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"Scientific analysis cannot take the place of moral reasoning; science, including the science of ecology, promotes, at least in some of its manifestations, a few of our darker ambitions toward nature and therefore itself needs to be morally examined and critiqued from time to time. Ecology should never be taken as an all-wise, always trustworthy guide. We must be willing to challenge this authority, and indeed challenge the authority of science in general; not be quick to scorn or vilify or behead, but simply, now and then, to question."

- Donald Worster

This issue of the **Reprint Mailing** is entirely devoted to the essay "The Ecology of Order and Chaos" which is Chapter 13 of **The Wealth of Nature:** Environmental History and the Ecological Imagination (Oxford University Press, N.Y.1993) by Donald Worster. Professor Worster teaches the environmental history of North America at the University of Kansas, Lawrence, KS. His other published works include **Dust Bowl**, **Rivers of Empire**, **The Ends of the Earth**, **Under Western Skies** and the just released Second Edition of **Nature's Economy**: A History of Ecological Ideas.

The Ecology of Order and Chaos

by

Donald Worster

THE SCIENCE of ecology has had a popular impact unlike that of any other academic field of research. Consider the extraordinary ubiquity of the word itself: it has appeared in the most everyday places and the most astonishing, on day-glo T-shirts, in corporate advertising, and on bridge abutments. It has changed the language of politics and philosophy—springing up in a number of countries are political groups that are self-identified as "Ecology Parties." Yet who ever proposed forming a political party named after comparative linguistics or advanced paleontology? On several continents we have a philosophical movement termed "Deep Ecology," but nowhere has anyone announced a movement for "Deep Entomology" or "Deep Polish Literature." Why has this funny little word, *ecology*, coined by an obscure nineteenth-century German scientist, acquired so powerful a cultural resonance, so widespread a following?

Behind the persistent enthusiasm for ecology, I believe, lies the hope that this science can offer a great deal more than a pile of data. It is supposed to offer a pathway to a kind of moral enlightenment that we can call, for the purposes of simplicity, "conservation." The expectation did not originate with the public but first appeared among eminent scientists within the field. For instance, in his 1935 book *Deserts on the March,* the noted University of Oklahoma, and later Yale, botanist Paul Sears urged Americans to take ecology seriously, promoting it in their universities and making it part of their governing process. "In Great Britain," he pointed out,

> the ecologists are being consulted at every step in planning the proper utilization of those parts of the Empire not yet settled, thus . . . ending the era of haphazard exploitation. There are hopeful, but all too few signs that our own national government realizes the part which ecology must play in a permanent program.[1]

Sears recommended that the United States hire a few thousand ecologists at the county level to advise citizens on questions of land use and thereby bring an end to environmental degradation; such a brigade, he thought, would put the whole nation on a biologically and economically sustainable basis.

In a 1947 addendum to his text, Sears added that ecologists, acting in the public interest, would instill in the American mind that "body of knowledge," that "point of view, which peculiarly implies all that is meant by conservation."[2] In other words, by the time of the 1930s and 40s, ecology was being hailed as a much needed guide to a future motivated by an ethic of conservation. And conservation for Sears meant restoring the biological order, maintaining the health of the land and thereby the well-being of the nation, pursuing by both moral and technical means a lasting equilibrium with nature.

While we have not taken to heart all of Sears's suggestions—have not yet put any ecologists on county payrolls, with an office next door to the tax collector and sheriff—we have taken a surprisingly long step in his direction. Every day in some part of the nation, an ecologist is at work writing an environmental impact report or monitoring a human disturbance of the landscape or testifying at a hearing.

Twelve years ago I published a history, going back to the eighteenth century, of this scientific discipline and its ideas about nature.[3] The conclusions in that book still strike me as being, on the whole, sensible and valid: that this science has come to be a major influence on our perception of nature in modern times; that its ideas, on the other hand, have been reflections of ourselves as much as objective apprehensions of nature; that scientific analysis cannot take the place of moral reasoning; that science, including the science of ecology, promotes, at least in some of its manifestations, a few of our darker ambitions toward nature and therefore itself needs to be morally examined and critiqued from time to time. Ecology, I argued, should never be taken as an all-wise, always trustworthy guide. We must be willing to challenge this authority, and indeed challenge the authority of science in general; not be quick to scorn or vilify or behead, but simply, now and then, to question.

During the period since my book was published, there has accumulated a considerable body of new thinking and new research in ecology. I mean to survey some of that recent thinking, contrasting it with its predecessors, and to raise a few of the same questions I did before. Part of my argument will be that Paul Sears would be astonished, and perhaps dismayed, to hear the kind of advice that ecological experts have got to give these days. Less and less do they offer, or even promise to offer, what he would consider to be a program of moral enlightenment: of "conservation" in the sense of a restored equilibrium between humans and nature.

There is a clear reason for that outcome, I will argue, and it has to do with drastic changes in the ideas that ecologists hold about the structure and function of the natural world. In Sears's day ecology was basically a study of equilibrium, harmony, and order; it had been so from its beginnings. Today, however, in many circles of scientific research, it has become a study of disturbance, disharmony, and chaos, and coincidentally or not, conservation is often not even a remote concern.

At the time *Deserts on the March* appeared in print, and through the time of its second and even third edition, the dominant name in the field of American ecology was that of Frederic L. Clements, who more than any other individual introduced scientific ecology into our national academic life. He called his approach "dynamic ecology," meaning it was concerned with change and evolution in the landscape. At its heart Clements's ecology dealt with the process of vegetational succession—the sequence of plant communities that appear on a piece of soil, newly made or disturbed, beginning with the first pioneer communities that invade and get a foothold.[4] Here is how I have defined the essence of the Clementsian paradigm:

> Change upon change became the inescapable principle of Clements's science. Yet he also insisted stubbornly and vigorously on the notion that the natural landscape must eventually reach a vaguely final climax stage. Nature's course, he contended, is not an aimless wandering to and fro but a steady flow toward stability that can be exactly plotted by the scientist.[5]

Most interestingly, Clements referred to that final climax stage as a "superorganism," implying that the assemblage of plants had achieved the close integration of parts, the self-organizing capability, of a single animal or plant. In some unique sense, it had become a live, coherent thing, not a mere collection of atomistic individuals, and exercised some control over the non-living world around it, as organisms do.

Until well after World War II Clements's climax theory dominated ecological thought in this country.[6] Pick up almost any textbook in the field written forty, or even thirty, years ago, and you will likely find mention of the climax. It was this theory that Paul Sears had studied and took to be the core lesson of ecology that his county ecologists should teach their fellow citizens: that nature tends toward a climax state and that, as far as practicable, they should learn to respect and preserve it. Sears wrote that the chief work of the scientist ought to be to show "the unbalance which man has produced on this continent" and to lead people back to some approximation of nature's original health and stability.[7]

But then, beginning in the 1940s, while Clements and his ideas were still in the ascendant, a few scientists began trying to speak a new vocabulary. Words like "energy flow" and "trophic levels" and "ecosystem" appeared in the leading journals, and they indicated a view of nature shaped more by physics than botany. Within another decade or two nature came to be widely seen as a flow of energy and nutrients through a physical or thermodynamic system. The early figures prominent in shaping this new view included C. Juday, Raymond Lindeman, and G. Evelyn Hutchinson. But perhaps its most influential exponent was Eugene P. Odum, hailing from North Carolina and Georgia, discovering in his southern saltwater marshes, tidal estuaries, and abandoned cotton fields the animating, pulsating force of the sun, the global flux of energy. In 1953 Odum published the first edition of his famous textbook, *The Fundamentals of Ecology.*[8] In 1966 he became president of the Ecological Society of America.

By now anyone in the United States who regularly reads a newspaper or magazine has come to know at least a few of Odum's ideas, for they furnish the main themes in our popular understanding of ecology, beginning with the sovereign idea of the ecosystem. Odum defined the ecosystem as "any unit that includes all of the organisms (i.e., the 'community') in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (i.e., exchange of materials between living and nonliving parts) within the system."[9] The whole earth, he argued, is organized into an interlocking series of such "ecosystems," ranging in size from a small pond to so vast an expanse as the Brazilian rainforest.

What all those ecosystems have in common is a "strategy of development," a kind of game plan that gives nature an overall direction. That strategy is, in Odum's words, "directed toward achieving as large and diverse an organic structure as is possible within the limits set by the available energy input and the prevailing physical conditions of existence."[10] Every single ecosystem, he believed, is either moving toward or has already achieved that goal. It is a clear, coherent, and easily observable strategy; and it ends in the happy state of order.

Nature's strategy, Odum added, leads finally to a world of mutualism and cooperation among the organisms inhabiting an area. From an early stage of competing against one another, they evolve toward a more symbiotic relationship. They learn, as it were, to work together to control their surrounding environment, making it more and more suitable as a habitat, until at last they have the power to protect themselves from its stressful cycles of drought and flood, winter and summer, cold and heat. Odum called that point "homeostasis." To achieve it, the living components of an ecosystem must evolve a structure of interrelatedness and cooperation that can, to some extent, manage the physical world—manage it for maximum efficiency and mutual benefit.

I have described this set of ideas as a break from the past, but that is misleading. Odum may have used different terms than Clements, may even have had a radically different vision of nature at times; but he did not repudiate Clements's notion that nature moves toward order and harmony. In the place of the theory of the "climax" stage he put the theory of the "mature ecosystem." His nature may have appeared more as an automated factory than as a Clementsian super-organism, but like its predecessor it tends toward order.

The theory of the ecosystem presented a very clear set of standards as to what constituted order and disorder, which Odum set forth in the form of a "tabular model of ecological succession." When the ecosystem reaches its end point of homeostasis, his table shows, it expends less energy on increasing production and more on furnishing protection from external vicissitudes: that is, the biomass in an area reaches a steady level, neither increasing nor decreasing, and the emphasis in the system is on keeping it that way—on maintaining a kind of no-growth economy. Then the little, aggressive, weedy organisms common at an early stage in development (the r-selected species) give way to larger, steadier creatures (K-selected species), who may have less potential for fast growth and explosive reproduction but also better talents at surviving in dense settlements and keeping the place on an even keel.[11] At that point there is supposed to be more diversity in the community—i.e., a greater array of species. And there is less loss of nutrients to the outside; nitrogen, phosphorous, and calcium all stay in circulation within the ecosystem rather than leaking out. Those are some of the key indicators of ecological order, all of them susceptible to precise measurement. The suggestion was implicit but clear that if one interfered too much with nature's strategy of development, the effects might be costly: a serious loss of nutrients, a decline in species diversity, an end to biomass stability. In short, the ecosystem would be damaged.

The most likely source of that damage was no mystery to Odum: it was human beings trying to force up the production of useful commodities and stupidly risking the destruction of their life support system.

> Man has generally been preoccupied with obtaining as much "production" from the landscape as possible, by developing and maintaining early successional types of ecosystems, usually monocultures. But, of course, man does not live by food and fiber alone; he also needs a balanced CO_2-O_2 atmosphere, the climatic buffer provided by oceans and masses of vegetation, and clean (that is, unproductive) water for cultural and industrial uses. Many essential life-cycle resources, not to mention recreational and esthetic needs, are best provided man by the less "productive" landscapes. In other words, the landscape is not just a supply depot but is also the *oikos*—the home—in which we must live.[12]

Odum's view of nature as a series of balanced ecosystems, achieved or in the making, led him to take a strong stand in favor of preserving the landscape in as nearly natural a condition as possible. He suggested the need for substantial restraint on human activity—for environmental planning "on a rational and scientific basis." For him as for Paul Sears, ecology must be taught to the public and made the foundation of education, economics, and politics; America and other countries must be "ecologized."

Of course not every one who adopted the ecosystem approach to ecology ended up where Odum did. Quite the contrary, many found the ecosystem idea a wonderful instrument for promoting global technocracy. Experts familiar with the ecosystem and skilled in its manipulation, it was hoped in some quarters, could manage the entire planet for improved efficiency. "Governing" all of nature with the aid of rational science was the dream of these ecosystem technocrats.[13] But technocratic management was not the chief lesson, I believe, the public learned in Professor Odum's classroom; most came away devoted, as he was, to preserving large parts of nature in an unmanaged state and sure that they had been given a strong scientific rationale, as well as knowledge base, to do it. We must defend the world's endangered ecosystems, they insisted. We must safeguard the integrity of the Greater Yellowstone ecosystem, the Chesapeake Bay ecosystem, the Serengeti ecosystem. We must protect species diversity, biomass stability, and calcium recycling. We must make the world safe for K-species.[14]

That was the rallying cry of environmentalists and ecologists alike in the 1960s and early 1970s, when it seemed that the great coming struggle would be between what was left of pristine nature, delicately balanced in Odum's beautifully rational ecosystems, and a human race bent on mindless, greedy destruction. A decade or two later the situation has changed considerably. There are still environmental threats around, to be sure, and they are more dangerous than ever. The newspapers inform of us of continuing disasters like the massive 1989 oil spill in Alaska's Prince William Sound, and reporters persist in using words like "ecosystem" and "balance" and "fragility" in describing such disasters. So do many scientists, who continue to acknowledge their theoretical indebtedness to Odum. For instance, in a recent British poll, 447 ecologists out of 645 questioned ranked the "ecosystem" as one of the most important concepts their discipline has contributed to our understanding of the natural world; indeed, "ecosystem" ranked first on their list, drawing more votes than nineteen other leading concepts.[15] But all the same, and despite the persistence of environmental problems, Odum's ecosystem is no longer the main theme in research or teaching in the science. A survey of recent ecology textbooks shows that the concept is not even mentioned in one leading work and has a much diminished place in the others.[16]

Ecology is not the same as it was. A rather drastic change has been going on in this science of late: a radical shifting away from the thinking of Eugene Odum's generation, away from its assumptions of order and predictability, a shifting toward what we might call a new *ecology of chaos.*

In July 1973 the *Journal of the Arnold Arboretum* published an article by two scientists associated with the Massachusetts Audubon Society, William Drury and Ian Nisbet, and it challenged Odum's ecology fundamentally. The title of the article was simply "Succession," indicating that old subject of observed sequences in plant and animal associations. With both Frederic Clements and Eugene Odum, succession had been taken to be the straight and narrow road to equilibrium. Drury and Nisbet disagreed completely with that assumption. Their observations, drawn particularly from northeastern temperate forests, strongly suggested that the process of ecological succession does not lead anywhere. Change is without any determinable direction and goes on forever, never reaching a point of stability. They found no evidence of any progressive development in nature: no progressive increase over time in biomass stabilization, no progressive diversification of species, no progressive movement toward a greater cohesiveness in plant and animal communities, nor toward a greater success in regulating the environment. Indeed, they found none of the criteria Odum had posited for mature ecosystems. The forest, they insisted, no matter what its age, is nothing but an erratic, shifting mosaic of trees and other plants. In their words, "most of the phenomena of succession should be understood as resulting from the differential growth, differential survival, and perhaps differential dispersal of species adapted to grow at different points on stress gradients."[17] In other words, they could see lots of individual species, each doing its thing, but they could locate no emergent collectivity, nor any strategy to achieve one.

Prominent among their authorities supporting this view was the nearly forgotten name of Henry A. Gleason, a taxonomist who, in 1926, had challenged Frederic Clements and his organismic theory of the climax in an article entitled "The Individualistic Concept of the Plant Association." Gleason had argued that we live in a world of constant flux and impermanence, not one tending toward Clements's climaxes. There is no such thing, he argued, as balance or equilibrium or steady-state. Each and every plant association is nothing but a temporary gathering of strangers, a clustering of species unrelated to one another, here for a brief while today, on their way somewhere else tomorrow. "Each . . . species of plant is a law unto itself," he wrote.[18] We look for cooperation in nature and we find only competition. We look for organized wholes, and we can discover only loose atoms and fragments. We hope for order and discern only a mishmash of conjoining species, all seeking their own advantage in utter disregard of others.

Thanks in part to Drury and Nisbet, this "individualistic" view was reborn in the mid-1970s and, by the present decade, it had become the core idea of what some scientists hailed as a new, revolutionary paradigm in ecology. To promote it, they attacked the traditional notion of succession; for to reject that notion was to reject the larger idea that organic nature tends toward order. In 1977 two more biologists, Joseph Connell and Ralph Slatyer, continued the attack, denying the old claim that an invading community of pioneering species, the first stage in Clements's sequence, works to prepare the ground for its successors, like a group of Daniel Boones blazing the trail for civilization. The first comers, Connell and Slatyer maintained, manage in most cases to stake out their claims and successfully defend them; they do not give way to a later, superior group of colonists. Only when the pioneers die or are damaged by natural disturbances, thus releasing the resources they have monopolized, can latecomers find a foothold and get established.[19]

As this assault on the old thinking gathered momentum, the word "disturbance" began to appear more frequently in the scientific literature and be taken far more seriously. "Disturbance" was not a common subject in Odum's heyday, and it almost never appeared in combination with the adjective "natural." Now, however, it was as though scientists were out looking strenuously for signs of disturbance in nature—especially signs of disturbance that were not caused by humans—and they were finding them everywhere. By the present decade these new ecologists have succeeded in leaving little tranquility in primitive nature. Fire is one of the most common disturbances they have noted. So is wind, especially in the form of violent hurricanes and tornadoes. So are invading populations of microorganisms and pests and predators. And volcanic eruptions. And invading ice sheets of the Quaternary Period. And devastating droughts like that of the 1930s in the American West. Above all, it is these last sorts of disturbances, caused by the restlessness of climate, that the new generation of ecologists has emphasized. As one of the most influential of them, Professor Margaret Davis of the University of Minnesota, has written: "For the last 50 years or 500 or 1,000—as long as anyone would claim for 'ecological time'—there has never been an interval when temperature was in a steady state with symmetrical fluctuations about a mean. . . . Only on the longest time scale, 100,000 years, is there a tendency toward cyclical variation, and the cycles are asymmetrical, with a mean much different from today."[20]

One of the most provocative and impressive expressions of the new post-Odum ecology is a book of essays edited by S. T. A. Pickett and P. S. White, *The Ecology of Natural Disturbance and Patch Dynamics* (published in 1985). I submit it as symptomatic of much of the thinking going on today in the field. Though the final section of the book does deal with ecosystems, the word has lost much of its former meaning and implications. Two of the authors in fact open their contribution with a complaint that many scientists assume that "homogeneous ecosystems are a reality," when in truth "virtually all naturally occurring and man-disturbed ecosystems are mosaics of environmental conditions." "Historically," they write, "ecologists have been slow to recognize the importance of disturbances and the heterogeneity they generate." The reason for this slowness? "The majority of both theoretical and empirical work has been dominated by an equilibrium perspective."[21] Repudiating that perspective, these authors take us to the tropical forests of South and Central America and to the Everglades of Florida, showing us instability on every hand: a wet, green world of continual disturbance—or as they prefer to say, "of perturbations." Even the grasslands of North America, which inspired Frederic Clements's theory of the climax, appear in this collection as regularly disturbed environments. One paper describes them as a "dynamic, fine-textured mosaic" that is constantly kept in upheaval by the workings of badgers, pocket gophers, and mound-building ants, along with fire, drought, and eroding wind and water.[22] The message in all these papers is consistent: the climax notion is dead, the ecosystem has receded in usefulness, and in their place we have the idea of the lowly "patch." Nature should be regarded as a landscape of patches, big and little, patches of all textures and colors, a patchwork quilt of living things, changing continually through time and space, responding to an unceasing barrage of perturbations. The stitches in that quilt never hold for long.

Now, of course, scientists have known about gophers and winds and the Ice Age and droughts for a considerable time. Yet heretofore they have not let those disruptions spoil their theories of balanced plant and animal associations, and we must ask why that was so. Why did Clements and Odum tend to dismiss such forces as climatic change, at least of the less catastrophic sort, as threats to the order of nature? Why have their successors, on the other hand, tended to put so much emphasis on those same changes, to the point that they often see nothing but instability in the landscape?

One clue comes from the fact that many of these disturbance boosters are not and have never been ecosystem scientists; they received their training in the subfield of population biology and reflect the growing confidence, methodogical maturity, and influence of that subfield.[23] When they look at a forest, the population ecologists see only the trees: see them and count them—so many white pines, so many hemlocks, so many maples and birches. They insist that if we know all there is to know about the individual species that constitute a forest, and can measure their lives in precise, quantitative terms, we will know all there is to know about that forest. It has no "emergent" or organismic properties. It is not some whole greater than the sum of its parts, requiring "holistic" understanding. Outfitted with computers that can track the life histories of individual species, chart the rise and fall of populations, they have brought a degree of mathematical precision to ecology that is awesome to contemplate. And what they see when they look at population histories for any patch of land is wildly swinging oscillations. Populations rise and populations fall, like stock market prices, auto sales, and hemlines. We live, they insist, in a non-equilibrium world.[24]

There is another reason for the paradigmatic shift I have been describing, though I suggest it quite tentatively and can offer only sketchy evidence for it. For some scientists, a nature characterized by highly individualistic associations, constant disturbance, and incessant change may be more ideologically satisfying than Odum's ecosystem, with its stress on cooperation, social organization, and environmentalism. A case in point is the very successful popularizer of contemporary ecology, Paul Colinvaux, author of *Why Big Fierce Animals Are Rare* (1978). His chapter on succession begins with these lines: "If the planners really get hold of us so that they can stamp out all individual liberty and do what they like with our land, they might decide that whole counties full of inferior farms should be put back into forest." Clearly, he is not enthusiastic about land-use planning or forest restoration. And he ends that same chapter with these remarkably revealing and self-assured words:

> We can now . . . explain all the intriguing, predictable events of plant successions in simple, matter of fact, Darwinian ways. Everything that happens in successions comes about because all the different species go about earning their livings as best they may, each in its own individual manner. What look like community properties are in fact the summed results of all these bits of private enterprise.[25]

Apparently, if this example is any indication, the Social Darwinists are back on the scene, and at least some of them are ecologists, and at least some of their opposition to Odum's science may have to do with a revulsion toward what they perceive are its political implications, including its attractiveness for environmentalists. Colinvaux is very clear about the need to get some distance between himself and groups like the Sierra Club.

I am not alone in wondering whether there might be a deeper, half-articulated ideological motive generating the new direction in ecology. The Swedish historian of science Thomas Söderqvist, in his recent study of ecology's development in his country, concludes that the present generation of evolutionary ecologists

> seem to do ecology for fun only, indifferent to practical problems, including the salvation of the nation. They are mathematically and theoretically sophisticated, sitting indoors calculating on computers, rather than traveling out in the wilds. They are individualists, abhorring the idea of large-scale ecosystem projects. Indeed, the transition from ecosystem ecology to evolutionary ecology seems to reflect the generational transition from the politically consciousness generation of the 1960s to the "yuppie" generation of the 1980s.[26]

That may be an exaggerated characterization, and I would not want to apply it to every scientist who has published on patch dynamics or disturbance regimes. But it does draw our attention to an unmistakable attempt by many ecologists to disassociate themselves from reform environmentalism and its criticisms of human impact on nature.

I wish, however, that the emergence of the new post-Odum ecology could be explained so simply in those two ways: as a triumph of reductive population dynamics over holistic consciousness, or as a triumph of Social Darwinist or entrepreneurial ideology over a commitment to environmental preservation. There is, it seems, more going on than that, and it is going on all through the natural sciences—biology, astronomy, physics—perhaps going on through all modern technological societies. It is nothing less than the discovery of chaos. Nature, many have begun to believe, is *fundamentally* erratic, discontinuous, and unpredictable. It is full of seemingly random events that elude our models of how things are supposed to work. As a result, the unexpected keeps hitting us in the face. Clouds collect and disperse, rain falls or doesn't fall, disregarding our careful weather predictions, and we cannot explain why. Cars suddenly bunch up on the freeway, and the traffic controllers fly into a frenzy. A man's heart beats regularly year after year, then abruptly begins to skip a beat now and then. A ping pong ball bounces off the table in an unexpected direction. Each little snowflake falling out of the sky turns out to be completely unlike any other. These are ways in which nature seems, by all our previous theories and methods, to be chaotic. If the ultimate test of any body of scientific knowledge is its ability to predict events, then all the sciences and pseudo-sciences—physics, chemistry, climatology, economics, ecology—fail the test regularly. They all have been announcing laws, designing models, predicting what an individual atom or person is supposed to do; and now, increasingly, they are beginning to confess that the world never quite behaves the way it is supposed to do.

Making sense of this situation is the task of an altogether new kind of inquiry calling itself the science of chaos. Some say it portends a revolution in thinking equivalent to quantum mechanics or relativity. Like those other twentieth-century revolutions, the science of chaos rejects tenets going back as far as the days of Sir Isaac Newton. In fact, what is occurring may be not two or three separate revolutions but a single revolution against all the principles, laws, models, and applications of classical science, the science ushered in by the great Scientific Revolution of the seventeenth century.[27] For centuries we have assumed that nature, despite a few appearances to the contrary, is a perfectly predictable system of linear, rational order. Give us an adequate number of facts, scientists have said, and we can describe that order in complete detail—can plot the lines along which everything moves and the speed of that movement and the collisions that will occur. Even Darwin's theory of evolution, which in the last century challenged much of the Newtonian worldview, left intact many people's confidence that order would prevail at last in the evolution of life; that out of the tangled history of competitive struggle would come progress, harmony, and stability. Now that traditional assumption may have broken down irretrievably. For whatever reason, whether because empirical data suggest it or because extrascientific cultural trends do, the experience of so much rapid social change in our daily lives, scientists are beginning to focus on what they had long managed to avoid seeing. The world is more complex than we ever imagined, they say, and indeed, some would add, ever can imagine.[28]

Despite the obvious complexity of their subject matter, ecologists have been among the slowest to join the cross-disciplinary science of chaos. I suspect that the influence of Clements and Odum, lingering well into the 1970s, worked against the new perspective, encouraging faith in linear regularities and equilibrium in the interaction of species. Nonetheless, eventually there arrived a day of conversion. In 1974 the Princeton mathematical ecologist Robert May published a paper with the title "Biological Populations with Nonoverlapping Generations: Stable Points, Stable Cycles, and Chaos."[29] In it he admitted that the mathematical models he and others had constructed were inadequate approximations of the ragged life histories of organisms. They did not fully explain, for example, the aperiodic outbreaks of gypsy moths in eastern hardwood forests or the Canadian lynx cycles in the subarctic. Wildlife populations do not follow some simple Malthusian pattern of increase, saturation, and crash.

More and more ecologists have followed May and begun to try to bring their subject into line with chaotic theory. William Schaefer is one of them; though a student of Robert MacArthur, a leader of the old equilibrium school, he has been lately struck by the same anomaly of unpredictable fluctuations in populations as May and others. Though taught to believe in "the so-called 'Balance of Nature'," he writes, ". . . the idea that populations are at or close to equilibrium," things now are beginning to look very different.[30] He describes himself has having to reach far across the disciplines, to make connections with concepts of chaos in the other natural sciences, in order to free himself from his field's restrictive past.

The entire study of chaos began in 1961, with efforts to simulate weather and climate patterns on a computer at MIT. There, meteorologist Edward Lorenz came up with his now famous "Butterfly Effect," the notion that a butterfly stirring the air today in a Beijing park can transform storm systems next month in New York City. Scientists call this phenomenon "sensitive dependence on initial conditions." What it means is that tiny differences in input can quickly become substantial differences in output. A corollary is that we cannot know, even with all our artificial intelligence apparatus, every one of the tiny differences that have occurred or are occurring at any place or point in time; nor can we know which tiny differences will produce which substantial differences in output. Beyond a short range, say, of two or three days from now, our predictions are not worth the paper they are written on.

The implications of this "Butterfly Effect" for ecology are profound. If a single flap of an insect's wings in China can lead to a torrential downpour in New York, then what might it do to the Greater Yellowstone Ecosystem? What can ecologists possibly know about all the forces impinging on, or about to impinge on, any piece of land? What can they safely ignore and what must they pay attention to? What distant, invisible, minuscule events may even now be happening that will change the organization of plant and animal life in our back yards? This is the predicament, and the challenge, presented by the science of chaos, and it is altering the imagination of ecologists dramatically.

John Muir once declared, "When we try to pick out anything by itself, we find it hitched to everything else in the universe."[31] For him, that was a manifestation of an infinitely wise plan in which everything functioned with perfect harmony. The new ecology of chaos, though impressed like Muir with interdependency, does not share his view of "an infinitely wise plan" that controls and shapes everything into order. There is no plan, today's scientists say, no harmony apparent in the events of nature. If there is order in the universe—and there will no longer be any science at all if all faith in order vanishes—it is going to be much more difficult to locate and describe than we thought.

For Muir, the clear lesson of cosmic complexity was that humans ought to love and preserve nature just as it is. The lessons of the new ecology, in contrast, are not at all clear. Does it promote, in Ilya Prigogine and Isabelle Stenger's words, "a renewal of nature," a less hierarchical view of life, and a set of "new relations between man and nature and between man and man"?[32] Or does it increase our alienation from the world, our withdrawal into post-modernist doubt and self-consciousness? What is there to love or preserve in a universe of chaos? How are people supposed to behave in such a universe? If that is the kind of place we inhabit, why not go ahead with all our private ambitions, free of any fear that we may be doing special damage? What, after all, does the phrase "environmental damage" mean in a world of so much natural chaos? Does the tradition of environmentalism to which Muir belonged, along with so many other nature writers and ecologists of the past, people like Paul Sears, Eugene Odum, Aldo Leopold, and Rachel Carson, make sense any longer? I have no space here to attempt to answer those questions, or to make predictions, but only a warning that they are too important to be left for scientists alone to answer. Ecology cannot today, no more than in the past, be assumed to be all-knowing or all-wise or eternally true.

Whether they are true or false, permanent or passingly fashionable, it does seem entirely possible that these changes in scientific thinking toward an emphasis on chaos will not produce any easing of the environmentalist's concern. Though words like ecosystem or climax may fade away, and some new vocabulary take their place, the fear of risk and danger will likely become greater than ever. Most of us are intuitively aware, whether we can put our fears into mathematical formulae or not, that the technological power we have accumulated is *destructively* chaotic; not irrationally, we fear it and fear what it can do to us as well as the rest of nature.[33] It may be that we moderns, after absorbing the lessons of today's science, find we cannot love nature quite so easily as Muir did; but it may also be that we have discovered more reason than ever to respect it—to respect its baffling complexity, its inherent unpredictability, its daily turbulence. And to flap our own wings in it a little more gently.

Notes

1. Paul Sears, *Deserts on the March,* 3rd ed. (Norman: University of Oklahoma Press, 1959), 162.

2. *Ibid.*, 177.

3. Donald Worster, *Nature's Economy: A History of Ecological Ideas* (New York: Cambridge University Press, 1977).

4. This is the theme in particular of Clement's book *Plant Succession* (Washington: Carnegie Institution, 1916).

5. Worster, *Nature's Economy,* 210.

6. Clement's major rival for influence in the United States was Henry Chandler Cowles of the University of Chicago, whose first paper on ecological succession appeared in 1899. The best study of Cowles's ideas is J. Ronald Engel, *Sacred Sands: The Struggle for Community in the Indiana Dunes* (Middletown, Conn.: Wesleyan University Press, 1983), 137-59. Engel describes him as having a less deterministic, more pluralistic notion of succession, one that "opened the way to a more creative role for human beings in nature's evolutionary adventure" (150). See also Ronald C. Tobey, *Saving the Prairies: The Life Cycle of the Founding School of American Plant Ecology, 1895-1955* (Berkeley: University of California, 1981).

7. Sears, *Deserts on the March,* 142.

8. This book was co-authored with his brother Howard T. Odum, and it went through two more editions, the last appearing in 1971.

9. Eugene P. Odum, *Fundamentals of Ecology* (Philadelphia: W. B. Saunders, 1971), 8.

10. Odum, "The Strategy of Ecosystem Development," *Science,* 164 (18 April 1969), 266.

11. The terms "K-selection" and "r-selection" came from Robert MacArthur and Edward O. Wilson, *Theory of Island Biogeography* (Princeton: Princeton University Press, 1967). Along with Odum, MacArthur was the leading spokesman for the view of nature as a series of thermodynamically balanced ecosystems during the 1950s and 60s.

12. Odum, "Strategy of Ecosystem Development," 266. See also Odum, "Trends Expected in Stressed Ecosystems," *BioScience,* 35 (July/August 1985), 419-22.

13. A book of that title was published by Earl F. Murphy: *Governing Nature* (Chicago: Quadrangle Books, 1967). From time to time, Eugene Odum himself seems to have caught that ambition or lent his support to it, and it was certainly central to the work of his brother, Howard T. Odum. On this theme see Peter J. Taylor, "Technocratic Optimism, H. T. Odum, and the Partial Transformation of Ecological Metaphor after World War II," *Journal of the History of Biology,* 21 (Summer 1988), 213-44.

14. A very influential popularization of Odum's view of nature (though he is never actually referred to in it) is Barry Commoner's *The Closing Circle: Nature, Man, and Technology* (New York: Knopf, 1971). See in particular the discussion of the four "laws" of ecology (33-46).

15. Communication from Malcolm Cherrett, *Ecology,* 70 (March 1989), 41-42.

16. See Michael Begon, John L. Harper, and Colin R. Townsend, *Ecology: Individuals,*

Populations, and Communities (Sunderland, Mass.: Sinauer, 1986). In another textbook, Odum's views are presented critically as the traditional approach: R. J. Putnam and S. D. Wratten, *Principles of Ecology* (Berkeley: University of California Press, 1984). More loyal to the ecosystem model are Paul Ehrlich and Jonathan Roughgarden, *The Science of Ecology* (New York: Macmillan, 1987); and Robert Leo Smith, *Elements of Ecology*, 2nd ed. (New York: Harper & Row, 1986), though the latter admits that he has shifted from an "ecosystem approach" to more of an "evolutionary approach" (xiii).

17. William H. Drury and Ian C. T. Nisbet, "Succession," *Journal of the Arnold Arboretum*, 54 (July 1973), 360.

18. H. A. Gleason, "The Individualistic Concept of the Plant Association," *Bulletin of the Torrey Botanical Club*, 53 (1926), 25. A later version of the same article appeared in *American Midland Naturalist*, 21 (1939), 92–110.

19. Joseph H. Connell and Ralph O. Slayter, "Mechanisms of Succession in Natural Communities and Their Role in Community Stability and Organization," *The American Naturalist*, 111 (Nov.–Dec. 1977), 1119–44.

20. Margaret Bryan Davis, "Climatic Instability, Time Lags, and Community Disequilibrium," in *Community Ecology*, ed. Jared Diamond and Ted J. Case (New York: Harper & Row, 1986), 269.

21. James R. Karr and Kathryn E. Freemark, "Disturbance and Vertebrates: An Integrative Perspective," *The Ecology of Natural Disturbance and Patch Dynamics*, ed. S.T.A. Pickett and P. S. White (Orlando, Fla.: Academic Press, 1985), 154–55. The Odum school of thought is, however, by no means silent. Another recent compilation has been put together in his honor, and many of its authors express a continuing support for his ideas: L. R. Pomeroy and J. J. Alberts, eds., *Concepts of Ecosystem Ecology: A Comparative View* (New York: Springer-Verlag, 1988).

22. Orie L. Loucks, Mary L. Plumb-Mentjes, and Deborah Rogers, "Gap Processes and Large-Scale Disturbances in Sand Prairies," in Pomeroy and Alberts, *ibid.*, 72–85.

23. For the rise of population biology see Sharon E. Kingsland, *Modeling Nature: Episodes in the History of Population Biology* (Chicago: University of Chicago Press, 1985).

24. An influential exception to this tendency is F. H. Bormann and G. E. Likens, *Pattern and Process in a Forested Ecosystem* (New York: Springer-Verlag, 1979), which proposes (in chap. 6) the model of a "shifting mosaic steady-state." See also P. Yodzis, "The Stability of Real Ecosystems," *Nature*, 289 (19 February 1981), 674–76.

25. Paul Colinvaux, *Why Big Fierce Animals Are Rare: An Ecologist's Perspective* (Princeton: Princeton University Press, 1978), 117, 135.

26. Thomas Söderqvist, *The Ecologists: From Merry Naturalists to Saviours of the Nation. A Sociologically Informed Narrative Survey of the Ecologization of Sweden, 1895–1975.* (Stockholm: Almqvist & Wiksell International, 1986), 281.

27. This argument is made with great intellectual force by Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos: Man's New Dialogue with Nature* (Boulder: Shambala/ New Science Library, 1984). Prigogine won the Nobel Prize in 1977 for his work on the thermodynamics of nonequilibrium systems.

28. An excellent account of the change in thinking is James Gleick, *Chaos: The Making of a New Science* (New York: Viking, 1987). I have drawn on his explanation extensively here. What Gleick does not explore are the striking intellectual parallels between chaotic theory in science and post-modern discourse in literature and philosophy. Post-Modernism is a sensibility that has abandoned the historic search for unity and order in nature, taking an ironic view of existence and debunking all established faiths. According to Todd Gitlin, "Post-Modernism reflects the fact that a new moral structure has not yet been built and our culture has not yet found a language for articulating the new understandings we are trying, haltingly, to live with. It objects to all principles, all commitments, all crusades—in the name of an unconscientious evasion." On the other hand, and put more positively, the new sensibility leads to a new emphasis on democratic coexistence: "a new 'moral ecology'—that in the preservation of the other is a condition for the preservation of the self." Gitlin, "Post-Modernism: The Stenography of Surfaces," *New Perspectives Quarterly*, 6 (Spring 1989), 57, 59. See also N. Catherine Hayles, *Chaos Bound: Orderly Disorder in Contemporary Literature and Science* (Ithaca: Cornell University Press, 1990), esp. chap. 7.

29. The paper was published in *Science*, 186 (1974), 645–47. See also Robert M. May, "Simple Mathematical Models with Very Complicated Dynamics," *Nature*, 261 (1976), 459–67. Gleick discusses May's work on pages 69–80 of *Chaos*.

30. W. M. Schaeffer, "Chaos in Ecology and Epidemiology," in *Chaos in Biological Systems*, ed., H. Degan, A. V. Holden, and L. F. Olsen (New York: Plenum Press, 1987), 233. See also Schaeffer, "Order and Chaos in Ecological Systems," *Ecology*, 66 (Feb. 1985), 93–106.

31. John Muir, *My First Summer in the Sierra* (1911; Boston: Houghton Mifflin, 1944), 157.

32. Prigogine and Stengers, *Order Out of Chaos*, 312–13.

33. Much of the alarm that Sears and Odum, among others, expressed has shifted to a global perspective, and the older equilibrium thinking has been taken up by scientists concerned about the geo- and biochemical condition of the planet as a whole and about human threats, particularly from the burning of fossil fuels, to its stability. One of the most influential texts in this new development is James Lovelock's *Gaia: A New Look at Life on Earth* (Oxford: Oxford University Press, 1979). See also Edward Goldsmith, "Gaia: Some Implications for Theoretical Ecology," *The Ecologist*, 18, nos. 2/3 (1988): 64–74.

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