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Self-organized criticality of forest fire in China

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Abstract

Self-organized criticality (SOC) of forest fire is studied from an analysis of a large series of forest-fire records from 1950 to 1989 in China. The time-invariant, scale-invariant characteristics of SOC of forest fire in China are analyzed in detail. The deviations between the occurrence frequency of very large fires and the power-law relation are explained by the forest-fire model with tree immunity (FFMTI). Actual forest-fire records are compared with the simulation results of a self-organized critical forest-fire model. It is shown that the forest-fire model applies well to explain the SOC characteristics of a forest fire. SOC characteristics have practical implications on forest-fire protection. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Self-organized criticality; Cellular automata; Forest-fire model; Fire-safety science

1. Introduction

Self-organized criticality (SOC) was originally introduced as a general theory to understand fractals and $1/f$ noise as the natural coupled degrees of freedom (Bak et al., 1987, 1988; Bak and Chen, 1990). Irreversible dynamics would drive the system into a critical state without the fine tuning of parameters. When the system reaches the critical state, the 'frequency-size' distribution of energy dissipation events satisfies a power-law relation. The SOC idea is illustrated by computer models that have slow driving or energy input and rare, avalanche-like dissipation events that are instantaneous on the time scale of driving. These models include the sand-pile model (Bak and Chen, 1990), slide-block model (Carson and Langer, 1989) and forest-fire model (Drossel and Schwabl, 1992), etc. The ecosystem is a self-organized critical system (Jørgensen et al., 1998). The abundance of species versus the size of the species, the variations of changes in ecosystems versus the frequency, the sizes of the avalanches are plotted versus the frequencies all show power-law behaviors. SOC might ultimately explain the ubiquity of the fractal, which has been paid great attention in ecology (Li, 2000).

The forest-fire model proposed by Drossel and Schwabl (1992) is a stochastic cellular automaton. The forest is represented by a two-dimensional lattice, in which trees grow with a low probability, and fire occurs with less probability. A burning

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tree will ignite all its neighboring trees with the same probability, 1, so that a forest cluster will burn down in case it contains a burning tree. The forest-fire model will automatically reach a steady state characterized by the power-law relation of the 'frequency-size' distribution of forest fires. Drossel and Schwabl (1993) and Albano (1995) introduced tree immunity, g, to the forest-fire model and studied the change of forest-fire distribution versus g. In this generalized model, a tree will become a burning tree with probability $1-g$ if at least one of its nearest neighbors is burning. Schenk et al. (2000) studied finite-size effects in the self-organized critical forest-fire model by numerically evaluating the tree density and fire-size distribution. As the system size becomes smaller, the system contains fewer patches and finally becomes homogeneous, with large density fluctuations in time.

Compared with other models (Li et al., 1997; Miller and Urban, 1999; Peng and Apps, 1999; Mailly et al., 2000), the forest-fire model proposed by Drossel focuses on abstracting the basic characteristics of forest fires and investigating the global behaviors, especially SOC, of the forest and forest fires. Casagrandi and Rinaldi (1999) investigated fire regimes through a minimal model. Hargrove et al. (2000) developed a very similar model, with which they simulated fire patterns in different parameters. In these researches, the SOC characteristics were not studied.

Actual forest fires have SOC characteristics, and the forest-fire model can be used to describe actual forest fires (Malamud et al., 1998; Ricotta et al., 1999) and epidemics, etc. (Johansen, 1994; Rhodes and Anderson, 1996). 'Frequency-size' distributions of natural hazards provide important information on calculating risk and are used in hazard mitigation (Turcotte, 1989, 1999a).

Ricotta et al. (1999) analyzed a large series of wildfire records of the Regional Forest Service of Liguria from 1986 to 1993 and found a power-law relation between the frequency of occurrence and the size of the burned area. The idea of SOC applies well to explain wildfire occurrence on a regional basis. The records of burned area show a fractal distribution with a fractal dimension being about 1.446.

Malamud et al. (1998) analyzed some forest-fire data in USA and Australia and found that forest fires exhibit a power-law dependence of occurrence frequency on burn area over many orders of magnitude and that actual forest fires can be directly associated with the forest-fire model.

However, the occurrence frequency of very large fires shows obvious deviations from the power-law relation. A common reason of the deviations is because actual forest fires are affected by tree species, meteorological conditions and human fire-fighting efforts, etc. (Malamud et al., 1998; Ricotta et al., 1999).

This paper aims to explain these deviations through the forest-fire model and examine the SOC and fractal characteristics of actual forest fires in China. To explain the deviations between the occurrence frequency of large fires and the power-law relation, we make use of the forest-fire model with tree immunity (FFMTI) and generalize the meaning of tree immunity to involve external conditions such as tree species, meteorological conditions and human fire-fighting efforts. To examine the SOC characteristics of actual forest-fire data, we check SOC together with its time-invariant and scale-invariant attributes. The fractal characteristics of forest cluster and forest fires are also inspected. Based on these studies, we try to provide some suggestions to actual forest-fire protections.

2. Model and simulation

The forest-fire model is a cellular automata model combined with Monte Carlo simulation. The forest is denoted by a two-dimensional lattice. Each site is occupied by either a tree, a burning tree, or it is empty. The state of the system is updated in parallel by the following rules:

1. A burning tree becomes an empty site.
2. A tree becomes a burning tree if at least one of its nearest neighbors is burning.
3. At an empty site, a tree grows with probability p.
4. A tree without a burning nearest neighbor becomes a burning tree with probability f.

Rules (1)–(4), respectively, describe the burning of tree, spreading of fire, growth of tree and ignition of fire. If $f > 0$, and if time scales of tree growth and burning down of forest clusters are separated, the system will evolve into a self-organized critical state.

It was claimed (Drossel and Schwabl, 1992) that there is the following scaling law for the cluster distribution $N(s)$ and the area of the cluster, s:

$$N(s) \sim s^{-\tau}. \tag{1}$$

Here, τ is the critical exponent. Eq. (1) indicates that a forest is composed of clusters with different sizes. The larger is the cluster size, the less cluster number will be. The 'frequency-size' distribution of forest clusters obeys a power law. The probability for a cluster with s trees to catch fire, $N^*(s)$, is:

$$N^*(s) \equiv sN(s) \sim s^{-(\tau-1)} \tag{2}$$

So, the 'frequency-size' distribution of forest fires is also a power law, as shown in Fig. 1. Consequently, the occurrence frequency of fires with burned areas greater than s is also a power law:

$$\sum_{s'=s}^{\infty} N^*(s') = \sum_{s'=s}^{\infty} s'N(s') \sim s^{-(\tau-2)}. \tag{3}$$

As noted by Mandelbrot (1982), from Eq. (3), we have

$$D_{\text{fire}} = 2(\tau - 2). \tag{4}$$

Here, D_{fire} is the fractal dimension of forest fires. Obviously, D_{fire} is relevant to the size distribution of forest fires and is calculated through power-law exponent $\tau - 2$.

The forest cluster is a fractal with fractal dimension being μ (Drossel and Schwabl, 1992). That is to say that a forest cluster with length scale being L will contain L^{μ} trees. The fractal dimension, μ, and the topological dimension, d (equal to 2 here) for the forest cluster, have the following scaling relation (Henley, 1993):

$$d = \mu(\tau - 1). \tag{5a}$$

Eq. (5a) is satisfied in the percolation theory. In the forest-fire model, there are many regions that contain no large forest cluster, which spans the whole region, so that $d < \mu(\tau - 1)$ (Clar et al., 1994). Consequently, we have:

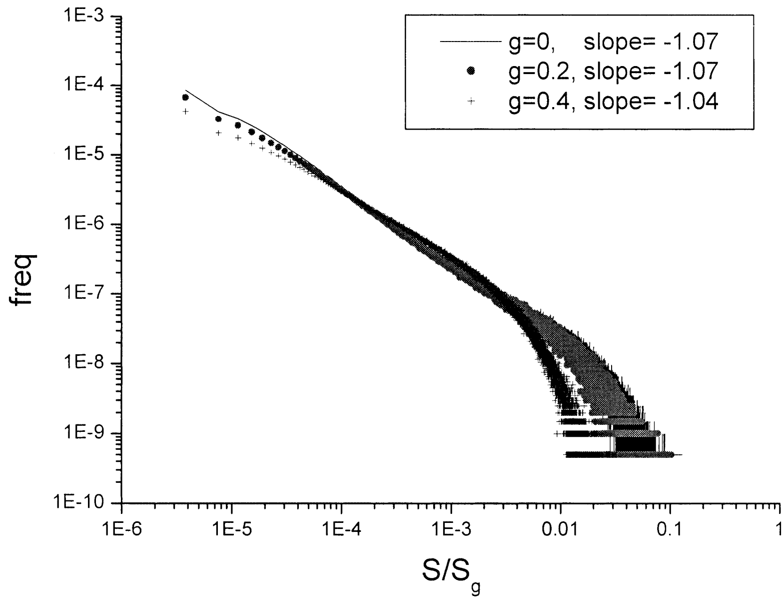

Fig. 1. Simulation results of the generalized forest-fire model. The 'frequency-size' distribution of the forest fire satisfies the power-law relation with a small g value. Simulation steps $N_s = 2 \times 10^9$; forest lattice size $s_g = 512 \times 512$; Fire ignition probability $f_s = f/p = 1/500$; Tree immunity, g, is set to several different values. Fire frequency freq $= N(s)/N_s$.

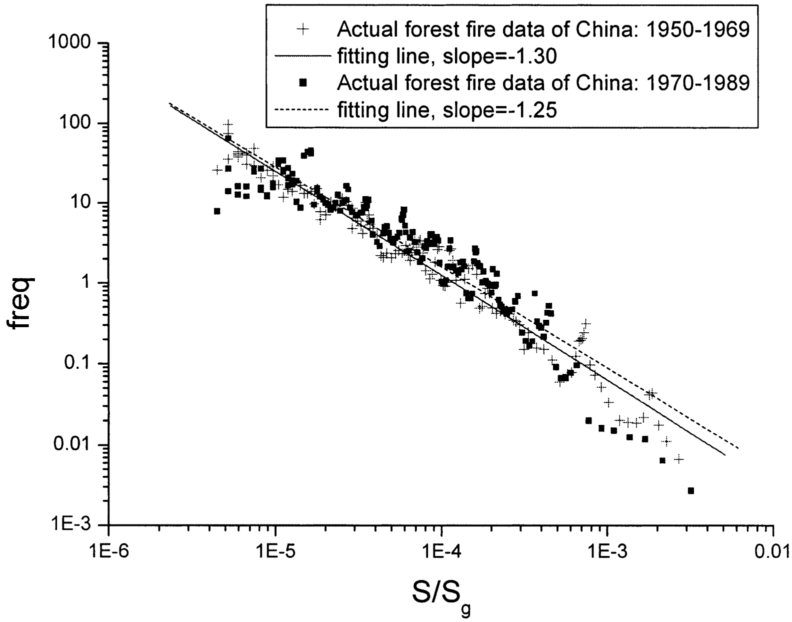

Fig. 2. Actual forest-fire data in China.

$$\frac{d}{(\tau-1)} < \mu \leq d. \tag{5b}$$

Note that d equals 2 here.

A more general model was introduced and studied by Drossel and Schwabl (1993) and Albano (1995). In the generalized model, rule (2) was modified as "(2) A tree becomes a burning tree with probability $(1-g)$ if at least one of its nearest neighbors is burning'. Here, g is the tree immunity from fire. The value of g is relevant to tree species (Drossel and Schwabl, 1993; Albano, 1995).

Considering that external conditions, including tree species, meteorological conditions and human fire-fighting efforts and so on, have similar influences on forest fires, we redefine g as the 'generalized tree immunity' that is decided by external conditions. The larger is the value of g, the more rigorous the external conditions are.

Simulation results of the generalized forest-fire model are shown in Fig. 1. There is a range of small to large fires, with much more smaller fires than the larger ones. The 'frequency-size' distribution of the small and medium fires accords well with the power-law relation, as shown in Eq. (2) and with a slope value approximately being equal to -1.0 in the logarithm coordinate. With the increase in g value, the occurrence frequencies of very large fires deviates more and more obviously from the power-law relation. It is shown that the FFMTI qualitatively explains the deviations between occurrence frequency of very large fires and the power-law relation.

3. Results and discussion

Simulation results of forest-fire model are compared with the actual forest-fire data in China from 1950 to 1989 (Chinese Academy of Forestry, 1999). Fire frequencies with different burned areas are calculated. As shown in Figs. 2–4, the occurrence frequency for the actual fire data is:

$$\text{freq} = -\,\mathrm{d}\dot{N}_{(s'>s)}/\mathrm{d}s. \tag{6}$$

Here, $\dot{N}_{(s'>s)}$ is the annual number of fires with a burned area being greater than a threshold area, s. In all figures of this paper, the burned area of fire is set to the quotient of burned area to the total forest area, i.e. s/s_g.

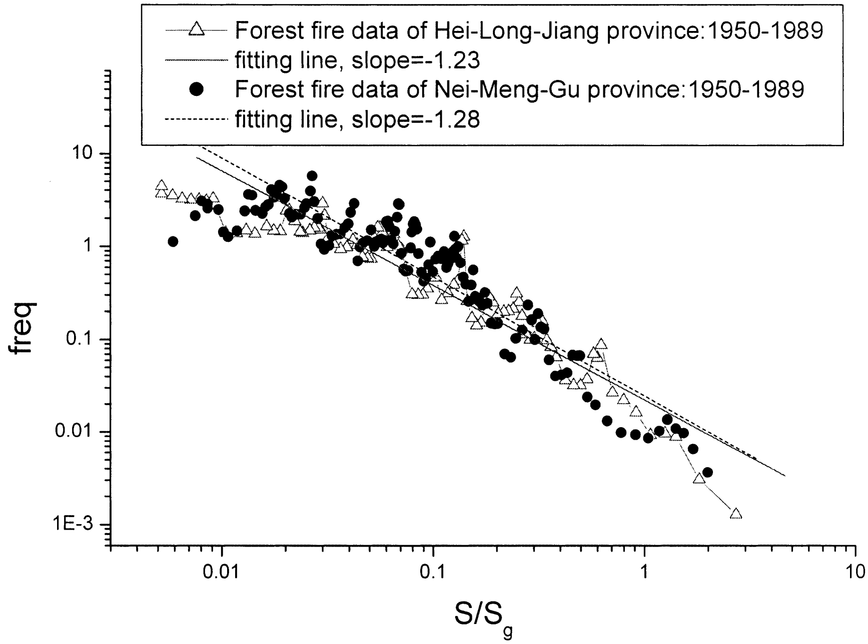

Fig. 3. Forest-fire data of two neighboring provinces: Hei-Long-Jiang and Nei-Meng-Gu.

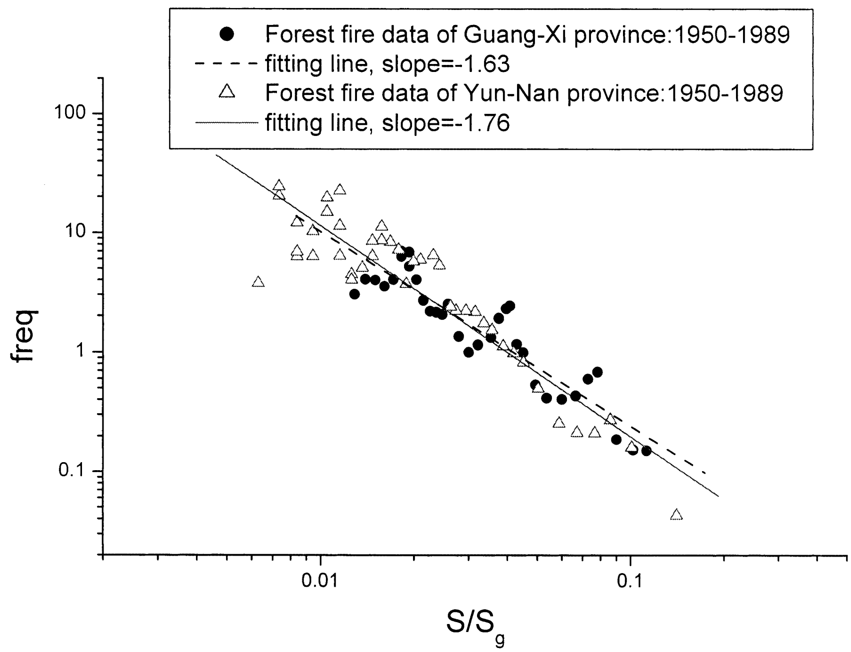

Fig. 4. Forest-fire data of another two neighboring provinces: Yun-Nan and Guang-xi.

Table 1
Fractal dimension of forest cluster μ and forest fires D_{fire}.

	China[a]	China[b]	N-M-G	Y-N	FWS[c]	ACT[d]	Liguria[e]
μ	$1.60\sim2$	$1.54\sim2$	$1.56\sim2$	$1.14\sim2$	$1.53\sim2$	$1.34\sim2$	$1.16\sim2$
D_{fire}	0.50	0.60	0.56	1.52	0.62	0.98	1.45

[a] Forest-fire records from 1970 to 1989 as shown in Fig. 2.
[b] Forest-fire records from 1950 to 1969 as shown in Fig. 2.
[c] Forest-fire records of US Fish and Wildlife Lands (1986–1995) from Malamud et al. (1998).
[d] Forest-fire records of Australian Capital Territory (1926–1991) from Malamud et al. (1998).
[e] Wildfire records in Liguria from Ricotta et al. (1999).

Now, we analyze actual forest-fire data in China from 1950 to 1989. The 'frequency-size' distribution of actual forest-fire data is shown in Fig. 2. The non-cumulative annual number of fires with area, freq, is given as a function of burned area. The results accord well with the power-law relation shown in Eq. (2) with slopes $-(\tau-1)=-1.25\sim-1.30$. An absolute value of slope greater than 1.0 means that small fires contribute more to the total burned area than large fires do.

In Fig. 2, actual forest-fire data in China are divided into two groups: those from 1950 to 1969 and those from 1970 to 1989. Both groups of data show a reasonable power-law relation with almost the same value of $(\tau-1)$: 1.30 for the first group and 1.25 for the other. Therefore, it can be concluded that actual forests in China have reached a critical state after long-term evolution, and the SOC characteristics for a forest are steady and invariant with time.

In Fig. 3, actual forest-fire data in two neighboring provinces of China, i.e. Hei-Long-Jiang and Nei-Meng-Gu, for which the external conditions such as meteorological conditions, tree species and human efforts are similar, are compared. 'Frequency-size' distributions of both forests show a good power-law behavior. Very close values of $(\tau-1)$, 1.23 for Hei-Long-Jiang forest and 1.28 for Nei-Meng-Gu forest, are obtained. It is shown that SOC is a connatural characteristic of forest fire. Under similar external conditions, the critical exponents of SOC of the two forests are similar. Furthermore, for the two forests, the deviations between the occurrence frequencies of very large fires and the power-law relation are also similar. Forest-fire data in another two provinces, Yun-Nan and Guang-Xi, are shown in Fig. 4. The same conclusion can be reached. Comparing Figs. 2–4, it is shown that the SOC of the forest is invariant within a broad range of forest size. This accords well with research results of the forest-fire model (Albano, 1995; Turcotte, 1999b; Schenk et al., 2000).

From Figs. 2–4, it is shown that there are obvious deviations between the occurrence frequency of very large fires and the power-law relation. When the external conditions are similar, as shown in Figs. 3 and 4, the deviations are similar, too. Compared with the simulation results of the forest-fire model, it can be concluded that the external conditions are important, if not the only, reasons for the deviations.

Fractal dimensions of forest cluster and forest fires can be calculated through the critical exponents that we have obtained above. The results are shown in Table 1. The fractal dimension of the forest cluster μ is calculated from Eq. (5b), and the fractal dimension of size distribution of forest fires, D_{fire}, is calculated from Eq. (4). Besides forest-fire records in China, we also examine another three sets of forest-fire data, i.e. FWS data (forest-fire records of US Fish and Wildlife Lands 1986–1995 from Malamud et al., 1998), ACT data (forest-fire records of Australian Capital Territory 1926–1991 from Malamud et al., 1998) and Liguria data (wildfire records in Liguria from Ricotta et al., 1999). As shown in Table 1, for all seven sets of forest-fire data, the value of μ varies between 1.14 and 2, and the D_{fire} value varies from 0.50 to 1.52. The broad range of μ values indicates that forest regimes differ greatly. However, all forests examined in the paper have SOC characteristics, i.e. the 'frequency-size' distribution of forest fires satisfies the power-law relation. All seven sets of forest-fire data show fractal behaviors well. Because the fractal dimension is determined by SOC exponents, forests with similar SOC characteristics have a similar fractal dimension D_{fire}.

Having obtained SOC parameters, such as τ and D_{fire}, and a sufficient number of history forest-fire records of a forest, we can characterize the regime of forest fires with their 'frequency-size' power-law distribution, which is invariant with time and forest size, as described above. Consequently, we can forecast the future forest-fire regime, for which the 'frequency-size' distribution will obey the same power-law relation as that of history data. The occurrence frequency of small and medium fires can be used to quantify the risk of large fires through the power-law relation or fractal characteristics of forest fires.

As indicated by Malamud et al. (1998), excessively successful suppression of small and medium fires will lead to the accumulation of combustible materials in the forest and hereby cause very large fires. They thus suggested that we should allow small and medium fires to burn to prevent very large fires. The simulation results of FFMTI show that if fire protection is performed, even to all sizes of fires, through increasing the generalized tree immunity, g, very large fires can also be prevented or reduced. Nowadays, firebreaks, fire-immune trees and so on can all increase generalized tree immunity, g, hold back fires, and consequently prevent very large fires.

4. Conclusions

In summary, in this paper, we have shown that actual forest-fire data in China have SOC behavior characterized by power-law relation of 'frequency-size' distribution of forest fires. The SOC characteristics of a forest are invariant with time and a broad range of forest size, and can be explained by the forest-fire model. The forest cluster and the forest-fire distribution are fractal, and the fractal dimensions are decided by SOC exponents. It is shown that forest-fire regimes are dominated by SOC and are influenced by external conditions.

The SOC characteristics of forest fires have practical implications. The forest-fire regimes in the next several decades can be forecast with enough history forest-fire data for a forest from the SOC characteristics. The occurrence frequency of small and medium fires can be used to quantify the risk of large fires. If fire protection is performed, even to all types of fires, through increasing the difficulty of fire spread, i.e. increasing the generalized tree immunity, very large fires can be prevented or reduced.

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References

Albano, E.V., 1995. Spreading analysis and finite-size scaling study of the critical behavior of a forest-fire model with immune trees. Physica A 216, 213–226.

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: an explanation of $1/f$ noise. Phys. Rev. Lett. 59, 381–384.

Bak, P., Tang, C., Wiesenfeld, K., 1988. Self-organized criticality. Phys. Rev. A 38, 364–374.

Bak, P., Chen, K., 1990. A forest-fire model and some thoughts on turbulence. Phys. Lett. A 147, 297–300.

Carson, M., Langer, J.S., 1989. Mechanical model of an earthquake fault. Phys. Rev. A 40, 6470–6484.

Casagrandi, R., Rinaldi, S., 1999. A minimal model for forest fire regimes. Amer. Nat. 153, 527–539.

Chinese Academy of Forestry, 1999. Annual Forest Fire Table of China 1950–1990 (unpublished data).

Clar, S., Drossel, B., Schwabl, F., 1994. Scaling laws and simulation results for the self-organized critical forest-fire model. Phys Rev E 50 (2), 1009–1018.

Drossel, B., Schwabl, F., 1992. Self-organized critical forest-fire model. Phys. Rev. Lett. 69, 1629–1992.

Drossel, B., Schwabl, F., 1993. Forest-fire model with immune trees. Physica A 199, 183–197.

Hargrove, W.W., Gardner, R.H., Turner, M.G., Romme, W.H., Despain, D.G., 2000. Simulating fire patterns in heterogeneous landscapes. Ecol. Model. 135, 243–263.

Henley, C.L., 1993. Statistics of 'self-organized' percolation model. Phys. Rev. Lett. 71, 2741–2744.

Johansen, A., 1994. Spatio-temporal self-organization in a model of disease spreading. Physica D 78, 186–193.

Jørgensen, S.E., Mejer, H., Nielsen, S.N., 1998. Ecosystem as self-organizing critical systems. Ecol. Model. 111, 261–268.

Li, B.L., 2000. Fractal geometry applications in description and analysis of patch patterns and patch dynamics. Ecol. Model. 132, 33–50.

Li, C., Mikaelian, M.T., Perera, A., 1997. Temporal fire disturbance patterns on a forest landscape. Ecol. Model. 99, 137–150.

Mailly, D., Kimmins, J.P., Busing, R.T., 2000. Disturbance and succession in a coniferous forest of northwestern North America: simulations with DRYADES, a spatial gap model. Ecol. Model. 127, 183–205.

Malamud, B.D., Morein, G., Turcotte, D.L., 1998. Forest fires: an example of self-organized critical behavior. Science 281, 1840–1841.

Miller, C., Urban, D.L., 1999. A model of surface fire, climate and forest pattern in the Sierra Nevada, California. Ecol. Model. 114, 113–135.

Peng, C., Apps, M.J., 1999. Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. Ecol. Model. 122, 175–193.

Rhodes, C.J., Anderson, R.M., 1996. Power laws governing epidemics in isolated populations. Nature 381, 600–602.

Ricotta, C., Avena, G., Marchetti, M., 1999. The flaming sandpile: self-organized criticality and wildfires. Ecol. Model. 119, 73–77.

Schenk, K., Drossel, B., Clar, S., Schwabl, F., 2000. Finite-size effects in the self-organized critical forest-fire model. Eur. Phys. J. 15, 177–185.

Turcotte, D.L., 1989. A fractal approach to probabilistic seismic hazard assessment. Tectonophysics 167, 171–177.

Turcotte, D.L., 1999a. Application of statistical mechanics to natural hazards and landforms. Physica A 274, 294–299.

Turcotte, D.L., 1999b. Self-organized criticality. Rep. Prog. Phys. 62, 1377–1429.