires less than 72 500 ha (~30% of the region studied). Others mention the truncated behaviour of power law distribution in forest fires without specifying the truncation limits, for example DiBari (2003) from the western United States and Díaz-Delgado *et al.* (2004) from Spain. Furthermore, some researchers described a 'piece-wise' characteristic in the power law distribution of FSD. For example, Holmes *et al.* (2004) found that the slope values for forest fires followed power law with different slopes for three size class ranges in the observed fires.

Some researchers also have fitted empirical forest fire size data using Pareto distribution (Robertson 1972; Strauss *et al.* 1989; Alvarado *et al.* 1998; Cumming 2001; Schoenberg *et al.* 2003). The cumulative distribution function of a Pareto distribution $P(X > A)$ can be expressed as:

$$P(X > A) \sim A^{-k} \tag{3}$$

where $P(X > A)$ is the probability distribution function, X is a random variable, A is a given fire size, and constant k is the Pareto distribution shape parameter. If $P(X > A)$ only works for part of the range of A, then it is a truncated Pareto distribution. If $P(X > A)$ works for several segments of the range of A, then it is a segmented Pareto distribution.

The literature that reported FSD that fitted a truncated Pareto distribution includes Strauss *et al.* (1989) for Southern California and the Baja region; Alvarado *et al.* (1998) for fires >200 ha in Alberta; Cumming (2001) for fires up to 650 000 ha in Alberta, and Schoenberg *et al.* (2003) in California. The only report on segmented Pareto distribution is Robertson (1972), who studied forest fires up to 26 800 ha in California.

Negative exponential, power law, and Pareto distributions for the logarithm of fire size are basically the same family of distributions (Reed and McKelvey 2002), except that each one uses a different mathematical expression from a different perspective. For example, power law distribution explains how many fires

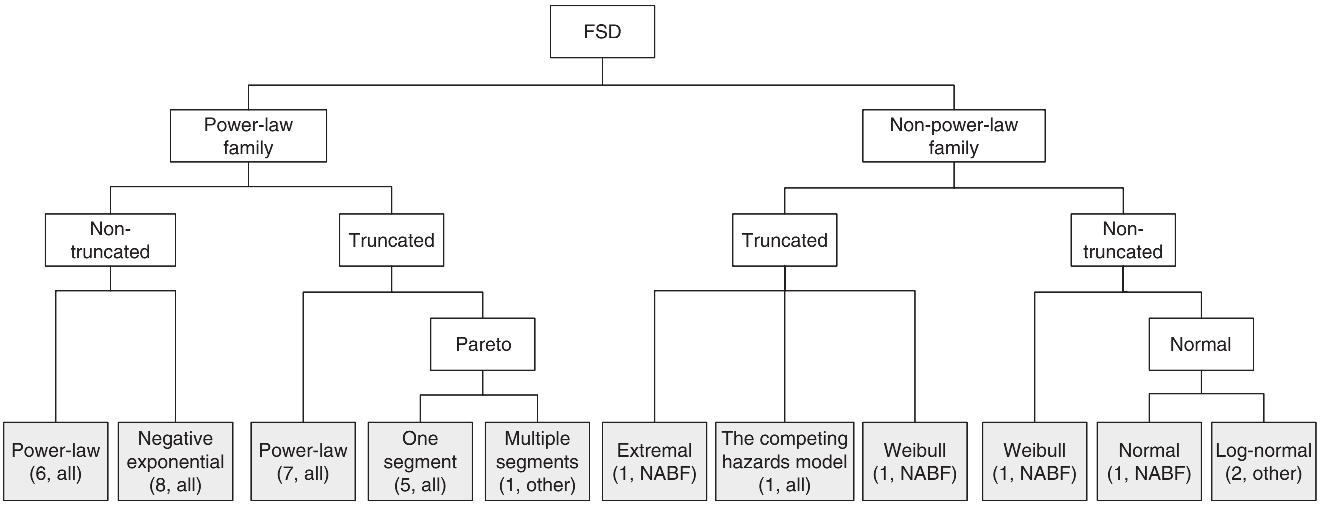

Fig. 3. A grouping of major forest fire size distributions reported in publications. Note: the numbers in parentheses refer to the number of publications; NABF refers to North American boreal forest; 'other' refers to non-NABF forests; 'all' includes both NABF and 'other'.

have a size that is exactly A. Pareto distribution explains how many fires have a size that is greater than A.

Non-power law distributions of forest fire sizes

To avoid the overgeneralisations that arise during attempts to derive one distribution function for a wide range of fire sizes, some authors have derived FSD to explain specific fire sizes. For example, extremal distribution (Moritz 1997) has been used to describe extreme (large and rare) fire events, whereas the competing hazards model (Reed and McKelvey 2002) has been used to describe smaller and more common fire events.

An extremal distribution can be expressed as (Moritz 1997):

$$F(A) = \exp\left(-\left[\frac{\alpha - \beta A}{\alpha - \beta\varepsilon}\right]^{1/\beta}\right) \tag{4}$$

where $F(A)$ is the cumulative distribution to estimate the probability that the largest fire in a single time period will be smaller than some specific size A. Parameters α, β and ε are dimensionless, and they determine the category of distributions to which $F(A)$ belongs. As the 'slope' parameter β approaches 0, this distribution approaches the Extreme Value distribution. For $\beta < 0$, the distribution is of Cauchy family, and for $\beta > 0$, it is of Weibull family. ε is the modal event magnitude; α measures how quickly $F(A)$ rises with the natural logarithm of time, and $\frac{\alpha}{\beta}$ estimates the limiting magnitude observable.

α, β and ε must be estimated empirically using the maximum likelihood method. By creating a time series of the largest event per time event interval (e.g. the annual maximum series making up the extreme fire regime) and ranking the sample values, A_i (where i is the rank of the event in the time series and the smallest has rank = 1), an estimate of the cumulative distribution can be made from the following expression:

$$F(A_i) = i/(N+1) \tag{5}$$

Here N is the number of extreme events observed (e.g. number of years in fire record), which is also equivalent to the highest rank. Maximum likelihood techniques are commonly used for parameter estimation from this sample distribution.

The competing hazards model (Reed and McKelvey 2002) is developed to describe FSD for small- to medium-sized fires (excluding very large fires).

For a hazard rate of the form:

$$\rho(A) = aA^{-bA} + ce^{-dA} \tag{6}$$

fire size has a probability distribution function:

$$P(A) = a(A^{-b} + \theta e^{-dA}) \times \exp\left\{-a\left[\frac{A^{1-b} - A_0^{1-b}}{1-b} - \frac{\theta(e^{-dA} - e^{dA_0})}{d}\right]\right\} \tag{7}$$

where $\rho(A)$ is the hazard rate, $P(A)$ is the probability distribution function, A is the fire size, a, b, c, d are parameters that can be estimated using the maximum likelihood method, and $\theta = c/a$.

Other FSDs mentioned briefly and qualitatively in literature include Weibull and truncated Weibull distributions (Li 2000; Pereira *et al.* 2004), normal distributions (Weber and Stocks 1998), and log-normal distributions (He and Mladenoff 1999; Haydon *et al.* 2000) without supporting evidence.

We summarise the probability distribution types discussed above, with reference to their characteristics and geographies of origin as well as the frequency of their mention in literature in Fig. 3.

Spatial and temporal variability of forest fire size distributions

As exemplified by the discussion above, there are differences in probability distribution types of FSD and parameters within a given distribution type (for example the slopes of power law distribution). This variability may be a result of differences in study methods employed, such as study area extents and observation periods, but there may also be innate reasons why FSDs vary both spatially and temporally.

Spatially, FSDs may vary at the broadest scale owing to differences in regional geoclimate (Malamud *et al.* 2005*b*) that influence the broader fire regime. At relatively finer spatial scales, FSDs may vary from place to place owing to differences in incidence and size of fires as influenced by many factors.

To simplify our examination of the temporal variability in FSD, we grouped the published FSD studies into two periods based on the length of the observation period: (1) less than 20 years, and (2) over 20 years. This was based on the assumption that significant contextual changes, such as forest cover types and climate of a studied area, would not occur within two decades. Several reports mention FSD could change even within a period of 20 years (Cramer 1959; Robertson 1972; Van Wagtendonk 1986; Moreno *et al.* 1998; Díaz-Delgado *et al.* 2004; Pereira *et al.* 2004). For example, Cramer (1959) found that the number of fires increased at an average rate of 37 fires per year over a period of 14 years in the north-western United States, while the fire sizes decreased continuously over the same period, thus changing the FSD.

There are many reports of changes in FSD during observation periods longer than two decades. Díaz-Delgado *et al.* (2004) reported that while the total number of fires decreased over a 24-year period, the number of large fires increased. Other reported FSD changes over time include: over 35 years in Ontario's boreal forest (Ward *et al.* 2001), over 40 years in British Columbia, Canada (DeLong 1998), over 40 years in China (Song *et al.* 2001), over 60 years (1930–1989) in the boreal forest in Ontario (Weber and Stocks 1998), and over 76 years in Ontario, Canada (Bridge *et al.* 2005). From a study of fire sizes over a very long period, Niklasson and Granstrom (2000) reported counteracting trends in fire size in the European boreal forest: the number of fires per unit area and time increased 10-fold between the period 1350–1650 AD and 1840–60 AD, whereas the proportion of the area burned per unit time increased only four-fold. The only exception to the evidence on temporal variability in FSD is Malamud *et al.* (2005*b*), who reported a constant FSD for the continental United States over a 30-year period from 1970 to 2000 AD.

In addition to natural factors, human interventions such as fire suppression could also cause spatial and temporal viability in FSD. For example, Weber and Stocks (1998) stated that 'modified or selective fire suppression of this sort results in a negative exponential distribution which favours smaller fire size classes'. This is evident with Ward *et al.* (2001), where the FSDs (i.e. slopes of power law distributions) were found to be different in zones with different fire suppression strategies in Ontario's boreal forest.

Factors that influence forest fire size distributions

The literature does not adequately address direct determinants of the spatial and temporal variability of FSD. Therefore, here we discuss the many interacting factors that directly affect *fire occurrence* (which determine the number of fires) and *fire behaviour* (which determine the sizes of fires), and therefore are factors that influence FSD. We consider spatial fire barriers, such as water bodies and fuel breaks, as spatial constraints because these can limit final fire sizes. Although the extent and shape of the study areas and temporal period of study impose constraints on FSD observed, we do not consider those to be factors that influence intrinsic properties of FSD. Fig. 4 illustrates all factors we consider as determinants and constraints of FSD. Although some linkages among factors are shown, for simplicity of illustration not all possible interactions are shown. These factors are grouped based on temporal perspective (short-term and long-term, mainly depending on contextual changes) and source of origin (human and natural).

Short-term factors include those that directly influence fire occurrence and fire behaviour, and together with spatial constraints determine FSD. These include natural factors such as weather, terrain, and composition and spatial configuration of land cover types. The short-term human factors of influence are forest cover modifications that alter fuel patterns, people-caused fire occurrence, and forest fire suppression. The long-term factors and constraints affect FSD indirectly, mainly by influencing forest succession, which in turn determines composition and spatial configuration of fuel and non-fuel cover types and changes fire weather. The long-term natural factors mainly include long-term climate patterns, and other recurring natural disturbances such as pest epidemics and windthrow, which modify initial land cover patterns (composition and spatial configuration of fuel types). Long-term constraints include the past fire and forest succession history that affects forest succession trajectories.

Environmental factors

Weather is one of the most important determinants of fire occurrence and behaviour (Forestry Canada, Fire Danger Group 1992; Johnson 1996; Flannigan and Wotton 2001; Wotton 2004), and therefore a significant short-term factor influencing FSD (Hunter 1993; Minnich and Chou 1997; Malamud *et al.* 2005*b*). Weather conditions affect fire occurrence by controlling fire ignitions through lightning strikes as well as moisture content of fuel. For example, number of fires is positively correlated with the total number of rainless days (Cramer 1959). Local weather determines fire behaviour and burn time, and therefore final fire size (Heinselman 1981), by controlling moisture content of fuel, and wind speed and direction. It is well understood that climate influences FSD (Cramer 1959; Minnich 1983; Van Wagtendonk 1986; Chou *et al.* 1993; Hawkes *et al.* 1997*b*; Moritz 1997; DeLong 1998; Malamud *et al.* 1998; Rollins *et al.* 2001; Reed and McKelvey 2002; Bergeron *et al.* 2004; Li 2004; Telesca *et al.* 2005). Specifically, the synoptic climate regulates short-term weather patterns (Johnson 1996) and the length of the fire season, which directly affect FSD in the short term. Possible temporal changes in climate also may affect the long-term trends of FSD (Lefort *et al.* 2003) by changing the fire cycle (Bridge *et al.* 2005).

Composition and spatial configuration of fuel and non-fuel cover types is another important natural determinant of FSD (Van Wagtendonk 1986; Hunter 1993; Hawkes *et al.* 1997*b*; Malamud *et al.* 1998, 2005*b*; Moreno *et al.* 1998; Cumming 2001; Song *et al.* 2001; Bergeron *et al.* 2004; Telesca *et al.* 2005) through its influence on fire behaviour (Malamud *et al.* 1998; Ricotta *et al.* 1999; Reed and McKelvey 2002). If a landscape is interspersed with deciduous forest cover and other less-burnable land cover types (Ricotta *et al.* 1999; Parisien *et al.* 2004) and lakes (Hunter 1993; Bergeron *et al.* 2004), fire spread is hindered, especially under non-severe fire weather conditions, leading to

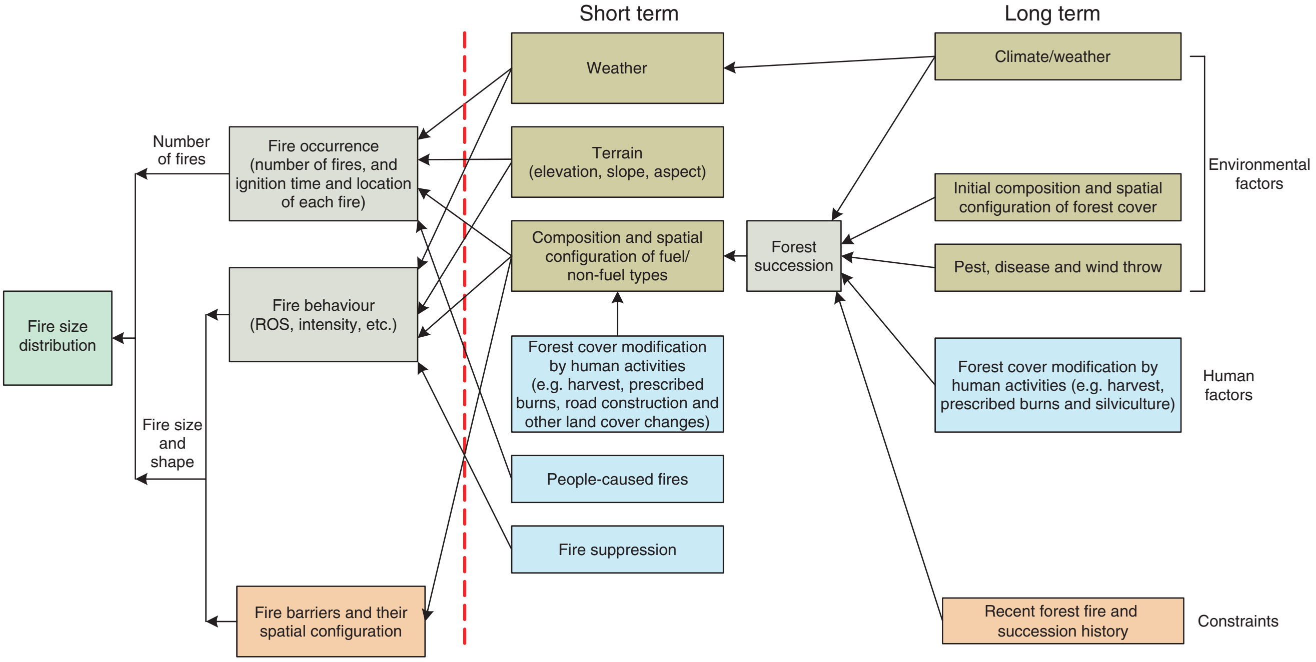

Fig. 4. An abstraction of the major causal factors of forest fire size distributions. To simplify the illustration, not all possible interactions among these factors are shown.

power law FSD with relatively steeper slopes (i.e. many smaller fires and fewer large fires). Terrain influences FSD by its direct influence on fire behaviour (Heinselman 1981; Minnich 1983; Van Wagtendonk 1986; Chou *et al*. 1993; Hawkes *et al*. 1997*b*; Minnich and Chou 1997; DeLong 1998; Bergeron *et al*. 2004; Malamud *et al*. 2005*b*; Telesca *et al*. 2005) and its effect on spatial configuration of cover types and compositional changes in the long term. Terrain is often used to refer to elevation, slope, and slope aspect. It may also include local features such as valley orientation. All of these factors affect fire behaviour. For example, slope affects rate of spread while aspect affects spread direction.

Human factors

Human influence on FSD is manifest in three ways: land cover modifications, and thus fuel availability and flammability; increased fire occurrence; and limitations in fire size through suppression. Forest harvest, for example, creates temporary gaps in fuel availability while associated road building may create permanent fire barriers and thus limit fire sizes (Malamud *et al.* 2005*b*). Land cover type conversion (e.g. forest cover to agriculture or vice versa) is an important factor influencing FSD (Ricotta *et al*. 1999; Lefort *et al*. 2003) over the long term by modifying the course of forest succession, and thereby changing the composition and spatial configurations of fuel types. Forest management practices such as prescribed burns create temporary fire barriers that might limit sizes of subsequent forest fires or even prevent fire ignitions for many years (Piñol *et al*. 2005). Human settlements increase the propensity for fire ignitions, resulting in increased fire occurrence (Moreno *et al*. 1998), and such fires differ from lightning-caused fires in location, time, and size. These may be concentrated in areas where human activities are more frequent, their temporal pattern may be different from lightning-caused fires, and their final sizes may be smaller owing to increased likelihood of early detection and suppression than lightning-caused fires.

Fire suppression is a direct anthropogenic factor affecting FSD, even though its significance has been a point of debate (Miyanishi and Johnson 2001; Ward *et al*. 2001). There is evidence that fire suppression during initial stages of fire reduces the number and frequency of large fires in several regions: sub-boreal forest of northern British Columbia (Hawkes *et al.* 1997*a*), boreal forest of north-eastern Alberta (Cumming 2005), and Mediterranean forest of southern Italy (Telesca *et al*. 2005). At the same time, some believe that intense fire suppression may result in fires larger than normal because of fuel build-up, for example, in boreal forest of north-eastern Alberta (Cumming 2000) and Yellowstone National Park of the United States of America (DiBari 2003). Fire suppression is also believed to increase the frequency of smaller fires (Malamud *et al*. 1998; Ward *et al*. 2001; Li 2004) but results in more fires per year under simulated scenarios (Li *et al*. 2005). In spite of the varying arguments and findings above, we assert that fire suppression leads to many small fires and therefore increased slopes of power law FSD over short periods such as several decades. However, some consider that several decades are not long enough to decide the effect of fire suppression (Bridge *et al*. 2005).

Self-organisation of forest fires

As presented above, a broad range of natural and human factors influence forest fire occurrence and fire behaviour, and thus FSD. In a finite space, present (and past) fire events can influence the occurrence and behaviour, and thus the size, of future fires. This characteristic has been observed in many regions, for example, southern California (Minnich 1983; Minnich and Chou 1997), boreal forest in Alberta (Cumming 2001), and spruce-fir and lodgepole pine forest in the United States (Sweaney 1983). Niklasson and Granstrom (2000) found that past fires that occurred within 15 to 20 years acted as fire-breaks and limited the sizes of subsequent fires in a Scandinavian boreal forest. Therefore, as Cumming (2001) reported from boreal north-eastern Alberta, the expected size of a fire is negatively correlated with the abundance of previously disturbed areas in the same space. This phenomenon is known as the self-organisation of forest fires: natural processes such as forest fires, which are controlled by complex and interdependent factors, exhibit characteristics of self-organisation (Malamud *et al.* 1998; Ricotta *et al.* 1999) and, at equilibrium, follow a truncated power law distribution (Ricotta *et al.* 1999; Burroughs and Tebbens 2001). Self-organisation behaviour has also been observed as an emergent property in simulation modelling (Malamud *et al.* 1998, 2005*a*; Turcotte *et al.* 1999; Schenk *et al.* 2000; Song *et al.* 2001). Although these studies used simplified simulation premises, such as non-diverse fuel, instant burn times, and fire extinction because of fuel discontinuity, due to self-organisation of fires, the resulting FSD was power law.

As presented above, there are many natural and human spatio-temporal factors that interactively modify (promote and constrain) fire occurrence and fire behaviour, and thereby influence FSDs. In the short term, weather patterns, composition and spatial configuration of forest fuel types and fire barriers appear to be important modifiers of FSDs. The long-term modifiers of FSDs may include shifts in synoptic climate and forest succession.

Using the knowledge of forest fire size distributions in forest and fire management

There has been a recent increase in popularity in applications of FSD knowledge in forest management and forest fire management, in parallel with the growth in the knowledge of FSD. Here we summarise the most common areas of application of the knowledge of FSD based on that literature.

Forest fire size distribution in forest management

Most interest in applications of FSD in forest management has arisen from regions where forest fires are large and forest management is extensive, as is the case in North American boreal forests. Knowledge of FSD has been used to formulate policies and design long-term management strategies that guide harvest and forest management planning.

One area of application that has received considerable attention is using natural fire patterns in forest management (Hunter 1993; Attiwill 1994; Delong and Tanner 1996; Bergeron and Harvey 1997; Bergeron *et al.* 2002). Emulating natural forest disturbances is being embraced as a forest management paradigm across all northern regions of North America (Perera *et al.* 2004*a*), and some jurisdictions have even embedded this premise in forestry acts (e.g. Government of Ontario 1995). For example, forest policies in Ontario include a specific management guide (OMNR 2001) that specifies directions to design forest harvest patterns based on FSD derived from empirical observations of recent fire history (OMNR 1997). Spatially explicit simulated knowledge of FSD is a logical basis for designing forest harvest schemes, especially during regional-scale planning of forest management (Li 2004; Perera *et al.* 2004*b*). More specifically, the temporal and spatial variability of FSD, as well as spatial probability of incidence of fires of different size classes within ecoregions can be used as emulation criteria in designing size-class distributions of forest harvest patches and spatial distribution of those harvest patches, while accounting for among- and within-regional geoclimatic differences (Perera *et al.* 2004*b*). Even minor differences in the slopes of power law distribution among and within ecoregions would indicate a significant shift in size-class distribution of forest harvest that would emulate the FSDs.

Following the principle of coarse-filter approach to conserving biodiversity, which also is considered as the basis for emulating natural disturbances (Hunter 1993), there are applications of FSD in designing forest conservation efforts. Because the patch sizes of forest age–species composition are a direct consequence of the fire sizes of disturbance regimes, the knowledge of FSD is an important component in understanding the hierarchy of biodiversity in forest landscapes. Therefore, the knowledge of FSD provides considerable insight to planning for habitats of wildlife species such as caribou and marten in North America, which require large areas of forest of specific ages (Fisher and Wilkinson 2005) This notion is embodied in arguments for designing forest conservation reserves by determining the size and shape of the reserve based on the possible maximum fire size and FSD so that the conservation efforts are sustainable given the local fire regime (e.g. Baker 1989, 1992).

Beyond conservation efforts, knowledge of spatially explicit FSD is important for optimising the sequence (Martell 1994) and spatial arrangement of forest harvest blocks to reduce the impact of fire on timber supply (Palma *et al.* 2007) Assessing the impact of stand-level harvests and fuel treatments on the flammability of forest landscapes). Hirsch *et al.* (2001) suggested that strategically harvesting particular sections of the managed forest and regenerating it with a less flammable species could be used to reduce fire impact to the forest, thus reducing timber loss. Some have suggested applying knowledge of fire disturbance sizes in regional land use design to protect properties and settlements (e.g. Romme *et al.* 2004).

Forest fire size distribution in forest fire management

FSD can be used in strategic and operational forest fire management planning. Predictions of FSD are an important input for fire management planning, and this knowledge can guide development of fuel management and fire suppression policies (Minnich 1983; Chou *et al.* 1993; Minnich and Chou 1997). For example, if fire managers know the FSD of a particular region over a certain period under a certain fire suppression level, they can estimate the cost of fire suppression (Cumming 2000; Calkin *et al.* 2005; Donovan and Noordijk 2005) based on the cost of suppressing each fire, including average cost of successful initial attack and the cost of suppression of escaped fires by fire size class. Because extremes in fire behaviour during a fire season can be used to estimate the FSD, planning and deployment of suppression resources can be conducted accordingly.

Along with aggregates in area burned and number of fires, a temporal pattern in FSD of a given area is a good indicator of changes in fire regime over time. Therefore the knowledge of changes in FSD over a given period can be used to evaluate the effect of forest fire suppression policies, strategies, and actions (Davis 1965; Ward and Tithecott 1993; Ward *et al.* 2001; Bridge *et al.* 2005; Piñol *et al.* 2005). Furthermore, FSDs are also useful to evaluate effect of the prescribed fire on fire occurrence and area burned, especially the effect of large fires (Piñol *et al.* 2005).

Large fires are rare events and it is difficult to predict their occurrence, especially if the landscape is not large and the observation period is relatively short. However, the present FSD could also help to predict maximum fire size or the probability of large fire events based on the statistics of small- and medium-sized fires (Malamud *et al.* 1998; Song *et al.* 2001; Díaz-Delgado *et al.* 2004).

Considerations for using forest fire size distribution information in applications

During its application in forest and fire management, the knowledge of FSD could be misused, and hence misinform the ensuing policies and practices. In this context, below we briefly address the appropriateness of the use of FSD knowledge. One important *a priori* consideration for users of FSD knowledge is its appropriate application. Although FSDs are highly specific to regions and landscapes (because of natural conditions or human intervention) and can vary from one application to another, following are some general issues that merit consideration when applying FSD knowledge. As seen in the literature, FSDs are a family of values with substantial degrees of variability in time and space, as well as unaccountable stochasticity within a given time and space. Therefore in their applications, FSDs must not be treated as deterministic and singular entities. Furthermore, it can be argued that the most valuable insight gained from information on FSD lies in its variability and stochasticity and not, for example, in specific slope values. This is especially true when knowledge of FSD is used in quantitative models and decision-support systems, where estimates of variability and probabilities of FSD help to estimate errors and variation associated with predictions. Because FSDs are affected by a complex range of interacting natural and anthropogenic processes, their use must be context-specific and possibly spatially explicit. For example, FSD parameters derived from one geoclimatic or land-use region may not be extrapolated to another, at least without calibration.

Furthermore, knowledge of FSD is scale-related, i.e. its derivation is specific to spatio-temporal scales of observation, and consequently, its applications must conform to similar spatial extents and resolutions, and temporal periods and intervals. In addition to the stochasticity, variability, context, and scale, applications of FSD knowledge must take into account that all quantitative derivations are non-linear (i.e. based on log-log relationship between number of fire occurrences and their sizes).

The level of detail required about FSD would vary depending on the application of FSD information. For instance, it may not be important to know about all of the very small fire events for forest management applications as these disturbances will happen anyways and it is the mid- to large fire disturbances that are approximated by harvests. Thus truncated FSD is useful for these applications.

Limitations in the knowledge of forest fire size distributions and directions for future research

Even when the use of FSD knowledge is appropriate in forest management applications, users must be aware that there is a considerable degree of uncertainty associated with published knowledge of FSD due to gaps in knowledge as well as limitations in what is considered to be known. Most gaps and uncertainties in present FSD knowledge appear to be due to lack of available data and the limitations of research methods.

What are the major limitations in knowledge?

Studies based on records of past forest fires constitute the major source of present knowledge of FSD. Consequently, inadequacies such as poor-quality or insufficient data associated with empirical observations affect the reliability of FSDs thus derived (Ricotta *et al.* 2001; Ward *et al.* 2001; Telesca *et al.* 2005). A common error relating to accurately estimating fire occurrences, especially over large areas, occurs where many small fires may not be recorded owing to difficulties in their detection (Ricotta *et al.* 1999; Holmes *et al.* 2004; Telesca *et al.* 2005). This is especially true when small fires are not considered important enough to record, and few resources are allocated to detect those (Ward *et al.* 2001; Bridge *et al.* 2005). Sometimes the evidence of increased number of fires observed in recent years may be due to improved detection capabilities rather than actual increases in number of fires (Hawkes *et al.* 1997*b*).

Inconsistency in delineating sizes of fire events is another major source of error. Researchers use different methods to identify fire perimeters (Haydon *et al.* 2000), which can result in different boundaries for historical fires, and therefore different fire sizes (Jordan *et al.* 2005). For example, researchers sometimes extract the data by mapping historical fires using aerial photos (DeLong and Tanner 1996; DeLong 1998; Rasmussen and Ripple 1998; Bergeron *et al.* 2004) or satellite imagery (Haydon *et al.* 2000). Some others resort to field investigations, such as collecting dendrochronological data (Payette *et al.* 1989; Bergeron *et al.* 2004), crossdating fire scars in dead wood and living trees (Niklasson and Granstrom 2000), or a combination of techniques based on fire scars, abrupt changes in ring width, and cohort establishment dates (Heyerdahl *et al.* 2001). These methods may result in different biases in fire numbers and accuracies in their sizes, and therefore FSD estimates for a given study area.

Another source of uncertainty in empirical FSD studies is relatively small temporal and spatial scales of observations. Short observation periods necessarily mean fewer fires (Ricotta *et al.* 1999; Ricotta *et al.* 2001; Ward *et al.* 2001; Li 2004), which may not be sufficient to derive reliable FSDs. Sometimes researchers acknowledge (e.g. Rollins *et al.* 2001) that the period of records in fire databases may be too short to fully assess FSDs. More specifically, temporal limitations in collected data on forest fires may affect the upper truncation point of the power law distribution (Burroughs and Tebbens 2001). Spatial constraints that modify FSD in a given area include the size, shape, and boundary conditions of the study area. As with short study periods, small study areas are not only likely to result in fewer observed fires, but also limit the largest fire that can be observed. If the study area is not large enough, it may limit the number of large fires included and prevent fires larger than the size of study area from being accounted (Boychuk *et al*. 1997; Minnich and Chou 1997; Schenk *et al*. 2000; Heyerdahl *et al*. 2001), thereby imposing an artificial truncating point on the FSD. Burroughs and Tebbens (2001) indicated that the upper truncation point in such distributions is a function of the size of the study area.

As discussed earlier, variability in FSD is determined by many causal factors, singly or in combination. Some factors may interact to either enhance or neutralise their overall effect. Empirical observations alone cannot show these effects, as reflected by the dearth in knowledge about how these causal factors affect FSD. Even when FSD knowledge is derived from simulation studies, simplification in assumptions of models may oversimplify the fire occurrence and growth scenarios. For example, self-organised forest fire simulation models usually do not include parameters such as forest cover types, weather conditions, and fire barriers (Malamud *et al*. 1998; Turcotte *et al*. 1999; Schenk *et al*. 2000; Song *et al*. 2001).

What are some important research directions?

Further studies are needed to understand conceptual aspects of FSDs as well. For example, the relationship of FSDs to spatial and temporal scale, with respect to the extent of study areas and temporal periods, needs further investigation. For example, what is the effect of period of observation on FSDs derived? What is the effect of the extent studied on FSDs derived? At what spatial extents and time periods is the self organisation behaviour exhibited? Are occurrences and sizes of fires spatially independent? Are the FSD types interrelated? Are the FSD types nested in a hierarchy of scale? Certainly more studies are necessary to understand the variability and cause–effect relationship between FSD and factors that influence FSD. In particular, how specific FSDs are related to different geoclimates and anthropogenic effects such as forest and fire management regimes requires study. For example, what are the effects of shifts in synoptic climate on FSD? Which aspects of 'natural' fire disturbances differ or are similar to different aspects of 'anthropogenic' fire disturbances with regard to FSDs? How and when does fire suppression influence FSDs? How does fuel modification (i.e. forest and fire management activities) influence FSDs? In general, as the global emphasis on fire suppression increases, there will be a need to evaluate the effects of direct fire suppression and indirect fire management through fuel modifications on FSDs, and hence fire regimes. There will also be a need to understand effects of contextual changes in climate on fire incidence and fire sizes through natural changes in fire weather as well as forest cover types and landscape patterns. There also will be a need to understand how climate change will influence post-fire forest succession and thus fuel patterns, as well as the occurrence of other disturbances such as forest pest and disease epidemics, as these will in turn modify forest fire regimes and thus FSD.

All areas of research above would benefit from study approaches that complementarily combine empirical studies that use observations of past fires and simulation models that use process-based mechanistic knowledge of fire occurrence and behaviour. Such a hybrid approach would effectively use the strengths of empirical data with the exploratory power of simulation models. This would also allow the use of a hypothetico-deductive approach in FSD research, which presently is not common in FSD literature. As in other areas of natural science research, simulation models could generate scale-specific hypotheses based on process knowledge, and empirical observations of fires could be used to test those hypotheses to advance the knowledge of FSD in incremental steps.

We also suggest caution in using FSD in forest management because many uncertainties about FSD remain due to limitations in knowledge and data. The use of different distributions or even different parameters of the same distribution means great fire size class differences and thus means implications for forest management.

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Manuscript received 9 November 2006, accepted 17 September 2007