concentration rose by a factor of 100, to 4 nanomolar, the researchers monitored plankton growth and dissolved carbon dioxide.

"Most of us were wildly optimistic," says Johnson—optimism that seemed justified when the amount of phytoplankton in the patch and its rate of production more than doubled in the first 3 days. That observation left little doubt that iron is the limiting nutrient for plankton growth near the Galápagos, say Johnson and Barber, and probably in other low-productivity areas where iron is low and other nutrients high.

But after the initial surge, the phytoplankton stopped growing any faster, instead of reaching up to 10 times the starting population, as they can in a bottle. Even though other nutrients were still abundant, the enhanced but hardly extraordinary abundance held steady for the rest of the 9-day experiment. The abrupt stalling of the plankton's increase seems to have been due to the rapid loss of usable iron from the surface waters. By 4 days after the enrichment, dissolved iron concentrations had dropped from 4 nanomolar to below the detection level of shipboard analyses, 0.2 nanomolar. The iron was apparently precipitating out of solution as ultra-fine particles, coagulating, and sinking. Plant debris and animal wastes sinking out of the surface layers may also have been carrying off iron.

In fact, on the second leg of the cruise, IronEx researchers saw the same process at work in nature, says Barber. They found that westward currents washing around the Galápagos Islands pick up dissolved iron, apparently from the shallow-water sediments there. But the resulting plankton bloom fades downstream of the islands, where the iron-rich plume moves over deeper and deeper water. There, iron lost from surface waters doesn't return as it can in shallow waters, and its concentration drops. That's a process that an experiment in a closed bottle could never reproduce, says Johnson. "If you do this in a bottle, there's nowhere for the iron to go" and you get a dramatic greening of your "ocean."

This real-world demonstration of iron fertilization and its limits proves the value of large-scale experiments like IronEx, say oceanographers. "The big excitement is that you can do this sort of experiment in the ocean with the entire food web," says biological oceanographer Sallie W. Chisholm of the Massachusetts Institute of Technology. But she and most other oceanographers are, if anything, relieved that the experiment doesn't bode well for tampering with ocean ecology on an even larger scale, to cool the climate. Says Chisholm, "I've always believed that proposition is incredibly shortsighted." For now, Earth's Geritol stays on the shelf.

–Richard A. Kerr

ENVIRONMENTAL SCIENCE

Theoretical Ecology: Winning Its Spurs in the Real World

For most of its century-long history, ecology has been by and large a descriptive science. Researchers conducted field studies, aimed at describing, say, the interactions between predators and their prey or assessing the impact of the many pesticides that have come into use on nontarget species such as birds or helpful insects like bees. Studies like these have amassed a wealth of data. But they have usually been limited in scope and duration. And while some ecologists have long taken a broader, more theoretical approach, looking for principles that govern the dynamics and interactions of populations in whole ecosystems, these theorists were in a distinct minority.

This relative scarcity of a theoretical approach was at least partly due to the difficulties in collecting and analyzing the large data sets needed to describe complex ecological systems—especially in precomputer days. But it made it difficult, if not impossible, to apply the results of the smaller studies to the many environmental problems that have cropped up in recent decades—problems such as how to control insect and other pests without also killing desirable species, reverse declines in ocean productivity, or save endangered species such as the Northern Spotted Owl. "We may know a whole lot about a square meter of earth or ocean, but we need to have adequate theories for expanding this [small-scale] information to help deal with real-world problems," says theoretical ecologist Edward Rykiel Jr. of Texas A&M University in College Station.

In the past 5 years or so, however, theoretical ecology has begun to mature and provide insights into some of these practical problems. "People in theoretical ecology are feeling particularly bullish," says ecologist Jonathan Roughgarden of Stanford University, who uses both theoretical and experimental approaches. "We're beginning to figure out how ecosystems work."

And that enthusiasm is not limited to the 100 or so researchers specializing in theoretical ecology. Their much more numerous experimental colleagues are taking notice, too. One indication of their interest came last summer at the annual meeting of the Ecological Society of America (ESA). Until recently, theoretical ecologists often kept largely to themselves, publishing in specialized journals. But at its annual meeting, the ESA created a subsection on theoretical ecology, putting it on a par with established subspecialties such as aquatic ecology, paleoecology, and soil ecology. The growing interest was also apparent at the meeting's theoretical sessions, which were packed, sometimes to overflowing.

PAT AND TOM LEESON/PHOTO RESEARCHERS

At risk. Models showed Northern Spotted Owls need bigger ranges than originally planned.

Clues to AIDS spread. One example of how this budding theoretical approach to ecology has begun to affect practical problems comes from Roy Anderson and Robert May of Oxford University in England, who are among the small number of early theoretical ecology pioneers. About 20 years ago, they began modeling studies aimed at getting a better understanding of how, when, and where infectious parasites move in their nonhuman hosts. Then, shortly after the AIDS epidemic struck in the early 1980s, Anderson and May began looking to see what their models might reveal about the spread of the AIDS virus. The impetus for the work was their recognition that there are many parallels between the movement of successful parasites in nature and the epidemic spread of human pathogens. "We took some of our animal models off the shelf and made some adjustments," says May, adjustments for, among other things, the more complex social organization of human populations.

In those early days of the epidemic, it had become clear that gay males were particularly vulnerable to AIDS. But Anderson and May were among the first to go beyond descriptive work to predict the effect of behavioral patterns on the spread of the disease. Their models showed that the network of interactions by which the virus was transmitted could be as powerful a force in the spread of disease as the virulence of the pathogen itself. In particular, May says, they found that relatively small numbers of promiscuous individuals could be disproportionately responsible for the rapid spread of AIDS.

King Holmes, director of the Center for AIDS and Sexually Transmitted Diseases at the University of Washington, Seattle, says that while this all seems obvious now, at the time it wasn't, and Anderson and May's theoretical work strongly influenced his opinions on the development of more cost-effective approaches to preventing AIDS. "We realized that the spread of the disease is highly dependent on the rate of (sexual) partner change," Holmes says. And that means clinicians need to be particularly attentive to following up on a patient's sexual contacts as a way of preventing further spread.

Saving the Spotted Owl. Although ecological models may have an impact on human disease control, a more familiar role is in helping to solve environmental problems. The effort to save the Northern Spotted Owl, threatened with extinction because of extensive logging of its habitat in the old growth forests of Oregon, Washington, and northern California, is a case in point. An early plan to save the owl, developed in the mid-1980s by the U.S. Forest Service and the Bureau of Land Management (BLM), suggested preserving only small patches of old growth forest—just big enough to support one to three pairs of owls—that were sparsely distributed in the landscape.

The preserve sizes were largely based on knowledge of the size of the owls' home ranges and were set just big enough to accommodate a few pairs of birds so that inbreeding could be avoided. But says population biologist Russell Lande of the University of Oregon in Eugene, "The plan was misguided in many ways." In particular, he notes, it "completely neglected" the possibility of demographic accidents. All the males or all the females in a small, isolated preserve might die, for example, leaving the surviving birds unable to find mates. Nor did these first proposals consider how hard it would be for young birds in small preserves to find their own territories if they had to fly to distant patches. "For a young bird," Lande notes, "it would be like finding a needle in a haystack."

Disturbed by possibilities like these, Lande and his colleagues, including Dan Doak of the University of California, Santa Cruz, and Barry Noon of Humboldt State University in Arcata, California, developed new mathematical models for predicting the survival of bird populations that took account of more variables than just the size of the owl's home ranges. Among these were survival and reproductive rates and the spatial structures of the populations, all data obtained from field studies.

The more advanced models showed that small, isolated populations, of the sort that would be created by the proposed patchy preserves, would be especially vulnerable to extinctions because of demographic accidents, Lande says. After being forced by the federal courts to consider these findings, the Forest Service and the BLM redrew the plan to set aside larger patches of forest that can support more owls.

Still, recent work by Stuart Pimm of the University of Tennessee in Knoxville, Jared Diamond of the University of California, Los Angeles, and their colleagues suggests that even the improved models overestimate how long larger populations will last. Using data from bird censuses taken in Britain, Ireland, and the German North Sea Island of Helgoland, Pimm and Diamond compared the survival of actual bird populations with the models' predictions. They found that the models predicted the fates of the smallest populations accurately, but that larger isolated populations often died out faster than expected. The problem was that the models did not take into account other calamities such as fire, storms, or drought, which can annihilate even large populations. "It's important for conservation biologists to know that extremes of population (size) can be frequent, and that local extinctions increase with time," says Pimm.

These difficulties in devising models for predicting the survival of the Northern Spotted Owl point up one of the pitfalls of ecological model building: They're only as good as the data on which they are based. That's true even for small-scale studies, but especially so for large ecosystems, which require vast amounts of data collected over wide areas to describe fully.

BRIAN GRANTHAM/STANFORD UNIVERSITY

Coming up. Researchers collect plankton to improve their understanding of intertidal ecosystems.

But even there technical and scientific advances have brought big improvements. "We have always been able to survey things on a small scale," say ecologist Ted Case of the University of California, San Diego. "But now we have other tools, such as satellite imaging and other forms of remote sensing, for capturing large systems. Before we could not see the forest for the trees. Now we can see whole forest systems." Added to that, he says, is the advent of high-speed computers that can process the massive data sets the new sensing technologies are producing.

Another positive influence on theoretical ecology has been the trend to forge collaborations with outsiders, including researchers in other areas of biology, as well as in the physical sciences, mathematics, engineering, and resource economics. "There are few renaissance individuals who, on their own, can handle the theoretical and experimental aspects [of ecology]," says Simon Levin of Princeton University. "The way of the future is to build collaborations, with each person bringing something to the effort."

Among the studies now being carried out by such "renaissance collaborations" are those aimed at understanding marine production. Take the intertidal zone, one of the favorite research targets of Stanford's Roughgarden and also the source of many popular food species, including crabs, clams, and some shrimp. "Early models of the intertidal zone looked upon the area between high and low tides as a 'wet forest,' " he says, meaning that intertidal plants and animals were thought not to move very far. But Roughgarden's own studies suggest that the larvae of many marine organisms, including snails, mussels, and barnacles, often move great distances through the oceans before settling in the intertidal zone. That means that the zone and many other marine communities are constantly being fueled by outside systems.

As as result, Roughgarden says, researchers who want to model the population variations of intertidal species, an endeavor that may help in understanding why marine production fluctuates, need information about what's happening in the oceans as well as in coastal habitats. And that requires the participation of geologists, oceanographers, and meteorologists as well as ecologists. Indeed, in a paper in press in the *Philosophical Transactions of the Royal Society, London*, he writes that "ecological science has become increasingly an earth science and less a biological science."

Seeking the broad picture. In addition to performing these relatively specific studies aimed at modeling aspects of specific ecosystems, researchers are also trying to devise theories that might unify observations of a wide range of ecological studies—in effect, producing an equivalent of the physicists' "Standard Model," which seeks to describe all of high-energy physics in terms of a finite set of particles and forces. For example, Princeton's Levin is trying to understand how nature is structured by seeking patterns, especially mathematical ones, in large data sets.

Over the past several years, he has studied ecological systems on various scales of space, time, and organization. These have ranged from seasonal studies of how small mammals alter patches of grassland to longterm, aerial probes of large forest ecosystems in the Northeastern United States, which were done with his Princeton colleague Stephen Pacala.

From studies like these, Levin and his colleagues found that there is a remarkable regularity in the data on many ecosystem properties, such as species diversity and dispersal rates, that seems independent of the scale of the study in which the data were obtained. The researchers could show this by plotting the variations in the different properties against the sizes of the ecosystems in which they were determined, both on logarithmic scales. The resulting lines were linear with a characteristic slope for each variation measured over broad ranges of scale. The work suggests, Levin says, that there may be "laws that allow one to make comparisons among studies carried out on different scales." If so, ecologists could have more confidence about offering solutions for large-scale environmental problems based on studies carried out on more modest scales.

As might be expected in a science that is just now groping for mature theories, not all ecologists agree that such broad generalizations will ever be possible. Roughgarden, for one, maintains that biological systems may be far more complex than physical systems, and that it may be impossible, and not particularly useful, to wrap them up in neat packages of theory. Even Levin concedes the task of finding mathematical tools needed to information from one scale to another will be challenging. Still, there does seem to be agreement in the field that while theoretical ecology is a young science, it is now showing enough signs of maturity—including the ability to affect practical matters and to make predictions about the future—that it must be taken seriously.

–Anne Simon Moffat

Additional Reading

S. A. Levin, Ed., "Mathematics and Biology: The Interface—Challenges and Opportunities," pub. by Lawrence Berkeley Laboratory, University of California, 1992.

S. Pimm *et al.*, "Times to Extinction for Small Populations of Large Birds," *Proc. Nat'l. Acad. Sci.* **90**, 449 (1993).

ATOMIC PHYSICS

Atom Beams Split by Gentle Persuasion

An atom, says quantum mechanics, is both particle and wave, and researchers in the growing field of atom optics have been taking quantum mechanics at its word. They've shown they can manipulate beams of atoms just like light waves, developing lenses to focus the atom beams, mirrors to reflect them, and even gratings to create atomic diffraction patterns. But the tool with the most promising applications—an atom interferometer—has proved maddeningly hard to perfect. Now, however, two groups of physicists working independently have taken a big step toward practical atom interferometry.

An atom interferometer works in the same way as its cousin, the optical interferometer: It splits a single beam, sends the resulting pair of beams along different paths, and then recombines them, creating an interference pattern. The interference pattern is extremely sensitive to conditions encountered by the two beams on their separate paths, such as slight variations in distance or differing magnetic fields.

Atom interferometers are potentially far more sensitive than optical interferometers. But one major hurdle has stood in the way of putting atom interferometers to work: It has been impossible to get the beams very far apart. Not only does this make it difficult to expose the two beams to different conditions, but the sensitivity of one application —an atomic gyroscope—depends directly on the area enclosed by the two beams. That's the challenge taken on by the two groups, one at the National Institute of Standards and Technology and the University of Colorado and the other at Harvard University.

William Phillips of NIST, a member of one of the two teams, explains the problem: Attempts to push two atom beams apart usually damage the coherence between them, blurring the interference pattern. Moving the atoms with lasers, for instance, tends to create random differences between the beams, since the laser push is due to the atoms absorbing photons and later spontaneously emitting them—a random process. "You must avoid any randomness anywhere," Phillips says. (Researchers using a slightly different technique have managed to split beams coherently and at large angles, but the technique isn't suitable for interferometry.)

The key to deflecting beams of atoms without upsetting their composure, the two groups report in the 14 February *Physical Review Letters*, was to work with "dark state" atoms—atoms in quantum states that will not absorb and reemit laser light that is itself in certain states. For example, if an atom with three available spin states (1, 0 and -1) is in the spin 1 state, it cannot absorb laser light that is circularly polarized so that all its photons have spin 1—absorbing a photon would give the atom a spin of 2, which is not possible. The result, in these experiments, was that the atoms "stole" momentum from photons without ever absorbing them. "It's really amazing that light can be used to transfer momentum like that," says atom optics pioneer David Pritchard of MIT.

Mara Prentiss of the Harvard team offers the following analogy to explain how the process worked. Imagine a system of three pendulums in a row, coupled with springs. The three pendulums represent three possible quantum states of the atoms that Prentiss' team worked with. The pendulum on the left corresponds to the spin 1 state of the atoms, the one on the right to a spin -1 state, and the one in the middle to the excited state through which the atoms would normally pass as they changed their spin state. The atoms in the beam remain dark as long as the excited state remains empty—or, in the analogy, the middle pendulum never moves. The key to the experiment, Prentiss says, is to move atoms from the spin 1 state to the spin -1 state without exciting the middle state.

The experiment begins with a beam of helium atoms, some in a spin 1 state and the rest in a different state that will be unaffected throughout the effort. In the analogy, the left pendulum is swinging freely, attached to an infinitely weak spring, while the right pendulum, attached to an infinitely strong spring, is not moving at all. Now, Prentiss says, gradually strengthen the left spring and simultaneously weaken the right one, so that the left pendulum slows down somewhat and the right one starts to move. Continue the process, and eventually all the motion will be on the right, with the left pendulum still—and the middle one will have never moved.

In practice, the force exerted by the springs is provided by two circularly polarized lasers that are pointed across the beam of helium atoms. After passing through the slowing changing field created by these two lasers, the spin 1 atoms have all changed to spin -1, without ever passing through the excited state. They remained dark.

But why should this change of spin state cause the atoms to move? Prentiss explains this by "a bookkeeping argument." Conservation of spin implies that for every atom that changed from spin 1 to spin -1, a photon in the laser light must have changed from spin -1 to spin 1. And the photon could only switch its spin if it also reversed its momentum, which implies—by conservation of momentum—that the atom must have changed its momentum in an equal but opposite way. That change of momentum is what deflects the atoms in the spin 1 state without any absorption or emission of photons.

In theory, Prentiss says, this procedure should allow large separations of coherent atomic beams. Although the initial demonstrations only gave the atoms the barest nudge, the process can be repeated over and over again, separating the two beams as much as desired without hurting their coherence.

–Robert Pool