Technologies for a Sustainable Future: Therapeutic Intervention Versus Restructuring the System[1]

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> *The real problem of food production occurs within a complex, mutually influential relationship of soil, plants, animals, and people. A real solution to that problem will therefore be ecologically, agriculturally, and culturally healthful . . . a bad solution solves for a single purpose or goal, such as increased production. And it is typical of such solutions that they achieve stupendous increases in production at exorbitant biological and social costs.*
>
> —Wendell Berry

> *I had a strange feeling that a paradigm deeply embedded in modern biology was being chipped away at, and bits and pieces of an earlier paradigm were being revived.*
>
> —Harold Morowitz

As we enter the twenty-first century, we face at least seven major challenges that are likely to transform agriculture on this planet. Population growth, persistent poverty, energy needs, environmental degradation, food security, climate change, and an unprecedented explosion of infectious diseases all will likely force us to rethink the assumptions about food and agriculture that we have taken for granted for at least 50 years.

The United Nations estimates that the world's population, now more than 6 billion, will increase to 9.3 billion by the year 2050. Furthermore, the additional 3.2 billion people will be born in the developing world, many in poor rural areas. Seventy-two percent of the world's poorest people now live in rural communities (Brown, 2001).

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Currently, 1 billion of the world's population live on less than $1 a day and an additional 1.6 billion live on less than $2 a day. The number of people living in poverty increased by 100 million during the past decade and the United Nations predicts that another 100 million people will live in poverty by the year 2015 (Lee, 2002).

As population grows and poverty persists, the natural resources that have fueled the production increases of the past 50 years are in a state of decline. Industrialized agriculture, which enabled us to double and triple the yields of cereal grains, is largely fossil-fuel driven. Crop inputs, the manufacture of farm equipment, traction fuel, and the breeding of crop varieties that are responsive to chemical inputs and irrigation are all highly dependent on fossil-fuel energy. As fossil-fuel resources decrease, and, therefore, become more costly, this mode of production will become increasingly difficult to sustain.

At the same time that the natural resources that fueled industrial agriculture are declining, the natural sinks that absorbed the accompanying agricultural wastes are filling up. There are now fifty-three hypoxic zones on the planet, all of them related to watersheds that support industrial agriculture. Hypoxic zones are not isolated aberrations, but visible indicators of the larger environmental degradation that is inherent in industrial agriculture systems.

Masae Shiyomi and Hiroshi Koizumi have, in fact, argued that the combination of the decline of fossil fuels, and the increased environmental degradation caused, in part, by fossil-fuel-based agriculture, will necessarily *force* agriculture to change in the decades ahead, and they suggest that a shift toward an ecologically based agriculture may well pose the most viable alternative for the future (Shiyomi and Koizumi, 2001):

> *The present system of agriculture, which depends on consumption of tremendous quantities of fossil-fuel energy, is now being forced to change to a system in which interactions between organisms and the environment are properly used. There are two reasons for this transformation. The first is the depletion of readily available fossil-fuel resources. The second is that consumption of fossil fuels has induced deterioration of the environment. Is it possible to replace current technologies based on fossil energy with proper interactions operating between crops/livestock and other organisms to enhance agricultural production? If the answer is yes, then modern agriculture, which uses only the simplest biotic responses, can be transformed into an alternative system, in which the use of complex biotic interactions becomes the key technology.*

A fifth challenge facing agriculture is the increased interest in recognizing food as a basic human right. Not only is the world evolving into a global economy, but it is becoming a global civic society as well. Such a society carries with it increased awareness that a stable global community can be achieved only if all its inhabitants are food-secure. Securing food as a basic right for all of the planet's citizens, therefore, presents an additional challenge that global agriculture must face in the decades ahead.

The precise role that climate change will play in agriculture's future is not yet certain, but indicators suggest some formidable challenges. A recent report from the Soil and Water Conservation Society focused on just one climatic variable: precipitation. The study indicated that anticipated increases in precipitation due to climate change, together with the likelihood of more violent storms, "heighten the risk of soil erosion, runoff, and related environmental and ecological damages" (Soil and Water Conservation Society, 2003).

A recent Iowa State University study revealed similar concerns. Computer modeling suggested that the upper Mississippi River basin (UMRB) is likely to see significant increases in precipitation by 2050. The "model system produced an increase in future-scenario climate precipitation of 21% with a resulting 18% increase in snowfall, 51% increase in surface runoff, 43% increase in recharge, and 50% increase in total water yield in the UMRB" (Jha *et al.*, 2003). It is unlikely that Iowans will be able to continue growing massive quantities of annual crops such as corn and soybeans under these circumstances.

Finally, the unprecedented explosion of more than thirty-five new infectious diseases in the past 30 years presents agriculture with yet another challenge. The Institute of Medicine, a research arm of the federal government, recently convened a panel of scientists to discuss why this outbreak of infectious disease has taken place. They attributed the phenomenon to thirteen changes, a substantial proportion of which, according to Dr. Anthony Fauci, director of the National Institute of Allergy and Infectious Diseases, "relate to man's manipulation of ecology" (Borenstein, 2003). Agriculture, of course, has been a major contributor to such ecological manipulations.

THE ROLE OF TECHNOLOGY

What kind of agriculture can meet the requirements of an exploding human population in the face of entrenched poverty in a post-fossil-fuel era that must restore the ecological health of the natural resources on which agriculture depends, while the climate is changing, global society insists that food is a human right, and increased infectious diseases require that we attend to the ecological ramifications of human activities?

And a question for this conference is whether or not technology—especially transgenic technologies—can meaningfully address these challenges?

The complexities involved in meeting these challenges are, by now, readily apparent. Simply increasing food production, we know full well, will not solve the problem of hunger. If that were the case there would *be* no hunger today since we already produce enough food to provide the necessary calories for every person on the planet. And even if we were able to invent technologies that could put food in every new person's mouth, how do we address the problem of providing sufficient quantities of fresh water to support such a population, especially when agriculture currently uses 70% of the planet's freshwater resources? And how do we sufficiently shrink the ecological footprint of each global citizen to prevent further loss of the biodiversity that is so essential to the ecological health of global ecosystems? In his recent book, *Our Final Hour*, Martin Rees, Professor at Cambridge University and Fellow of the Royal Society, suggested that the planet simply could not sustain even our present population if everyone consumed as much as middle class Europeans and North Americans (Rees, 2003).

Furthermore, since populations are exploding primarily in poverty-ridden rural areas of the developing world where farmers live on fragile lands, inventing new technologies that they cannot afford and that do little to address local ecological issues will not serve to solve the problem. As Jeffrey McNeely and Sara Scherr pointed out (McNeely and Scherr, 2003), if…

> *…food is to be accessible to the rural poor, then much of it must be produced where they live, and in ways that increase both their consumption and income. Yet food-producing systems throughout the world are already stressed by eroding soils, declining freshwater reserves, declining fish populations, deforestation, desertification, natural disasters, and global climate change. These and various other factors are making it increasingly difficult to maintain, much less increase, food production in many areas of the world.*

Simply inventing a new technology—whether transgenic or non-transgenic—is not likely to address that multifaceted set of circumstances.

The problem, in other words, is quite complex, therefore, we cannot reasonably expect to solve it simply by introducing a few new technologies to increase the yields of a handful of crops. And we should stop misleading the public into believing that the problem can be solved with such simple technological innovations. Such misrepresentation is immoral even by the most rudimentary ethical standards of any civic society. We should end such deceptive rhetoric *now*!

Does this mean that technology, even transgenic technology, has no role to play in meeting agriculture's future challenges? Of course not.

The question we face is *not* whether we will use technology to help shape the new agriculture required to meet future challenges. Clearly we will. Nor is the pertinent question what *kind* of technology we will use. We likely will use all of the available technologies that hold any promise for developing an agriculture capable of meeting these challenges. The more important question is *how* we will use the technologies available to us.

To determine how best to use technology to meet these challenges, it might be useful to reassess *current* use of technology in agriculture.

Throughout most of the industrial era we have used technologies almost exclusively to perform one-dimensional, single-tactic functions. We developed and applied pesticides to control a target pest. We manufactured and applied fertilizers to replace nutrients. We produced and injected antibiotics to fight disease. It is a methodology that Joe Lewis, pest management specialist with the USDA's Agricultural Research Service, called "therapeutic intervention" (Lewis *et al.*, 1997). This approach uses technology to intervene in a system to alleviate a problem. It almost never uses technology to understand *why* the problem emerged or how inherent strengths within ecosystems could be enhanced to solve the problem. Based on field experience, Lewis argued that the therapeutic intervention approach has failed.

This is not to deny some short-term successes using single-tactic technologies. We dramatically reduced the labor required to produce essential crops. We increased the yields of those crops beyond anyone's expectations. And we made it possible for citizens of the United States to spend less of their disposable income on food than any other nation in the world—only 10% in 2001, according to USDA/ERS estimates.[2]

ECOLOGICAL FAILURE

This one-dimensional approach has, however, led to unforeseen consequences that have prevented us from solving some of agriculture's most persistent problems, and it has not prepared us to meet the challenges of the future. Manufacturing and applying nutrients to overcome deficiencies allowed us to ignore the larger issues of deteriorating soil quality and erosion. We are not likely to see many new yield gains in the future without addressing the complex issue of improving soil quality. Good quality soil, in turn, can provide a range of benefits to healthy, resilient production systems while making major contributions to water quality (National Research Council, 1993). Soil erosion not only seriously depletes our ecological capital but, together with excess nutrient application and highly specialized production systems, it fosters nutrient pollution of streams and rivers that eventually contributes to hypoxic zones in major bodies of water, like that in the Gulf of Mexico. Poor-quality soils also require increased irrigation, which further depletes aquifers and increases soil salinity.

Land degradation has reached epic proportions. By some estimates, 36% of the world's cropland is losing topsoil at a rate that is undermining its productivity (Brown, 2001). This does not bode well for meeting the twin challenges of feeding a growing population while reversing environmental degradation.

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[2] One should be cautious about translating the percent of disposable income spent on food into a "cheap food" claim, however. What Americans pay per calorie of food consumed is more than what 95% of the rest of humanity pays according to some estimates. See Charles Benbrook's unpublished manuscript, Principles Governing the Long-Run Risks, Benefits, and Costs of Agricultural Biotechnology (available from the author).

The use of broad-spectrum pesticides to control target pests has similarly failed to acknowledge ecological connections within the system in which the pesticide is applied. The results, once again, yield unintended side effects. As we now well know, pesticides not only kill the target pest, they also harm many beneficial organisms that previously kept other pests in check, creating new pest problems. Since a pesticide never kills all the target pests, those that survive become resistant to the pesticide and produce a new population of hardier pests. In the process, the *source* of the pest problem often is ignored, leaving the system ripe for pest resurgence. Meanwhile, the correlations among soil quality, nutrition, and plant protection remain largely unexplored, and too often the potential human and wildlife health effects of the pesticide are ignored.

Despite these signs of need for change, the culture of one-dimensional approaches to solving production problems continues. In introducing a new generation of technologies (transgenics, robotics and nano-technology), we continue to subscribe to the same paradigm that fueled earlier technologies. Most applications of transgenic technologies, for example, are still intended as single-tactic approaches to problems—designing corn plants to resist the corn borer; designing soybean plants to resist a broad-spectrum herbicide to control weeds; designing pharmaceutical crops to produce specific properties as therapeutic intervention in disease. Lewis *et al.* (1997) argued that since the new transgenic technologies follow a similar blueprint to yesterday's chemical technologies, they are likely to meet with similar constraints. In the process, he argued, they will actually *hamper* our progress toward the development of more ecologically sound strategies:

> *As spectacular and exciting as biotechnology is, its breakthroughs have tended to delay our shift to long-term, ecologically based pest management because the rapid array of new products provide a sense of security just as did synthetic pesticides at the time of their discovery in the 1940s . . . the crops engineered to express toxins of pathogens are simply targeted as replacements for synthetic pesticides and will become ineffective in the same way that pesticides have.*

Lewis's observation is now being corroborated, not only by the appearance of pest resistance to transgenic technologies in the field, but also by a growing awareness among scientists that genetic mechanisms are much more complex than biological determinists previously assumed. Richard Strohman (2002), molecular biologist at the University of California, described the matter succinctly:

> *Molecular biologists have rediscovered the profound complexity of the genotype-phenotype relationship, but are unable to explain it: Something is missing. The missing element was described 35 years ago by Michael Polanyi, who characterized live mechanisms and*

> *information in DNA as "boundary conditions with a sequence of boundaries above them."*

Harold Morowitz (2003), professor of biology and natural philosophy at George Mason University, also acknowledged this complexity and the paradigm shift it portends:

> *[There] is a startling change in the paradigm of genetics following from the dogma of molecular biology. It suggests bionic laws at the level of phenotype and a somewhat noisier background of genes that are required to reify these laws in a not overly precise way. It tends to turn the present paradigm rather on its head . . . All of this suggests the possibility of a substantive change in the paradigm of biology and a reconsideration of how we are spending our research funds.*

This growing awareness within the field of genetics will, as Evelyn Fox Keller (2001) has suggested, "necessitate the introduction of . . . other ways of thinking about biological organization, thereby loosening the grip that genes have had on the imagination of life scientists these many decades." She also states that this "success" will finally teach us the necessary "humility" that will lead us to appreciate, and perhaps honor, the complexity and interdependence of the living systems of which we are a part. In other words, we might begin to take ecology and evolutionary biology seriously in all of our human endeavors. And these new discoveries in the functions of biology and ecology may impose a significant paradigm shift on agricultural research.

It would seem prudent, therefore, on countless ecological fronts, to begin the shift from a one-dimensional strategy to a multi-dimensional systems strategy as the guiding principle of our agricultural research agenda. This shift would lead to the development of systems that focus on "harnessing inherent strengths within ecosystems," as Lewis *et al.* (1997) put it, rather than continuing to invent single-tactic solutions.

All of this suggests that the principal benefit from genetic research for meeting the challenges facing us in agriculture's future may not lie in the invention of specific transgenic technologies that modify plants and animals, but in the discoveries that help us better understand how systems function and, therefore, better utilize the strengths that are inherent in natural ecosystems.

UNDERSTANDING NETWORKS

Some of the insights garnered from network theory in the past decade or two also may be instructive. While we are, perhaps, still a long way from achieving scientific consensus with respect to the science of networks, one aspect of the theory is gaining widespread acceptance—namely that systems cannot be understood solely in terms of their component parts, and that it is often the "weak links" in a system that hold the key to understanding systems functions (Barabasi, 2002; Buchananan, 2002; Watts, 2003). Some of these findings may be instructive as we continue to struggle with the question of how to make the best use of new technologies in agriculture.

The practice of reducing a complex phenomenon into simple constituents is, of course, an important and time-honored convention in the scientific enterprise. And such reductionism certainly continues to be an important part of the work of science. The problem is that we often jump to the conclusion that a system can be fully understood in terms of its parts, when in fact it is important to understand *not only the parts but also the interactions between them*. It also may be important to acknowledge, as Mark Buchanan (2002) put it, "that the interactions between the parts of a complex network often lead to global patterns of organization that cannot be traced to the particular parts," and that there is, in fact, a "network architecture" that is the "property not of parts, but of the whole."

Why is this important to the question of how to use technologies in agriculture? It is important in at least two respects. First, if the existing network architectures are the property of the whole rather than of the parts, then we have to begin paying attention to how the network architecture is affected by our technological innovations and not just how component parts respond. In other words, if network architectures exist, we could succeed in increasing the productivity of a component part (a soybean plant, for example), while ignoring the fact that the ecosystem architecture is being affected in ways that are altering the ecosystem's productive capacity.

Isn't that exactly what happened when we increased the yields of wheat and rice by employing the single-tactic strategy of introducing varieties capable of higher yields through the use of fertilizers, pesticides and irrigation, but failed to see that the architecture of productivity was being compromised as a result of soil degradation, increased salinization, depleted aquifers, and compromised biodiversity? Are we paying any more attention to network architecture now as we introduce our new generation of technologies? I don't think so.

Second, if food webs consist of ecological communities that are tied together not only by connections that are obvious—like major predator/prey relationships—but also by many inconspicuous weaker links that go unnoticed, but often provide stability to entire ecosystems, then it might behoove us to use much more caution in introducing technologies that alter the functions of a specific organism.

Buchanan (2002) cited an instructive example. When Atlantic cod populations collapsed due to over-fishing, the Canadian government suggested that hunting expeditions be organized to kill North Atlantic harp seals, which were known to eat cod. The assumption was that by eliminating the seals, the principle cod predator, more cod would survive and, therefore, cod populations would recover. What the Canadian government failed to realize, however, was that the cod/seal relationship was affected by many other less prominent species in the system. Consequently, reducing the number of seals could affect cod populations in unpredictable ways by virtue of the many relationships among the cod, the seals, and the other species. Seals, for example, feed not only on cod but also on close to 150 other species, many of which also feed on cod. So, there is no way of knowing whether modifying the system through the single-tactic approach of reducing the number of seals would actually produce *more* cod or *fewer* cod. As Buchanan said, "It's anyone's guess." Since ecologists estimate that, in food chains involving as few as eight species, there are "more than ten million distinct chains of cause and effect that would link the seal to the cod" (Buchanan, 2002), it is impossible to predict the outcome of such a modification.

The seal/cod example serves as an analogy for production agriculture. Plant and animal agriculture consist of networks of organisms linked in numerous ways that we cannot readily comprehend. Can we anticipate all of the ways that millions of soil organisms may be affected by the introduction of a corn plant genetically redesigned to attack the corn rootworm, for example? What are the weak links in the complex system that service the stability of soil-microbial networks? It's probably anybody's guess. Given the millions of distinct chains of cause and effect that may link them together, there is simply no way to know.

Ecologist Kevin McCann suggested that the lessons for conservation implicit in such networks are obvious (quoted in Buchanan, 2002):

- if we wish to preserve an ecosystem and its component species then we are best to proceed as if each species is sacred; and
- species removals (that is, extinction) or species additions (that is, invasions) can, and eventually will, invoke major shifts in community structure and dynamics.

The lessons for agriculture may be just as obvious. Introducing technologies that significantly modify, disrupt, or otherwise alter network architecture could severely diminish production agriculture. And altering such networks is something that can be done quite inadvertently since we *do* not, and likely *cannot*, understand the many subtle connections that link organisms together into ecosystems.

Once again, it makes much more sense to use technology to increase our understanding of how natural systems function and to harness inherent strengths within those ecosystems than to invent technologies to modify components of the system to achieve single-tactic effects.

ECONOMIC CONSEQUENCES FOR FARMERS

It is now evident that one-dimensional technologies also have failed to provide *economic* sustainability for farmers. Richard Levins, Department of Applied Economics at the University of Minnesota, and Michael Duffy, Extension Economist at Iowa State University, each recently have demonstrated this with unusual clarity. Levins (2001) pointed out that "the one consistent part" of the farm economy story of the past 40 years is that "farmers, as a group, have been left out of the enormous growth in the value of what they sell." Levins pointed out that while *gross* farm income grew dramatically since 1960, *net* farm income remained essentially flat (Figure 1).

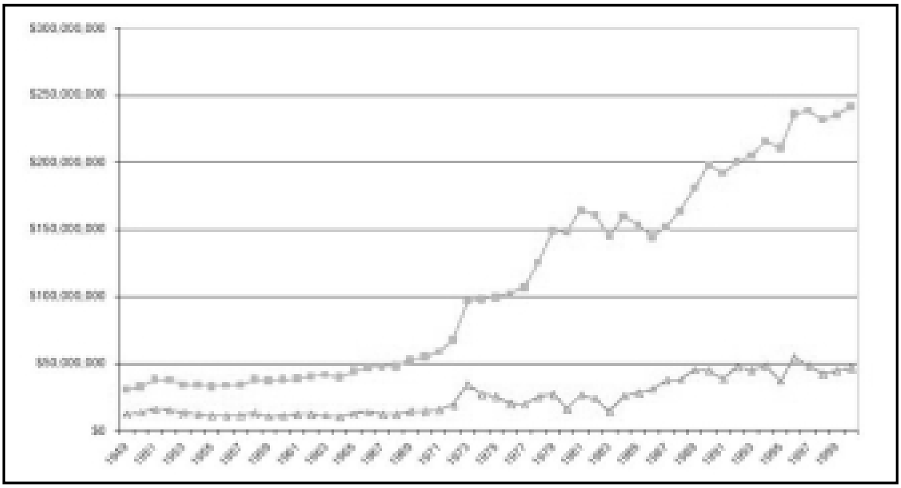

Figure 1. Gross (❑) and net (Δ) farm income in the United States.

Duffy demonstrated similar findings for Iowa farmers. His research demonstrated that, although they succeeded in dramatically increasing gross income between 1950 and 2001 (albeit with the help of government subsidies), their net income remained essentially flat. His study revealed that nearly all of the farmers' yearly gross income was used to pay the expenses required to produce the income (Figure 2).

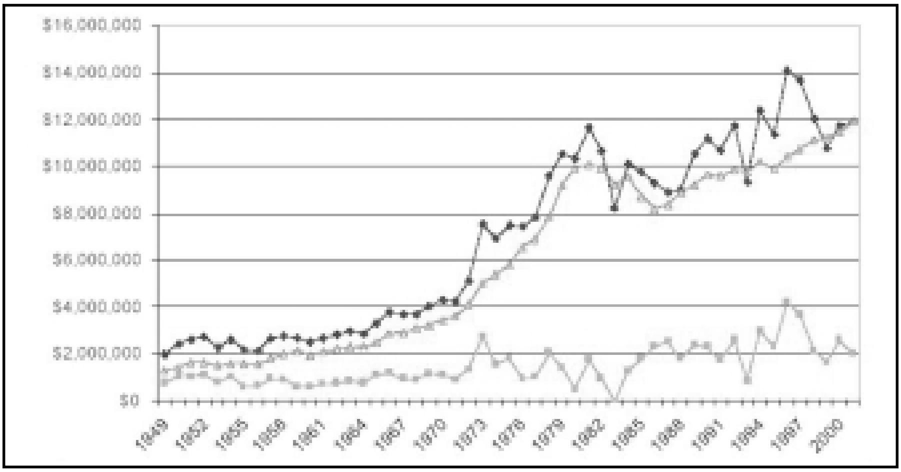

Figure 2. Total output (◊), total expenses (Δ), and net income (❑) for farms in Iowa.

The reason for this continuing dysfunction in the farm economy is not hard to pinpoint. Purchasing single-tactic solutions that fail to address the source of production problems and failure to take advantage of the inherent strengths in the system places farmers on an input-purchasing treadmill that requires them to buy more and more of the solution. That treadmill, furthermore, puts farmers under constant pressure to add more units (animals and/or acres) to their farms each year to generate more gross income just to pay the previous year's bills. It is the only way to stay in business.

As a consequence, of course, farmers are increasingly forced into predatory behavior, using any competitive advantage to acquire their neighbor's land, to borrow ecological or social capital from their communities, or to collect public subsidies. These are the only survival strategies available to them.

ANTICIPATING THE FUTURE

In his enlightening biological study of human history, Jared Diamond helped us understand why, throughout history, some societies flourished while others perished. Two factors consistently seem to play a prominent role in the outcome—local conditions and getting a head start. Prosperity, it would seem, goes to those who best interpret the changes taking place in their local environments and get a head start in taking advantage of them. The changes *per se* are largely beyond our control (Diamond, 1999). Diamond's analysis may provide some clues for determining how to use technology in agriculture to meet the challenges facing us. One thing seems certain: if we continue to insist on using technologies in accordance with old paradigms that seem unlikely to meet the challenges of the future, they will fail us.

In a comprehensive study of pioneering agricultural research in the developing world funded by the McKnight Foundation, Richard Manning concluded that our efforts to feed the world can never be successful if we fail to take into consideration the complexity and diversity of local cultures and local ecologies. Within the context of that complexity, Manning suggested that transgenic technologies may have a role to play, but they will be only one tool in a whole-systems solution. He conceded that the "genetic engineering business is going to get all the headlines," but added that attending to the needs of local culture and local ecology is "potentially far more earth-shaking. If there was a key mistake of the Green Revolution, it was in simplifying a system that is by its very nature complex" (Manning, 2000).

Understanding such complexity is surely part of the task of correctly assessing our local situation. Focusing at least part of our research agenda on the development of technologies and management practices that enable farmers to understand and take advantage of the inherent strengths in ecosystems, instead of continuing to have to buy technologies that address only one-dimensional components of the problem for only short durations, seems like a reasonable way to get a head start.

Broadening the research agenda to attend to such systems approaches is consistent with recommendations in a recent National Academy of Sciences (NAS) report, *Frontiers in Agricultural Research: Food, Health, Environment and Communities*, which recommends that the USDA refocus its $2 billion annual research budget, shifting emphasis from the singular objective of increasing food and fiber production to include environmentally sound farming alternatives, quality of life in rural communities, diet and health, food safety, and the impact of globalization on farming in the United States (National Academy of Sciences, 2003).

The NAS report writers were well aware that these new demands on agricultural researchers would tax the ability of the land grant system on many fronts. In a coda to the report, they warned, "To meet new demands, established processes and partnerships in agricultural research must evolve without losing their unique value. Those tensions in the research agenda can be managed only through sustained vision, leadership, and political will" (National Academy of Sciences, 2003).

All of this suggests that more of the research focused on the challenges facing twenty-first century agriculture should be devoted to solving for pattern, rather than developing single-tactic solutions. It may well be, therefore, that poet-philosopher Wendell Berry had it right all along. In an essay on "solving for pattern," published in 1980, he suggested (Berry, 1983):

> *A good solution acts within the larger pattern the way a healthy organ acts with the body. But it must at once be understood that a healthy organ does not—as the mechanistic or industrial mind would like to say—"give" health to the body, is not exploited for the body's health, but is a part of its health. The health of organ and organism is the same, just as the health of organism and ecosystem is the same.*

Or as Morowitz (2003) put it, in more scientific, but less poetic language:

> *The primary metabolic chart of every species maps onto the universal metabolic chart . . . The metabolic chart is part of the phenotype of every organism. The phenotype . . . has a robustness in spite of the constant buzz of noise in the underlying genomes.*

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