Destabilizing effects of controlling ecosystem behavior

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1 Abstract

The impact of human activities on the state and behavior of ecosystems has been growing dramatically in past decades. The purpose of such anthropogenic disturbances is varied, but in many cases the overall goal is to protect and stabilize the ecosystem and the services it provides. Nonetheless, our understanding of the long term affects of common managing practices with this goal in mind, such as pest removal or fire prevention, is quite limited. In particular, it is not well understood in what conditions might controlling the ecosystem's behavior to stabilize one aspect of its dynamics might lead to a significant destabilization of another aspect. We wish to explore this issue by focusing on a specific example of managing a forest to protect it from fire damage. In what conditions will decreasing the frequency of wildfires lead to less frequent but more damaging fire events? Starting from a conceptual model that demonstrates this scenario, we will try to answer several questions: In what conditions does inhibiting variability lead to higher collapse probability? What are the physical conditions where this may occur? Can other common managing practices lead to similar dynamics? Can similar parallels be drawn between other stability and integrity measures, such as biodiversity and resistance? By answering these questions we can gain theoretical insight into the feedbacks between ecosystems' dynamics and human activities, and better inform management practices in a wide range of ecosystems.

2 Example

To demonstrate the goal of this project, we use a simple model to show how controlling the ecosystem to decrease variability (of biomass) may lead to an increase of collapse probability of the entire ecosystem. The model describes dynamics of a forest, looking at the biomass of both live (N) and dead (W) trees, where the dynamics involve growth of trees, their natural death and later decay, and sporadic wildfire events. We use the following two equations to describe the deterministic dynamics:

$$\dot{N} = gN(1 - N/K)(N/A - 1)$$

$$\dot{W} = mN - dW$$

Here $\dot{N}$ and $\dot{W}$ are the derivatives in time for the amount of living trees and dead wood respectively, g is the growth rate of trees, K is the forest's carrying capacity, A is the tree density below which new trees cannot grow, m is the rate by which living trees create dead wood (natural death), and d is the decay rate of dead wood.

These equations have a stable equilibrium of a viable forest $N = K, W = mK/d$, and an additional stable equilibrium of bare-ground $N = W = 0$. To this deterministic dynamics we add two stochastic processes: white noise to the first equation (affecting only

N) to simulate changes in environmental conditions, and discrete disturbance events which decrease both N and W due to wildfires. The environmental noise term used is $cN\xi$ with ξ a normally distributed random variable with no correlations. The disturbances occur with a constant frequency f without correlations in time (a Poisson process), where each event sets the value of W to zero, while the value of N is decreased by $y = u(0, W(t))$, so that y is drawn from a uniform distribution between 0 and the value of W just before the disturbance.

The results of simulations of this model with the two described stochastic processes are shown in Fig. 1. For high f many disturbances occur but with a minimal impact, leading to a low variability (V) and nearly zero collapse probability (CP). Decreasing f leads to much stronger events, and therefore higher V but only a small increase of CP, since events are still very unlikely to lead to a collapse. As f is further decreased V grows only a little, and later starts to shrink, since wildfire events are quite rare and therefore have a minimal effect on variability, but CP is now quite high since each event has a significant change of leading to a collapse. Finally, for very low f both V and CP are very low again, since wildfire events are so rare. If we consider as an example a forest with a natural wildfire frequency of $f = 0.25$, then control attempts that will decrease the frequency to $f = 0.025$ will decrease V, but at the same time increase CP considerably.

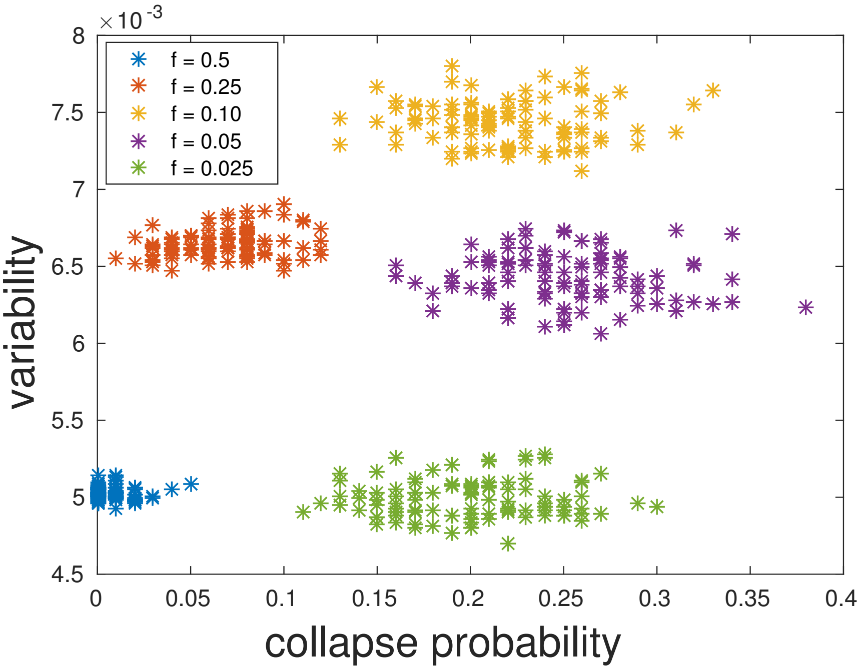

Figure 1: Variability and collapse probability with different disturbance frequency f. Each asterisk (100 asterisks per value of f) denotes an average of 100 simulations, with variability calculated only for simulations that did not collapse.

3 Agenda

In this research project we will use the preliminary results shown above (termed fire-control scenario for brevity), as a starting point for our goal of understanding how and when might controlling the ecosystem's dynamics in order to stabilize it actually lead to a more fragile ecosystem. We will do this by pursuing several research objectives:

1. Exploring the specific fire-control scenario, as described by the model above. Specifically, exploring the parameter space to understand which combination of processes lead to the destabilization phenomena, searching for a more tractable formulation (that might allow analytical results), and looking for threshold effects and/or simple parametric dependencies of the different processes in the model. Research into these issues will allow for a better comparison between theoretical findings and empirical data (see objective 2). It will also broaden the scope of the results of the fire-control scenario, which will help in efforts of generalization (see objective 3 and 4 below).

2. Searching for connections between the fire-control scenario and the literature. We will both look at theoretical studies to ask whether known models may exhibit this behavior, and look at empirical studies to find evidence of the specific phenomenon, as well as estimate the physical parameters of similar systems. This latter avenue of research should allow us to estimate the relevance of such behavior, even if specific evidence for it is not available.

3. Search for similar dynamics in other ecosystems and their managing practices. Our goal here is to look at other ecosystems to find similar phenomena, in which minimizing the noisy behavior of the ecosystem may lead to more extreme (if rare) detrimental events. This will be done both by focusing on other specific ecosystems with significant human impact to consider similar scenarios, and by using results of the generality of the fire-control scenario (see objective 1) to infer which ecosystems or management practices may be susceptible to such issues.

4. Attempt to generalize the relationship between management and other anthropogenic activities, and the various measures of stability and ecosystem health. Considering the expected results of the previous three objectives, we can then move on to a more general theory of such detrimental control of stability. Since it is likely that from a purely theoretical perspective there are few limitations of when such phenomena may occur, it would be more useful to focus on prevalent scenarios of management practices and anthropogenic influence on ecosystems. Some possible examples include the effect of preference of a species measure of biodiversity (e.g. functional biodiversity versus number of species), the consequences of stabilizing ecosystems in small scales on the larger landscape and global scales, and the interplay of controlling effective dispersal when considering rescue effects on the one hand, versus invasive species and pest outbreaks on the other.

The project will be started by focusing on the first objective. Results from this will help in pursuing both objectives 2 and 3. Finally, the combinations of the results of the first three objectives will lead to objective 4.

4 Profile

This project focuses on a theoretical approach to ecology. Therefore the student should have a strong interest in theoretical research, and in using analytical and numerical tools for it. In particular, the following list of skills and knowledge would be helpful:

1. Programming skills (e.g. Matlab, Python, R), and using these for numerical analysis.

2. Knowledge of mathematical tools, in particular calculus, linear algebra, differential equations and probability theory.

3. Proficiency in English, especially for reading scientific articles.