INVESTIGATING THE EFFECTS OF FUNCTIONAL DIVERSITY IN SPATIALLY DISTRIBUTED GEOGRAPHIC DOMAINS

Gary M. Pereira

Department of Geography, San Jose State University, San Jose, CA 95192-0116 Tel 408-924-5475; Fax 408-924-5477; Email gpereir1@email.sjsu.edu

BIOGRAPHY

Assistant Professor of Geography, San Jose State University, 2002-5. Research interests include the application of remote sensing and GIScience to socio-environmental dynamic models; visualization; geographical expressions of hazard and resilience; and geographic applications of complexity science. Recent publications include contributions to books on geographic scale and GIScience, and to the journal *Geographical Analysis*.

INTRODUCTION

Computational models of complex distributed spatial scenarios can improve our understanding of some of the most general characteristics of crisis, collapse, and resilience. A key hypothesis guiding the work presented here is that a diversity of autonomous actors in any domain implies a diversity of ideas, resources, options, approaches, and responses, which if wisely and flexibly negotiated provide greater resilience to external threats and more sustainable internal dynamics than comparable situations where such diversity is absent or discouraged.

Scenarios of dynamic spatial complexity without fundamental diversity can be often analyzed and modeled in terms of such paradigms as self-organized criticality, or SOC (Bak 1996), and highly optimized tolerance, or HOT (Carlson and Doyle 2000). These ideas can be linked to measures of production, risk, crisis, collapse, and resilience in environments without structural defenses (SOC) and with structural defenses (HOT). Both of these approaches have validity in geographic domains of various kinds. However, the presence of functional diversity in a population or landscape has been anecdotally demonstrated to provide greater resilience than simple redundancy, without the risk of collapse that SOC and HOT predict. The importance of functional diversity is seldom addressed in normative theory, since it often involves and invokes seemingly nonsystematic, irrelevant, or far-from-optimal functional agents whose potential importance defies traditional analysis. However, the importance of such an apparently useless diversity of functional agents under circumstances of unanticipated change has been demonstrated, for example in biology (Edelman and Gally 2001) and economics (Rammel and van den Bergh 2003).

In the work outlined here, agent based models built using NetLogo (Wilensky 1999) simulate diffusion, competition for common pool resources, and other archetypical scenarios found in geographical domains wherein the inherent functional diversity of both landscape and mobile agents can be adjusted. Adjustable functions include the inherent rationality, velocity, and metabolisms of mobile agents.

RESULTS

Having an individually diverse set of agents present on a landscape provides opportunities for competition and cooperation that do not occur in landscapes populated by functionally identical agents. Here, in models representing consumption of a landscape resource by mobile agents, the landscape resource imparts energy to the agent that consumes it. Afterward, the resource regenerates. Agents consume energy at some metabolic rate, and they may reproduce when sufficient energy is available. However, an agent dies if its energy falls to zero, and it cannot remain stationary, since its metabolic consumption exceeds the regeneration rate of the resource. Agents in these models are afforded a myopic version of bounded rationality, moving at each time step in the direction of greatest resource availability among the locations immediately adjacent to their current location. Agents are points that can lie anywhere within the grid cells. The landscape consists of 80x80 cells and may be set up with or without periodic boundaries. Model details and code are available from the author.

In one set of experiments, agents are afforded degrees of diversity in the values of velocity with which they move about the landscape, in terms of a normal distribution around a central value. Results consistently show that higher yields (average consumption of landscape resource per individual) are gained through a moderate diversity in velocity, and that stable pattern formation occurs only with such diversity (Figures 1, 2, and 3). Without diversity, the lack of stable landscape structure and the distribution of localized collapses in population clusters are reminiscent of SOC (Figure 1a). Another set of experiments demonstrates that of two competing sets of agents, the set with greatest diversity in either velocity or metabolic values is more likely to achieve and maintain dynamic equilibrium under adverse conditions than the set with lesser diversity. A set with no diversity among individual agents will often not survive (Figure 4).

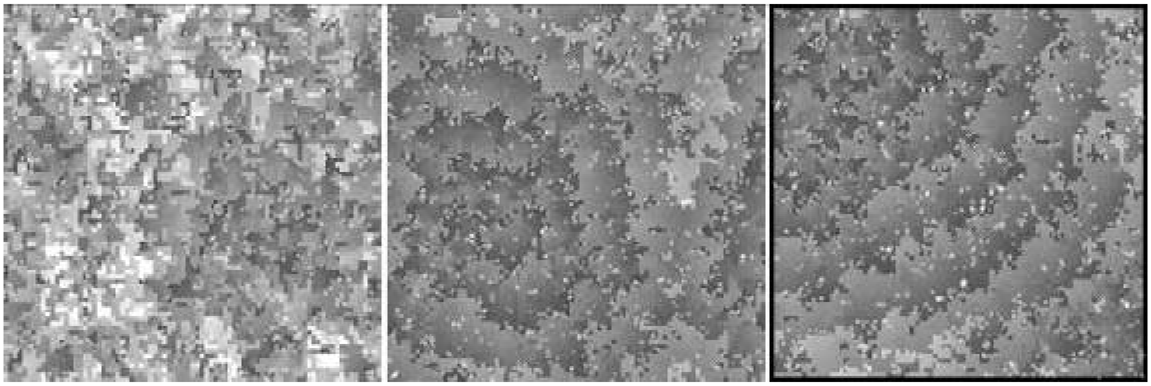

Figure 1. Mobile consumer agents with bounded rationality derive metabolic energy from the consumption of the landscape resource and reproduce or die depending on available individual energy at each time step. These are typical landscape snapshots after equilibrium is achieved, where resource availability is indicated by gray shades for a population of mobile agents descended from a single consumer, and wherein a) all consumers roam with a velocity of precisely 1 cell per time step; b) consumers roam with a distribution of velocities, centered at 1 c/s but with a standard deviation of 0.10; c) same conditions as b except that landscape boundaries are not periodic. The fringe patterns in both b and c are dynamic but spatially stable and emanate from the location of the initial parent consumer.

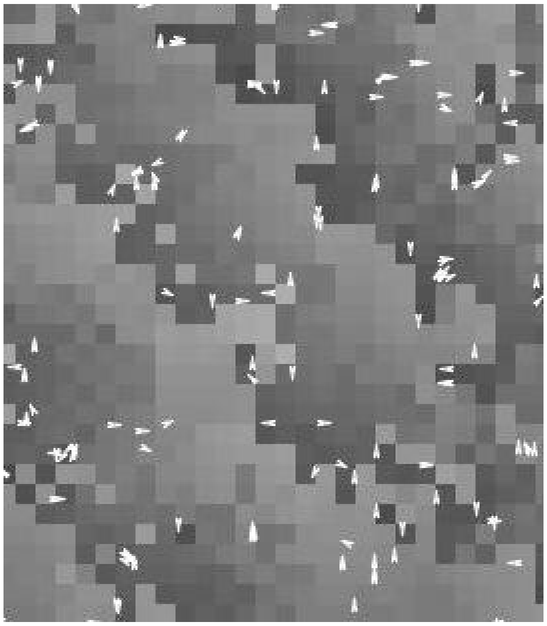

Figure 2. Close-up view of a snapshot of a portion of a landscape with conditions like those in Fig 1b or 1c, wherein the position and directionality of mobile consumer agents are indicated with arrows. Consumers have a form of bounded rationality whereby they move in the direction of greatest resource availability within the immediate neighborhood of cells at each time step. When the population of these agents is afforded a diversity of velocities, they organize the landscape into wavelike patterns of consumption. The highest densities of consumers are along the fringes of these waves. Agents sometimes break away from each fringe and move in the opposite direction as the landscape behind them regenerates. No such patterns are formed when the velocities of all agents are precisely the same.

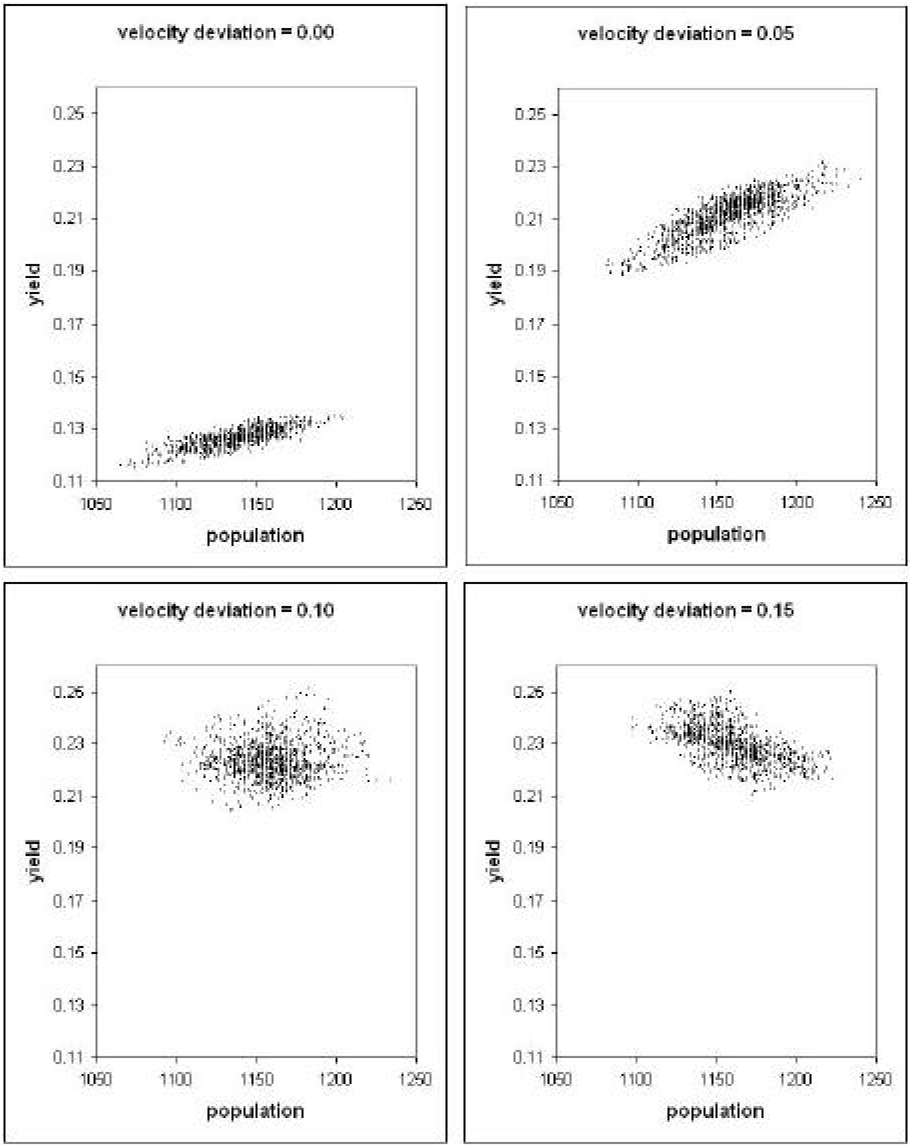

Figure 3. Phase portraits encompassing 1000 time steps after dynamic equilibrium is achieved in simulations like those shown in Figure 1, with consumer velocity diversity conditions indicated as standard deviation around 1 c/s. Points indicate consumer yield and population values at each time step. These portraits indicate that higher yield is achieved at similar population densities with greater velocity diversity, and that the instantaneous values of population and yield correlate differently with different diversities. These results are robust and repeatable over many runs.

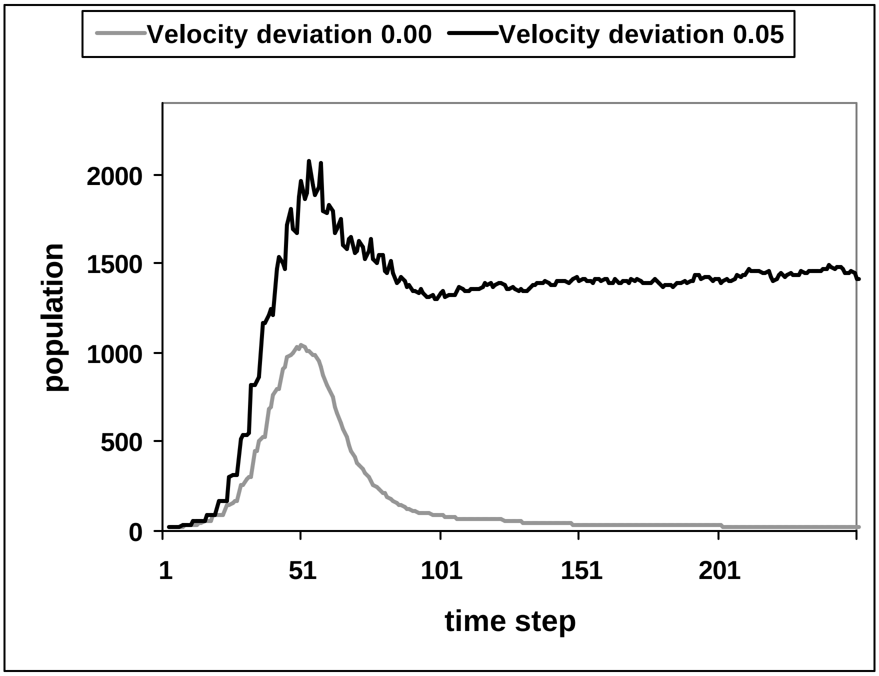

Figure 4. Two initial populations, each of ten randomly placed consumer agents, compete and evolve in a model like those in the previous figures. If all members of one population have a precise velocity of 1 c/s and the other population is afforded diversity in either velocity or metabolic rate, the former population will often not survive beyond the initial transient period.

CONCLUSIONS

These results are preliminary and highly generalized, but they are stable and repeatable. Diversity is often overlooked in normative science, with its concentration on analytic mean-field solutions. However, sciences that examine structurally and functionally complex and non-stationary domains, like geography, must do a better job of examining functional diversity. Computational simulations of such conditions can begin to provide such insight. Here, we have briefly demonstrated the effects of simple manifestations of diversity on spatiotemporal pattern formation and resilience.

The results regarding population or resource resilience can be situated in relation to SOC and HOT conditions. We can see evidence of SOC in the dynamics of many physical and biological geographic phenomena. Collapse can become more dramatic if a geographic domain is structurally optimized for highest production or yield, and which can be associated with HOT. However, neither of these constructs considers the functional diversity present in the real world. Decentralized systems of diverse individual elements may provide greater resilience to criticality and collapse than SOC, while maintaining the yield of HOT (Figure 5).

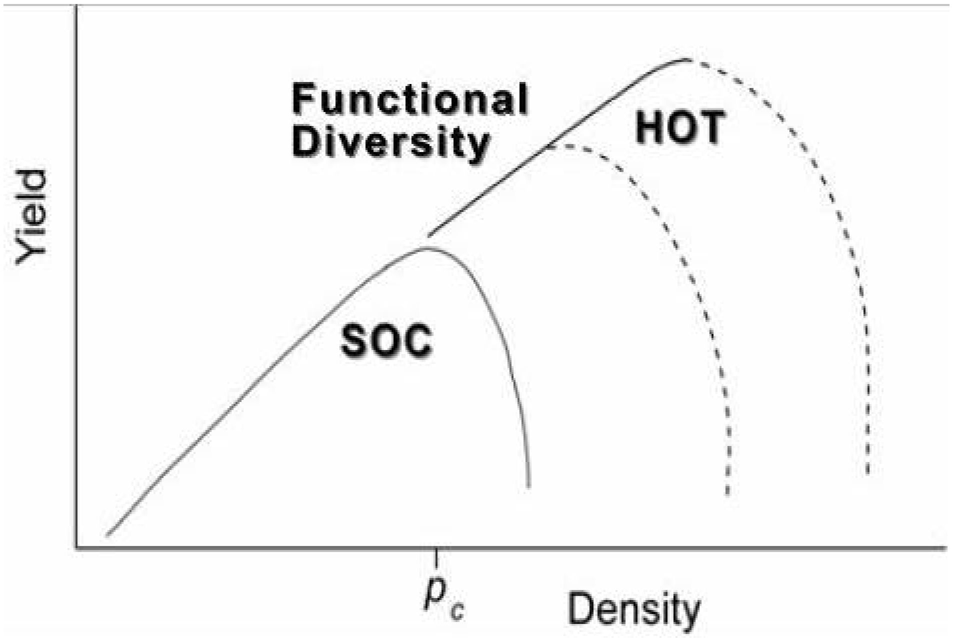

Figure 5. If a resource or population is randomly distributed on a landscape, it becomes more vulnerable to diffusive threats as its density increases. The percolation of collapse through this resource can become nearly global as its density surpasses a critical value p_c. Self-organized criticality (SOC) is characterized by a power law distribution of minor and major (but less than global) collapses and regeneration that maintain dynamic stability in many natural circumstances at densities just short of p_c. Structural defenses have evolved or have been constructed in anthropogenic situations that have allowed densities and yields (defined as production minus any diversions required for defense or survival) to surpass SOC thresholds, a condition described as highly optimized tolerance (HOT). However, such situations remain vulnerable to collapse due to the failure of defensive mechanisms or the advent of threats for which they are not designed. It is suggested here that complex domains characterized by functional diversity among individuals in a population or locations in a landscape may self-organize in ways such that yields comparable to those achieved in HOT are possible without the densities of resources or populations characteristic of HOT scenarios.

REFERENCES

Bak, P., 1996. *How Nature Works: The Science of Self-Organized Criticality*. New York: Copernicus.

Carlson, J. M., Doyle, J., 2000. Highly-Optimized Tolerance: Robustness and Design in Complex Systems. Physical Review Letters 84(11), 2529-2532.

Edelman, G. M., Gally, J. A., 2001. Degeneracy and complexity in biological systems. Proceedings of the National Academy of Sciences 98(24), 13763-13768.

Rammel, C., van den Bergh, J., 2003. Evolutionary policies for sustainable development: adaptive flexibility and risk minimizing. Ecological Economics 47, 121-133.

Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.