The Seed

The Case for a Second Green Revolution

Conditions of life are forcing a fundamental shift in the nature of agriculture. A generation ago, some advances—largely in plant breeding—produced a quantum leap in food production, especially in the developing world, averting worldwide famine. We feed ourselves largely on those earlier gains, which we call the Green Revolution. Now we are in need of another such leap, but we lack the technology to effect it. This is the dilemma that frames all the efforts and debates this book will follow.

A forecast of famine is nothing new. Since the time of Thomas Malthus, who gave his name to the whole enterprise of considering doom, supposedly ironclad calculations have demonstrated the onset of worldwide famine—and many times, they have ultimately proved incorrect. The most famous of these in modern times came from the respected biologist Paul Ehrlich, who in 1969 forecast a starving Japan and China invading Russia in a food war within a decade. Driving his conclusion was the seemingly inexorable collision course of two graph lines: it seemed certain that humanity would outbreed any possible gains in agricultural production. Ehrlich's scenario did not foresee a remarkable blip in one of those lines—the Green Revolution.

Ehrlich didn't know about Norman Borlaug's work, by then already twenty-five years old. Backed by the Rockefeller Foundation, Borlaug had been working in Mexico to breed high-yielding strains of wheat resistant to fungus and rust diseases. The experiment worked so well that wheat heads became top-heavy with fat kernels and toppled over, a problem called "lodging." More breeding, this time with a dwarf Japanese variety to prevent lodging. More breeding, to improve nitrogen use. More tweaking of fertilizers, and so on and so on with this wheat, with parallel work in rice and corn. ("Corn" is the Old English word for grain in general, now applied in the United States to what is more properly called maize. I use the terms "corn" and "maize" interchangeably.) Wheat, rice, and maize are the big three, the trio of grasses that were domesticated in separate parts of the world—rice in south China, wheat in the Middle East and Southwest Asia, maize in central Mexico—and now provide more than half the energy humans consume, in the dense, storable package of carbohydrates that is grain. The net result of the work Borlaug inspired was an average annual increase in harvests of 2.1 percent a year between 1950 and 1990, the compounding growth curve that led to a tripling of harvests during that period. The collision Ehrlich had predicted was avoided.

Asia, the predicted "basket case," became a bread basket that now mostly feeds itself, as does much of Latin America. Periodic pockets of famine remain, but by and large, the world is less hungry than it was a generation ago. When Ehrlich wrote *The Population Bomb*, 56 percent of the world's population lived in nations that provided less than 2,200 calories of food per day per person, a subsistence diet. In its 1992–94 report, the UN's Food and Agricultural Organization estimated that number had dropped to 10 percent. Indeed, a revolution. Hungry people still exist in the world, but proportionately fewer than a generation ago. So why not ride the happy results of this into the future and call the problem solved?

A fitting person to answer this might be Timothy Reeves, director general of CIMMYT, which is the acronym in Spanish for the

International Center for the Improvement of Wheat and Maize. CIMMYT evolved like modern wheat from Borlaug's work and, together with the IRRI, the International Rice Research Institute based in the Philippines, institutionalized the Green Revolution. Borlaug himself still maintains an apartment and offices at CIMMYT's headquarters just outside Mexico City.

Reeves, an Australian, articulate, confident, and direct, sits in his campus-like office building amid the experimental fields of wheat and looks across the brown haze toward Mexico City a half hour away. He's just back in Mexico after visiting state-of-the-art farmers in Nebraska and Australia.

"The thing that really alarms me is I feel most people have underestimated the task," he says. The task he refers to has a simple number attached to it: population growth will double demand for food as soon as the year 2020, by some estimates.

"There's an additional one of those Mexico Cities being added every twelve weeks," he says. "If you tell farmers in Australia or Nebraska that they have to double production in twenty years, they're stopped in their tracks, because . . . all they know is it's going to take new technology, but they can't think about what it would be . . . That gives you some idea of what has to be done in developing countries, if the cutting edge has no idea of what needs to be done."

From the beginning, the Green Revolution has had its critics, especially those who have suggested that its heavy reliance on high inputs of water, capital, and chemical fertilizers and pesticides are simply not sustainable. Reeves himself voices the critics' chief concern: "In feeding ourselves, are we starving our descendants?"

The sense of discomfort with the Green Revolution is no longer limited to its critics. There is consensus that the techniques that have brought us this far will not be able to sustain us in the future. Production is leveling off. Since 1989–90, world grain harvests have risen on average only .5 percent a year, a quarter of the rate of the Green Revolution boom years. Changed political circumstances, particularly the collapse of the Soviet Union and the resulting economic chaos in one of the world's most important grain-producing regions, offer partial explanations, but there are signs that, politics aside, Green Revolution techniques are approaching the limits of what they can produce.

If that's true, not only will supply be constricted but the demand side of the equation will also be thrown into flux. From the beginning, agriculture has been the primary engine of human population growth; the dense package of storable carbohydrates that grains provide allows mobility, cities, hierarchy, technology, medicine, longevity. We count on more agriculture to provide food for ever-growing numbers of people, the solution to the population problem. We forget that the relationship is circular, dynamic, and not at all simple.

Overall, a veneer of good news shines on the population front, what demographers sometimes call a "reproductive revolution," a mirror image of the Green Revolution that has given the planet some respite from the population bomb. What they mean is that, for a variety of reasons like birth control and increased prosperity, fertility worldwide has dropped to an overall annual growth rate of 1.5 percent now, compared to 2 percent in the 1960s. Indeed, in much of the developed world, especially Europe, population growth has stabilized.

This overarching trend, however, masks some problems embedded in the numbers. First, as with much that happens in the world, the trend is geographically lopsided. Large parts of the developing world, precisely the areas least able to grow their own food, still have high birth rates. Even with Green Revolution gains, regions of Africa have more than offset increased crop yields with increased population. Food production per person actually decreased in thirty-one of forty-six African countries in the decade beginning in 1985.

Probably these statistics mask an even greater food crisis, in that an undeniable effect of the Green Revolution has been to displace rural people through mechanization and larger-scale, capital-intensive farms. This occurred in both the developed and less developed world, but in the latter the people displaced were often subsistence farmers. Their produce often doesn't show up in yield statistics, but it used to feed people. Displaced to the cities, this class of people no longer feed themselves.

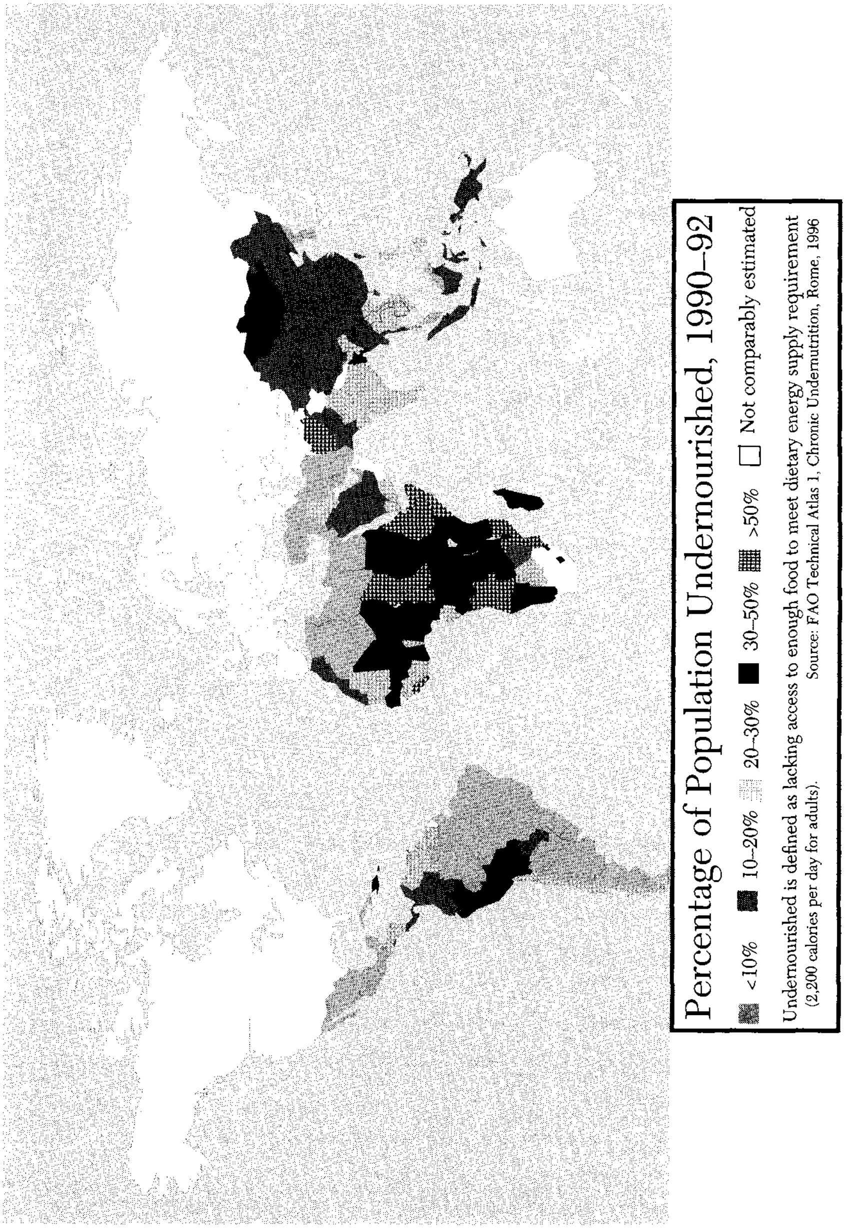
Meanwhile, there is a well-established correlation between an increase in income and declining birth rates, to the point that development accounts for much of the reproductive revolution. But there is also a correlation between increased income and consumption of meat, which in turn greatly ratchets up the demand on grain. (It takes about seven grams of grain to make a gram of beef.) Forecasters expect demand for grain for human food to increase by 47 percent in the developing world by the year 2020. At the same time, demand for grain for livestock is forecast to jump 101 percent during the same period.

Finally, the current low birth rate is only one factor determining population growth. Another factor is the bulge of people of reproductive age who were themselves the result of the earlier boom. A lower birth rate applied to a higher base still yields a lot of new mouths. UN projections say there will be 8 billion humans by 2025. This is what drives the sense of urgency among agronomists and agricultural economists.

According to projections by the International Food Policy Research Institute, there will be 150 million malnourished children under the age of six among us in the year 2020. That is a decline from the present percentage, but one out of four children on the planet would still be malnourished, with the heaviest concentration in South Asia and Africa. These projections are based on an agriculture that continues along the curves carved by the Green Revolution, an assumption perhaps more responsible for the uneasiness among experts than the raw numbers of people.

Begin by considering the United States, which represents the cutting edge of agricultural productivity. Average grain yields in 1960 were

Figure 1. Chronic Undernutrition



45 percent higher than in 1950. During the decade 1960–70, the increase was 43 percent, then 20 percent during the next decade, and 10 percent during the next.

During the same period, the United States and the rest of the world increased harvests by boosting yield per acre, and also by bringing more land under production. At present there is no more uncultivated land to be converted to crops. In some areas, the supply of arable land is decreasing, especially in the United States, where urbanization continues to chew up farms. In the 1970s, the United States brought into cultivation about 50 million hectares (a hectare is 2.5 acres) of land considered "highly erodable" and was forced to retire it a decade later, after it was found to be losing more than thirty tons of topsoil per year per hectare to erosion. The land was seeded back to grass. Furthermore, much of the yield increase came about by increasing irrigation, yet supplies of fresh water are rapidly being exhausted. Much of the United States' prime grain lands overlay the Ogallala Aquifer that lies under parts of Nebraska, Oklahoma, Texas, New Mexico, Kansas, South Dakota, and Colorado. This fossil water aquifer has been pumped to depletion in some irrigated areas, and will be entirely depleted at current rates in a few decades.

Much of the gain in yields came through increased use of fertilizer, yet fertilizer application rates have reached their maximum in the developed world, the point of diminishing returns. Any more fertilizer simply couldn't be absorbed by the crops and therefore would not bring a corresponding increase in yields. Farmers know this and are already starting to cut back.

Gain also came through improved crop varieties, yet this strategy, too, has an upper limit. Increasing yield is really a matter of coaxing plants through selection to adopt a strategy that favors seed over all other plant parts: roots, leaves, and stems. Agronomists measure the improvement with something called the harvest index, the weight of grain a plant produces compared to the weight of everything else. At the beginning of this century, grain crops typically had harvest indices of .25, a quarter of a plant's total bulk. The Green Revolution's plant breeders brought the index to about .50. There is some more yield to be gained this way, researchers think, but they also believe the maximum index possible is about .60. Beyond that, in a manner of speaking, there is no blood in the turnip.

In July 1998 reports of famine in Sudan became widespread, as did reports of the collapse of grain prices in the United States, a fall dominoed off the collapse of the Asian economy and its markets for grain. The Clinton administration quickly announced a major purchase of grain for famine relief to Sudan. Arguably it was sheer coincidence that the United States was but one month later firing missiles at Sudan, but nonetheless a somewhat dramatic illustration that food aid is more related to propping up U.S. grain prices than to genuine aid, and that it more often than not precipitates unrest. Aside from those selling the grain, few engaged in international food issues believe massive food aid—some call it dumping—does very much more than torpedo prices and undermine farmers' income in the countries receiving the aid.

"The biggest disincentive [to promoting food production] we have seen has been the dumping of low-cost grain," says CIMMYT's Timothy Reeves. "It tears the guts out of farmers, and it takes all the political resolve out of the government that they might have for farming."

Nor is helping simply a matter of good intentions. Take an example from Mozambique in the mid-nineties, typical of a phenomenon repeated through the Green Revolution. Researchers attacked hunger in Mozambique not by dumping grain but with fertilizer and improved maize varieties that led to a fivefold increase over traditional yields. *Scientific American* reported: "The poor conditions of local roads prevented farmers from transporting their produce. The northern area (of Mozambique) ended up awash in maize, with stockpiles rotting, and prices fell to a ruinous $40 per ton."

Failure can be even more finely tuned.

John Axtell is a genial man, a professor of agronomy at Indiana's Purdue University. From this base deep in the U.S. corn belt, he has spent a career tinkering with the mechanics of the Green Revolution, especially with sorghum in North and East Africa. Sorghum, now an important cereal crop worldwide, originated in the center of agriculture in Africa along a long, dry arc that extends from Niger and Sudan in the northeast through Ethiopia and south along the east edge of the continent. From this region Axtell has gathered a series of anecdotes to school some humility into students learning about what is known about food security—the effort to ensure an adequate long-term global food supply.

The Western agronomists who went to help these farmers found them using antiquated threshing techniques that involved spreading the grain on the ground on a pad and walking livestock over it, a problem fixed simply by replacing cow hooves with modern combines. Except that these people, who used traditional methods, did not suffer from iron deficiencies, while those eating a similar diet in India did. Their "old-fashioned" threshing methods were adding enough iron from the soil to compensate for the deficiency in the sorghum.

Through much of this region, farmers grow a dark sorghum, largely, researchers once believed, because they don't know about the more nutritious varieties of lighter sorghum. Sorghum's shade of brown deepens according to the amount of tannin it contains, and tannin, in addition to being bitter, blocks the human digestive system from processing the protein naturally available in the sorghum. Lab animals fed a diet of dark sorghum will waste away. The researchers urged farmers to adopt the light varieties.

There is, however, a common bird in the sorghum belt of Africa, the quelea, that likes sorghum and hates tannin, so the light varieties of sorghum hauled in by well-meaning developed-world agronomists went to the birds. Which is why the farmers of the region grow brown, high-tannin sorghum. The practice co-evolved with birds as a defense mechanism. Axtell says the final piece of the sorghum puzzle fell into place when a student at Purdue whose father was a chief in Uganda asked villagers about the processing of sorghum. He found they always soaked brown sorghum in wood ash before cooking it. The ashes removed the tannin. This bit of information led to a process that now helps U.S. growers raise high-tannin sorghums.

The base of Axtell's respect for the traditional wisdom of farmers was built in 1973, when a survey of 20,000 varieties of sorghum from throughout the world identified two with a very high protein content. The two varieties had been collected by the Rockefeller Foundation from the same area of Ethiopia, so Axtell went there and asked around. Everyone knew exactly what he was talking about. "Kids there know their cereal varieties the way our kids know cars and baseball," he says. One of the varieties was called *wetet begunche*, or "milk in my mouth." The other's name translated as "honey squirts out of it," because it was eaten as a sort of snack or treat, but an important one. The latter variety was generally the first harvested at the end of the dry season, the hungry season, and was roasted for a shot of protein just when hungry people needed it most. The names indicate that people somehow knew the protein was there.

The lesson Axtell takes from these stories is that securing a food supply rests on more than just boosting yield. Both varieties cited here produced less than others, yet local farmers preserved these sorghum strains, even when higher-yielding varieties were available. Survival in a difficult place demanded it.

The Green Revolution at its most fundamental level treated all the world the same, but the lessons being learned in agriculture now are local. A practice, a variety, a people, and a crop endure in a place because selection has finely tuned them to survival. They have evolved along with local conditions, and the path to a sustainable future requires some respect for the results of that process. Food security debates often began, as this one did, by pointing to Paul Ehrlich's failed prediction, but too often we forget that Ehrlich, along with Peter Raven, hatched the concept of co-evolution, an idea that will have much to say about where we go from here.

It is no stretch to say that Don Duvick owes his comfortable suburban home on the outskirts of Des Moines, Iowa, to the Green Revolution. He is a retired senior vice president for research at Pioneer Hi-Bred International, Inc., a lifelong plant breeder with a giant seed company pivotal in the development of industrial agriculture. He is also an affiliate professor of plant breeding at Iowa State University. But we can also understand some deeper layers of his loyalty to agribusiness by noting that the acre or so in front of his house—the spot usually devoted to clipped bluegrass lawns in these reaches of middle America—is given over to a restored tallgrass prairie, the ecosystem that row-crop agriculture eradicated here in Iowa.

Duvick speaks more like a professor than a retired executive. His conversation is thoughtful, measured with lots of alternatives modulating the even flow of his ideas. Like many in agribusiness in his generation, Duvick began life on a small Midwestern farm, an experience that no doubt laid some of the foundation for a journal article he published in 1995:

> Small farms and small towns are not necessarily a superior source of societal and environmental virtues. Small farmers supported by small towns despoiled their own countryside in the 18th and 19th centuries. The farms were then abandoned, and the despoilers went west to states such as Wisconsin where the cycle was repeated, inspiring Aldo Leopold to his monumental work on behalf of the environment. Small farmers supported by small towns in the Great Plains despoiled the grasslands of Oklahoma and Kansas in the late 19th and early 20th century, giving rise to the famous Dust Bowl in the drought years of the early 1930s. In our own time, I

> read every day in my local newspaper of the crimes that abound in small towns and on small farms in Iowa. They are as ferocious and as perverted as in any metropolis.
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> This recounting does not prove that small farms and small towns are worse than the rest of the nation in civic virtue or reverence for the environment. Nor does it say that large farms or large business firms are likely to be superior in these regards. It merely says that no group has a monopoly on virtue or vice, on wisdom or folly, on generosity or greed. To assume otherwise, to assign a class uniformity where one does not exist, will put needless roadblocks on the path to the solution of the real problems facing U.S. agriculture. We must look for solutions where we can find them.

Duvick's pragmatism is deep-seated and channeled by his particular small-farm experience in the 1930s. It is at the same time typical of a whole generation of people his age whose careers played out in agribusiness. That is, they grew up on tough, hand-to-mouth farms when a single event brought some prosperity, enough to send them off to a land-grant school someplace for an education that gave them a shot at a white-collar job. That single event, he says, was the coming of hybrid seed. It transformed Duvick's own life and those of many like him.

The term for the magic of hybrids is "heterosis," hybrid vigor. Hybrids, which are crosses of plants that do not normally cross, yield far more than either parent, the grip on the bootstraps that has boosted most of our yield gains in corn during the past thirty years. Wheat does not readily lend itself to hybridization, but plant breeding, conventional crosses, has created a parallel process. Hybrid or otherwise, new varieties have fueled the revolution.

Duvick, who sits on the board of the International Rice Research Institute, says the early high-yielding rice varieties produced about ten tons per hectare, and subsequent varieties have raised even that bar. But those same early varieties grown today yield only about seven tons per hectare. Cotton breeders report a similar phenomenon. "People are really scratching their heads, saying, Do we have to run this fast in order to stand still?" says Duvick.

He believes that growing conditions are deteriorating, probably because of microbial reactions in the soil, that resistance to disease is declining, and insect damage is on the rise. So far, breeding has more than offset the resulting losses. But breeding has its limits.

For instance, an agronomist in Nebraska has researched corn contest records for fifty years and found that there has been no real increase in the prizewinning yields, which represent a sort of theoretical maximum. True, average yields have increased, but the overall increase has been the result of latecomers, farmers finally adopting what is essentially old technology. The yield has a ceiling.

During this breeder's career, the critical past thirty years, corn yields have tripled. So can the next generation of breeders match that performance to meet projected increases in demand?

"I don't think so," Duvick says.

The more we chase our basic human desire to understand how the world works, the more we reveal our ignorance. People in agriculture might agree with this but are just as likely to say we are most ignorant about social systems, not science. We think we have the technical ability to deal with the problems of producing food, but we fail because of lack of knowledge about such areas as markets and government. True enough; our ignorance in these areas is vast, yet it is equally formidable concerning the raw science—for instance, knowing the workings of a single square foot of soil.

Dr. Eugene Kroonin of the National Center for Biotechnology summarized the situation for *The New York Times*: "Five years ago, we were very confident and arrogant in our ignorance. Now we are starting to see the true complexity of life."

There is a glimpse of this complexity in Robert Goodman's lab group at the University of Wisconsin at Madison, where a grad student might buttonhole you and insist that microbes rule the world. She will explain something of the recent work of microbiologists that has redrawn the tree of life.

Humans launched their first forays into the microbial world in the seventeenth century, with Antonie van Leeuwenhoek's invention of the microscope. That instrument, coupled with the capability to culture, grow, and compare colonies of microbes in the lab, produced a flourishing field of knowledge on which much of modern science rests. Like most tools, though, culturing of microbes obscured as much as it illuminated. Microbiology took a look at the universe by sampling it onto petri dishes and assumed incorrectly that what grew was what the world held. New tools, like techniques for sampling and cataloging DNA, are showing us some signatures not seen before. Now we are beginning to understand that culturing revealed something less than 1 percent of microbial life, leaving a rich world hidden in the shadows.

This new view, spelled out by Carl Woese, of the University of Illinois, in the mid-seventies, showed something even more profound, that the old picture missed a major branch on life's tree—that, earlier, life was plants and animals, fungi and bacteria, but now life is eukarya, bacteria, and the new stuff: the frontier, a whole new category of life, the archaea. In this scheme, most of life we know—visible life, plants, animals, and fungi—fall on the branch called eukarya, meaning organisms built from cells with nuclei. Both archaea and bacteria are prokaryotes, without nuclei. The implication of this grouping is that the latter two, co-equal branches on the tree, harbor the same degree of complexity and diversity as the eukarya. The more we come to understand about all this, the more this impression is justified.

Within the archaea there are forms of life as unrelated to each other as humans are removed from mushrooms. Archaea were the side of life missed by culturing. These are, like bacteria, single-celled organisms, but live by managing their DNA differently. Put in simpler terms, they are just plain weird. The initial work found archaea in places like hot pools at Yellowstone National Park and around volcanic vents along ocean floors. These are the thermophiles, or heat-loving archaea, that probably hold the key to the origins of life. At first it was generally believed the archaea were odd forms evolved to occupy the extreme niches, but then people started looking in ordinary places. Goodman's lab found them in soils and more recently in surprising abundance on the roots of plants. It is not known what they are doing there, but Goodman suspects they are mediating the flow of minerals and nutrients, especially nitrogen, warding off pathogens, coupling with other microbes to create the unseen ecosystem that is the basis of agriculture. The archaea may have begun all of life, taking energy from volcanic vents, yet it may be equally true that the archaea continue to sponsor the exchange between elemental and sentient, which is to say, food.

Jeff Dillen is an engaging young man who was working toward a law degree at the University of Wisconsin when I met him. At the same time, he became an accomplished microbiologist just for the mental exercise, the way some students would take up weight lifting in their spare hours. Like all the rest in Goodman's lab, he is animated by a sense of the frontier; the researchers' slides of the bar code–like registers of patterns in DNA are a window to something heretofore unseen. Dillen did an interesting and straightforward thing: he sampled soil from an organic farm and compared it to soil from one using Green Revolution methods. The archaeal microbes were present in the organic soil but not in the samples from the industrial ag land. We don't know what the archaeal bacteria have to do with the health of crops, but this simple result indicates we should.

Goodman's analogy is to the spotted owl, the endangered species of the Northwest rain forest that signals not so much its own peril as the status of the ecosystem it represents and, by extension, the hu-