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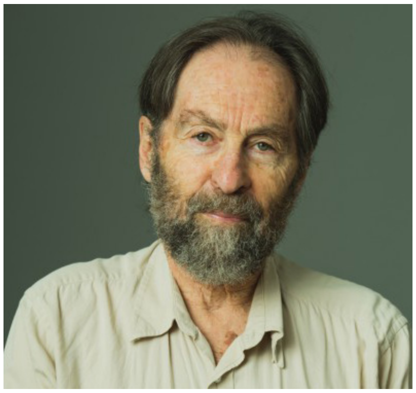
EXPLAINING PATTERNS IN ECOLOGY: CLIMATE MANIPULATION AND MATHEMATICAL MODELING

Interview with Professor John Harte

BY NIKHIL CHARI, ROSA LEE, PHILLIP DE LORIMIER, MOE MIJJUM, SONA TRIKA, & ELENA SLOBODYANYUK

Dr. John Harte is a Professor of the Graduate School in the Department of Environmental Science, Policy, and Management and the Energy and Resources Group at the University of California, Berkeley. Professor Harte's research interests include ecological field research, the theory of complex systems, and policy analysis. In this interview, we discuss his investigation of climate-ecosystem feedback dynamics and his application of information theory to ecological systems.



Professor John Harte

BSJ: We read that your background is in theoretical physics. How did you transition to the field of Environmental Science, Policy and Management?

JH: After my postdoctoral work, I was appointed an assistant professor of physics at Yale. During my appointment, I discovered that I could make contributions to the fields of ecology and environmental science. The major event that caused this realization was my participation in a 1969 study in the Everglades. A plan was afoot to drain the Big Cypress Swamp and build a massive airport for supersonic passenger planes. We knew that building the airport would have a destructive impact on wildlife, but we were looking for other kinds of harm it would cause because the wildlife aspect alone wasn't going to stop the project. A colleague and I got interested in the subterranean hydrology of South Florida, and we realized that draining the swamps for the airport would cause a massive amount of salt intrusion into the water supplies of people living along the Gulf Coast. We got some maps of the geology of South Florida, did several back-of-the-envelope calculations, and were able to show that if they built that airport there, half a million people would lose their freshwater supply. That argument convinced the Secretary of Transportation under President Nixon that it would be political suicide to destroy the water supply for Florida—a swing state. So, they cancelled the plans for the airport. And thus we used a little bit of physics to have a big impact on policy. That was a real watershed event in my career because it convinced me that you could do good science and actually influence policy. And so, I decided to switch fields and train myself in all the different areas of environmental science.

BSJ: What are positive and negative feedbacks in ecology, and what effect do these feedbacks have on climate change?

JH: Back in the 1980s, a group of scientists was doing a very exciting study. They were looking at a 2 km-deep ice core in the Antarctic, at a place called Vostok. When you look at that core, you're going back in time: each year's ice deposit is distinguishable. In any given year, you can extract two pieces of information. First, the bubbles of trapped air tell you what the atmosphere looked like when that ice layer formed. Carbon dioxide levels tended to be very low during ice ages and higher during the interglacial periods. The second piece of information is a global averaged temperature inferred by looking at the isotopes of oxygen in the ice. The ratio of heavy oxygen (^{18}O), which is not very abundant, to the common oxygen (^{16}O) tells us about temperature. Using these data, you see that temperature and carbon dioxide levels move in synchrony with one another. It gets more complicated, but the correlation is remarkable. Now, what does it mean? It means that when it's warmer, more carbon dioxide builds up in the atmosphere, which creates more warmth. That's a positive feedback. Cooling, in turn, pulls carbon dioxide out of the atmosphere, which causes more cooling, which pulls out more carbon dioxide. Such feedbacks in the Earth's climate system can be ocean-mediated, soil- and vegetation-mediated, or, most likely, both.

BSJ: We read about your experimental manipulations and long-term observational studies of an ecosystem in the Colorado Rocky Mountains. Could you tell us about the set-up of the climate manipulation experiment?

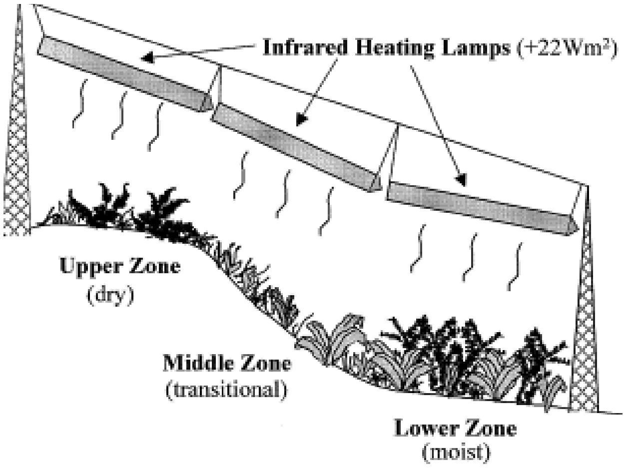


Figure 1. Schematic of a heated plot used in the Rocky Mountain Biological Laboratory long-term warming experiment.[1]

JH: In the late 1980s, I decided to experimentally heat an ecosystem that has a lot of carbon in its soil to try to understand feedback mechanisms. If we heat it, will the microbes speed up their activity and release carbon dioxide? That would be a positive feedback, and the heating would be exacerbated. Or maybe warming causes more photosynthesis and the plants take more carbon dioxide out of the air and put more carbon into the soil. That would be a negative feedback to global warming. We didn't know what would happen. We chose a large area of a subalpine meadow at the Rocky Mountain Biological Laboratory, where I had been working on other things for the previous decade. The experiment involves ten 10x3 meter plots on the side of a mountain. We built four tall steel towers and strung a web of cable from which we suspended electric heaters. We turned them on at the end of 1990, and they've been on ever since, running day and night, summer and winter—gently heating the ecosystem. The original idea was to see if we would discover mechanisms that on a larger scale would result in significant feedback to climate warming. Which, in fact, we did.

BSJ: One of the metrics you focused on in the warming experiment was loss or gain of soil organic carbon in response to temperature fluctuations. Why is this metric so important when discussing ramifications of climate change?

JH: Soil is a huge store of carbon. There's about five times more carbon in Earth's soil than there is in the atmosphere in the form of carbon dioxide. Potentially, this could be a big source of feedback. In our experiment, we mimicked the projected climate for the year 2050 assuming we keep burning fossil fuels. The experimental heating caused snow to melt a few weeks earlier each year, resulting in a longer growing season. In addition, in the first decade of the experiment, the plots lost 25% of their carbon—it was a dramatic change, and we were totally surprised. We started looking for a mechanism. There were some other changes that occurred simultaneously. Every year, we would see fewer and fewer wildflowers in the heated plots. A shrub—sagebrush—was replacing the wildflowers. Critically, the wildflowers are much more productive than the sagebrush; they pump a lot more

Figure 2. **Photographs of the Rocky Mountain Biological Laboratory experimental warming plots in summer (left) and winter (right). Photos courtesy of John Harte.**

carbon into the soil because of their high photosynthesis rates. Earlier snowmelt created a longer dry period in late spring that the wildflowers couldn't cope with. So we identified the mechanism behind the feedback, quantified it, and went on to make predictions for other habitats, using a mathematical model of the carbon cycle.

BSJ: We read about your work to develop predictive models for ecological systems using the maximum information entropy (MaxEnt) method. How does this method work?

JH: There's a subfield of ecology called macroecology that's all about patterns in the distribution and abundance of species. Up through the 1990s, ecology had been gathering more and more beautiful data from censusing, and patterns were emerging. The question is, how do you explain and predict them? We'd like to have a "Grand Unified Theory" of macroecology that would explain patterns at all different scales, habitats, and species. That's a tall order. The common approach was focusing on identifying driving mechanisms of the patterns. Hundreds of mechanisms have been proposed as important in ecology: pathogens, herbivory, and so on. How do you make a model when you have so many mechanisms to choose from? So, I turned back to my physics roots. Thermodynamics and statistical mechanics are concerned with metrics such as the distribution of the speeds of molecules in a cylinder of gas. I realized that there was an approach to measure the information content in such a probability distribution called Shannon entropy. It was called entropy because it has a similar mathematical form to the entropy function in physics. A physicist named Edwin Jaynes took the Shannon entropy function, maximized it subject to certain constraints, and was able to infer the shapes of probability distributions. Jaynes was a Bayesian statistician, so he used prior knowledge and acquisition of new data to upgrade predictions. When he maximized the Shannon information entropy of all the distributions in statistical physics, he was able to re-derive all of the results of statistical mechanics and thermodynamics. People then realized that they could use the same idea to derive distributions in economics, linguistics, neural net structure, and forensics. The method has been given a nickname—MaxEnt—for maximum entropy.

BSJ: How did you apply the MaxEnt method from thermodynamics to ecology?

JH: When Jaynes derived thermodynamics from MaxEnt, he used pressure, volume, and temperature as constraints. From those macroscale characterizations, he derived all the distributions at the microscale. In ecology, we have the total number of species on a hectare, the total number of individuals, and the total metabolic rate of the hectare of species—those are the analogous constraints. If we use those constraints and maximize information entropy of a certain well-defined probability distribution, we can calculate the shape of the distribution. Then we make predictions and compare them with the census data. It turns out that it works spectacularly. Interestingly, however, the theory breaks down when you apply it to ecosystems that are changing rapidly because of disturbance. This could be either human or natural disturbance—anything that causes the system to start changing year by year. We hope the new theory we're building, which includes disturbance, will actually explain the patterns better.

BSJ: How are you augmenting the static MaxEnt model?

JH: The original theory is a purely information theory approach—we do not assume any mechanisms. All we use as input are what we call the state variables: total number of species, total number of individuals, and total metabolic rate. Those are the result of mechanisms, of course, but we don't ask what the mechanisms are—we just use the variables as constraints for the patterns. In a disturbed system, we have to understand how the state variables are changing, so that requires explicit introduction of mechanisms. One such critical mechanism is migration from outside, so we can disturb the system by altering the parameter that describes the immigration rate. Other mechanisms include the birth, death, and growth of individuals, and the extinction of species. Now it becomes a hybrid theory, because it has both the MaxEnt component and the mechanistic component. We are quite sure that we can't develop a purely statistical MaxEnt theory of disturbance, because disturbances are all unique and responses critically depend on the mechanisms that create the disturbance.

BSJ: What are some of the most promising applications of the MaxEnt Theory of Ecology?

JH: So far, the most promising applications have been to accurately predict all of these patterns that are in the literature—to explain puzzles that have perplexed ecologists for decades: why do distributions and relationships look the way they do? If we can develop a successful MaxEnt-mechanism hybrid theory, it will be very useful for predicting things like the fate of ecosystems under human disturbance. Physics has great prestige today because we have theory that explains pattern. Ecology is still largely in the stage of lots of observation, with little understanding of the origins of patterns or ways to predict them. The Maximum Entropy Theory of Ecology is an attempt to give ecology more credibility. If astronomers have calculated that an asteroid is about to hit Earth and they go before Congress, no one would doubt the astronomers' calculations because they're based on good, solid theory. The physicists have credibility. If ecologists go to Congress, as we've done, and say a different kind of asteroid is hitting Earth: the global extinction of a sizable fraction of all the species on the planet, the response is typically, "Why should we believe you?" Helping to build a foundation of solid ecological theory will give ecologists more credibility in the policy arena.

> ***"Helping to build a foundation of solid ecological theory will give ecologists more credibility in the policy arena."***

BSJ: A lot of your work intersects with human population studies. How do we ensure food security into the future?

JH: A high priority of all governments should be to confront the problem of population. Our numbers are growing, and that is going to compound every other problem that we have, from climate change, to drought, to soil erosion, and so forth. This is partly a human rights issue. There are a few hundred million women around the world who don't have access to contraception. A combination of religious and political ideology has denied women a fundamental right, which is to control their own reproduction. Providing women everywhere with the means to implement family planning, if they so choose, would be the single most important step to ensure food security. There are many other things, too. Just as with income inequality, we have food access inequality. But all of these other problems are more and more difficult to solve when there are more and more people. Achieving sensible, workable governance under conditions of overpopulation is very difficult. So I would put the population focus at the top, but I would also add dealing with inequality and with land use management. Some of the farming techniques that would avoid soil erosion, improve yields, save water, produce more healthy food, and promote biodiversity, would also sequester more carbon and help deal with the climate issue. There's a synergy in the solutions to most of the problems that humanity faces. And no one solution, alone, will be enough.

BSJ: What are some future directions of your research?

JH: Right now, all of the focus is on extending the static MaxEnt theory—the one that worked in undisturbed systems—to systems that are changing rapidly because of disturbance. That's a massive project, and by no means have we completed it. That's the focus of ongoing work—turning a static theory into a dynamic theory.

BSJ: Thank you very much for your time!

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