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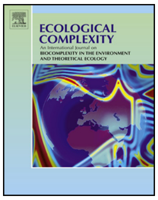

Original Research Article

The effect of fire on an abstract forest ecosystem: An agent based study

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ABSTRACT

Our model considers a new element in forest fire modeling, namely the dynamics of a forest animal, intimately linked to the trees. We show that animals and trees react differently to different types of fire. A high probability of fire initiation results in several small fires, which do not allow for a large fuel accumulation and thus the destruction of many trees by fire, but is found to be generally devastating to the animal population at the same time. On the other hand, a low fire initiation probability allows for the accumulation of higher quantities of fuel, which in turn results in larger fires, more devastating to the trees than to the animals. Thus, we suggest that optimal fire management should take into account the relation between fire initiation and its different effects on animals and trees. Further, wildfires are often considered as prime examples for power-law-like frequency distributions, yet there is no agreement on the mechanisms responsible for the observed patterns. Our model suggests that instead of a single unified distribution, a superposition of at least two different distributions can be detected and this suggests multiform mechanisms acting on different scales. None of the discovered distributions are compatible with the power-law hypothesis.

1. Introduction

Fire is an active element of many ecological habitats and at first glance it results in the destruction of vegetation and the degradation of natural resources. However, fire also plays an important role in the natural regeneration of the same resources (Vinton et al., 1993; Whelan, 1995). Yet Feng et al. (2009) estimated that roughly 6–7 million km^2 of forests have been lost in less than 200 years due to wildfires. Furthermore, fires do not only destroy plants and animals, but also change the ecology of the effected habitat. Therefore, gaining insights into the controlling mechanisms of fire effects are essential for disturbance ecology (Pascual and Guichard, 2005). The goal of fire management is to reduce fire intensity and to protect property, resources and human life (Laverty and Williams, 2000), to predict major fire events (Malamud et al., 1998) and to determine the sensitivity of fire regimes (Zinck and Grimm, 2008). Decades of fire exclusion commonly resulted in dense forest canopies, high fuel accumulations and fuel continuity where fires were historically frequent earlier (Brown, 1985; Ferry et al., 1995). These new circumstances likely foster fewer but more severe wildfires. The fire hazard can be assessed and quantified based on measuring canopies, fuel quantities and similar variables (Finney, 2005; Bajocco et al., 2009; Keane et al., 2010). The effect of fire on vegetation has been extensively studied, and studies on the effect of fire on animals have provided essential insights into the complex network of causality in ecosystems (Fons et al., 1993; Pons et al., 2003; Zamora et al., 2010).

Theoretical studies have revealed that fire sequences can be considered as fractal processes with a high degree of time-clusterization of events. Bak et al. (1990) used a forest fire model to demonstrate critical scaling behavior in a "turbulent" non-equilibrium system. Others Drossel and Schwabl (1992) analyzed and elaborated this early model and introduced a "lightning parameter" to initialize fires by direct control. These models, based on the mechanisms of self-organized criticality, generally have a slow driving energy input and rare avalanche-like dissipation events that by contrast have a more rapid dynamics (Song et al., 2001). It has been observed in a different context, that of the

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famous sand pile model of Bak (1996), that the power law distribution of avalanches is a consequence of the local conservation of sand particles.[1] In a forest fire model, the accumulation of fuel in terms of trees could serve a similar conservation role (Zinck and Grimm, 2008). Self-organized criticality is not the only possible mechanism for generating power law distributions in natural phenomena (Solow, 2005). In fact, power law relationships were found e.g., between the frequency of fires and the size of burned areas as well (Malamud et al., 1998; Ricotta et al., 1999; Song et al., 2001; Telesca and Lasaponara, 2010). Analyzing wildfires on US federal lands between 1986 and 1996 on the other hand showed that while the distribution of fires spans 6 orders of magnitude, the distribution at its tail shows an exponential cutoff rather than a power function (Newman, 2005). What the distribution is indeed like is thus an open question. While developing our model, we also deal with this problem.

In this paper we aim to understand the details of fire dynamics and its effect on living organisms. Earlier individual based models of forest dynamics have already attempted to grasp fire behavior at different levels (Busing and Mailly, 2004; DeAngelis and Gross, 1992; Grimm et al., 2006; Huston et al., 1988; Judson, 1994). Thus, Zinck and Grimm (2008) reinvigorated the earlier model of Drossel and Schwabl (1992); Niazi et al. (2010) developed a realistic, verified and validated agent based forest fire simulation (and also provided a recent overview of forest fire simulation models). There exist several further forest fire models (cf. the overview in Song et al., 2001) that add additional complexities, such as tree immunity (Albano, 1995), or studies of actual forest fires (Malamud et al., 1998; Ricotta et al., 1999, 2001). These models may lack case-specific predictions, yet offer new perspectives leading to testable hypotheses (Busing and Mailly, 2004).

We present a new theoretical individual based model and offer some new insights. Our model is essentially different from the well-known models of Bak et al. (1990) or Drossel and Schwabl (1992). In these, the field is a cellular automaton where spatial relations are fixed and dominant, such as in a checkerboard. In those studies, a burning tree is assumed to ignite all of its neighboring trees with probability $p = 1$, so that a connected forest cluster will deterministically burn down if it contains a single burning tree. In our model, the basic processes are different. A fire sprite will be born and move randomly, therefore a neighboring tree has a chance to avoid burning down. The basic mechanism of spreading has been earlier identified as a percolation process (see Von Niessen and Blumen, 1986; Henley, 1989; Beer and Enting, 1990), which we want to indeed invigorate in this model.

In developing the present model, our goal was thus threefold: (1) to keep the fire process simple, yet use the fuel-based mechanism based on a simple percolation system; (2) to be more realistic about the motion of active fires; (3) to follow also the behavior of an animal population which is dependent on the trees and fires. We use the now-standard ODD protocol for describing individual based models after (Grimm et al., 2006).

2. Material and methods

The model was developed in the NetLogo simulation environment, version 5.1.0 (Wilensky, 1999). The fully functional model and the source code are made available online.[2]

Table 1
Overview of processes and parameters with their default values.

Parameter (dimension)	Notation	Value
Area size (space units)	$n \times n$	39 × 39
Starting number of animals (individuals)	N_a	100
Starting number of trees (individuals)	N_t	500
Length of simulation (years)	T	100
Maximum number of fire seeds	N_f	Variable
Probability that a tree breeds/year	T_b	0.1
Animal movement speed (unit/month)	M_a	5
Probability for animals' dying during one time step (if no. of trees in neighborhood ≥ 5, it is D_a, if <5 it is $2 \times D_a$)	D_a	0.1
Maximum number of animals in a double neighborhood that will not impede breeding (individuals)	T_a	5
Number of trees necessary in a double neighborhood for animal reproduction to occur (individuals)	T_t	5
Number of offspring for animals (individuals)	O_a	1
Number of new fires from a fire (individuals)	O_f	1
Speed of fires/month(space units)	M_f	1

2.1. State variables and scales

The model has three hierarchical levels: entities, interactions, and environment, with the first two being modeled explicitly and the environment being modeled implicitly. The model consists of $N_t(t)$ of trees, $N_a(t)$ of animals, and $N_f(t)$ of fires, each with their own rule sets (see Table 1). As a convention, we fix $N_x(t_0) = N_x$ for $x = (t, a, f)$. Populations are characterized by the census of each organism type at the end of a given year. The number of burned trees and animals are counted every year.

Trees are characterized by their position (and can be alive or dead). Animals are characterized by two further internal state variables: the speed of movement as well as the current activity (i.e., moving or breeding). Fires are modeled as having a state variable describing their current status (i.e., live or dead, in other words, burning or extinguished).

The model is spatially explicit. We keep cells but they are occupied by active agents. Trees are immobile, while animals and fires can move, following explicit rules. The state of the agents is tracked through time and defined by the location of each individual and each interaction between individuals and the environment. The environment is a closed system modeled as an $n \times n$ square without reflective boundaries (i.e., periodic boundary conditions). A single tree agent or several animals can occupy one spatial position; if the number of individuals at the given position is zero, the position can be occupied by a new tree or a wandering animal.

Time evolves in ticks. We may think of a single tick as a month and 12 ticks a year. This scaling helps intuitive understanding and will be used in the paper throughout. The time and space scales chosen allow for a study of a large-scale dynamics for long periods whilst the model still runs quick enough for many parallel runs of extensive parameter sweeps. Animals and fires disperse monthly, other events such as tree and animal reproduction as well as the ignition of the fires (i.e., fire initiation) happen yearly. The selection of the speed parameter values was motivated by the desire to have sufficiently many interactions between different agents in a 100-year period, so that we do not need very long runs and a high number of replicates. The area is large enough to allow for a diversification by local events. The movement speed of animals is given by a parameter M_a, and at the value used in the simulations the probability that an animal would cross the whole area during its lifetime is very low. This ensures a delay effect: if the trees are burned down in an area, the animals cannot simply escape into a better habitat but tend to die. (In background experiments we have also scaled up the arena size and the speed parameters to see if the

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[1] When the probability of a value of a quantity varies inversely as a power of that value, the quantity is said to follow a power law (Zipf's law), for frequencies this is also known as a Pareto distribution (Newman, 2005).

[2] https://www.dropbox.com/s/7m5xj1egdzr6zyr/Fires-v1.0.nlogo, all code is the work of the present authors.