As the world's population grows, environmental stewardship will require science to find ways to produce more food on less land.

The Benefits of Biotech

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Ever since the publication of Rachel Carson's *Silent Spring*, environmental activists have warned of a slowly developing but widespread ecological catastrophe stemming from humankind's release of synthetic chemicals into the environment – particularly, the use of insecticides, herbicides, and fertilizers. Although the misuse of agricultural chemicals can have negative environmental impacts, fears that those chemicals would produce ecological catastrophe have proven unfounded. More importantly, any attempt to go without those chemicals would have meant sacrificing tremendous productivity gains and having to bring new, undeveloped land into agriculture.

What if similar benefits could be gained without such a heavy dependence on chemicals? Today, a new crop protection revolution is underway, and it is helping farmers combat pests and pathogens while reducing humanity's dependence upon agricultural chemicals. Biotechnology has made tremendous progress in transferring useful traits from one organism to another, allowing plants to better protect themselves from insects, weeds, and diseases.

The benefits have been so great that farmers have made bioengineered seeds perhaps the most quickly adopted agricultural technology in history. By 2002, just seven years after their introduction on the market, some 5.5 million farmers in more than a dozen countries planted over 145 million acres with gene-spliced crops. That year, 34 percent of all corn, 71 percent of all upland cotton, and 75 percent of all soybeans grown in the United States were bioengineered varieties. Biotech corn, cotton, and soybean have increased yields, reduced agricultural chemical use, and saved growers time, resources, and money. The increased productivity made possible by those advances allows farmers to grow substantially more food and fiber on less land. And each of those benefits helps to lighten agriculture's environmental footprint.

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Risk The introduction of bioengineered crop varieties onto the market has not been without controversy, however. Some critics have suggested that recombinant DNA modification could make foods unsafe to eat, though most concerns have revolved around the potential impact of bioengineered crops on the environment. Environmentalists have claimed, for example, that gene-spliced varieties could harm wild biodiversity by killing beneficial insects and other living organisms, or by becoming invasive weeds. Those and related concerns have been used as the justification for increasing regulation on biotechnology in the United States and abroad.

While it cannot be claimed that modified crops pose no risks to the environment, it is important that those risks be put into perspective. The threat posed by any plant — bioengineered, conventionally bred, or wild — has solely to do with the traits it expresses. Risk has nothing to do with how, or even if, a plant was modified. Countless scientific bodies, including the National Academy of Sciences, the American Medical Association, and others, have concluded that gene-splicing techniques themselves are actually safer than traditional breeding methods because breeders know which new genes are being added to plants and exactly what function those genes perform. Thus, bioengineered varieties are less likely, not more likely, to pose environmental or human health risks than are conventionally bred plants with similar traits. Critics of biotechnology, however, use out-of-context scare stories about such risks to argue for increasing the regulation of bioengineered crops across the board, regardless of the level of risk individual varieties may pose.

Benefits Risk aside, no examination of biotechnology would be complete without also considering the benefits such crops can deliver. After all, if the goal of regulation is to improve environmental health, we have to determine what benefits will be sacrificed when new products are delayed in reaching the market or made more costly by the regulation in question. Numerous human health benefits from bioengineered crops are on the horizon and a few have already been realized. However, most of the benefits that have already been delivered by gene-spliced plants are environmental. Since 1996, bioengineered crops have reduced agricultural chemical use, including insecticides and herbicides. Several varieties, nearly ready for market, will also help to reduce fertilizer use. Other products could increase agricultural productivity by allowing crop plants to better resist plant diseases or tolerate extremes of heat, cold, and drought.

Of course, many critics of modern industrial agriculture argue that the choice between biotechnology on the one hand and agricultural chemicals on the other poses a false dichotomy. They argue that organic production methods offer a more environmentally sensitive alternative to both systems. However, concluding that organic farming is better for the environment can only be done by ignoring the environmental costs imposed by organic methods. By most measures, organic farming is, in fact, more environmentally destructive than either conventional agriculture or the biotech alternative.

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PEST RESISTANCE

The use of agricultural chemicals is an environmental paradox. On the one hand, the runoff of agricultural chemicals into wetlands, streams, and lakes, as well as seepage of those chemicals into groundwater, can pose environmental problems. Overuse of chemical pesticides, for example, can damage biodiversity in areas adjacent to fields and kill fish or other important aquatic animals, insects, and plants. Overuse can even harm agricultural productivity itself by killing beneficial insects such as bees, other pollinators, and pest-eating insects in and around the fields. On the other hand, the failure to use such products means low productivity, which has its own adverse environmental impacts.

It is estimated that up to 40 percent of yield potential in Africa and Asia, and about 20 percent in the industrialized world, is lost to insect pests and pathogens despite the ongoing use of copious amounts of pesticides. One benefit of agricultural biotechnology that has already been demonstrated is its ability to help better control insect pests, weeds, and pathogens. Among the most prevalent first generation products of agricultural biotechnology have been crop varieties resistant to chewing insects. That pest-resistance trait was added by inserting a gene from the common soil bacterium *Bacillus thuringiensis* (Bt) into the DNA of crop plants. Bt produces proteins that are toxic to certain insects, but not to mammals, fish, birds, or other animals, including humans. The bacterial proteins occur naturally, and foresters and organic farmers have cultivated Bt spores as a "natural pesticide" for decades, so it was an obvious choice for investigation by genetic engineers. Today, more than a dozen varieties of corn, cotton, and potato with the Bt protein trait have been commercialized.

Consider the success of commercialized Bt corn in protecting plants from a range of chewing pests such as the European corn borer, a caterpillar pest that destroys an estimated $1 to $2 billion worth of corn each year. Caterpillars are difficult to control because they actually bore into stalks and ears of corn where they escape exposure to sprays. The Bt trait has provided farmers with the first truly effective means of controlling such infestations. Bt field corn varieties contributed to a modest reduction in insecticide use and increased yields by between three and nine percent, depending upon the intensity of infestation in a given year. Bt sweet corn has reduced insecticide use by between 42 and 84 percent. And Bt potato varieties cut pesticide applications by about half. In 2000, though, McDonald's and Burger King restaurants bowed to activist pressures and told their french-fry suppliers to stop using engineered potatoes, so the varieties were removed from the market the following year.

Bt cotton is perhaps the most remarkable story, generating both substantial reductions in pesticide use and substantial yield increases. Cotton production requires very high doses of pesticides — well over 25 percent of all insecticides used globally are sprayed on that crop. So, the introduction of Bt varieties made a significant contribution to reducing global insecticide use. Between 1995 and 1999, the total volume of insecticides to control the three worst cotton pests fell by 2.7 million pounds, or roughly 14 percent, in six U.S. states studied by the Department of Agriculture. An analysis of 1999 harvests of Bt and conventional cotton found an average yield increase of nine percent with the Bt varieties that year.

Such a large reduction in synthetic insecticide use also saves resources that otherwise would be used in pesticide application. Economists from Louisiana State University and Auburn University found that, in the year 2000 alone, farmers planting Bt cotton varieties saved 3.4 million pounds of raw materials and 1.4 million pounds of fuel oil in the manufacture and distribution of synthetic insecticides, while 2.16 million pounds of industrial waste were eliminated. On the user end, farmers were spared 2.4 million gallons of fuel, 93 million gallons of water, and some 41,000 ten-hour days needed to apply pesticide sprays. Similar figures could easily be calculated for other bioengineered crops as well.

In less developed nations where pesticides typically are sprayed on crops by hand, use of Bt crops has even greater benefits. In China for example, some 400 to 500 farmers die every year from acute pesticide poisoning. Since the 1997 introduction of Bt cotton varieties in China, farmers reduced the quantity of pesticides applied to cotton by more than 75 percent compared to conventional varieties. As a direct consequence, farmers who planted only Bt varieties reported just one-sixth as many pesticide poisonings per capita as those who planted only conventional cotton. Smallholder farmers in the KwaZulu-Natal province of South Africa have achieved similar productivity and resource savings.

The Monarch butterfly Unfortunately, Bt crops have been the primary target of many environmentalists who claim that bioengineered plants could hurt biodiversity. Interestingly, many of those same environmental organizations, including Environmental Defense and the National Wildlife Federation, actually supported the development of Bt crops in the late 1980s as a way to cut synthetic pesticide use. But once those products became a commercial reality, attitudes changed. And after a 1999 report in *Nature* suggested that pollen from Bt corn could kill Monarch butterfly caterpillars, activists stepped up lobbying efforts to heighten biotechnology regulation. The *Nature* report, however, was hardly news to plant scientists because the corn was engineered to kill caterpillars. Nevertheless, the paper's publication triggered an immediate frenzy of negative media coverage and activist protests.

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However, Monarch larvae would also die if they were to be exposed to the Bt bacilli that organic farmers use or to synthetic chemical pesticides. The unasked question, then, is which production method would be safest for Monarchs and other non-target organisms? Follow-up studies have concluded that, while Bt corn pollen could kill non-target insects including Monarch butterflies, in actual field conditions the spread of pollen is too small to represent a significant problem. Indeed, scaremongers who continue to fret about the effects of Bt corn pollen on Monarch butterflies seem to overlook the fact that Monarch populations have actually increased since the 1996 introduction of bioengineered corn in the United States. The gloomy scenario predicted by activists was authoritatively debunked by the September 2001 publication in the *Proceedings of the National Academy of Sciences* of six peer-reviewed papers describing two full years worth of intensive field research by 29 scientists who found little or no effect of Bt pollen on Monarchs.

That is not to suggest that no environmental harm could ever arise from bioengineered pest-protected plants. But, while Bt crop varieties do introduce a novel risk in the form of new vectors for insecticidal proteins, the sheer reduction in the use of synthetic chemical insecticides in fields planted with Bt varieties tends to reduce the likelihood of ancillary environmental effects. To date, the evidence depicts an overwhelmingly positive experience with commercialized varieties.

WEED MANAGEMENT

Among the most popular traits included in commercial bioengineered crop plants is herbicide tolerance. That feature allows farmers to apply a specific chemical herbicide spray over fields without damaging the growing crop. The trait has been developed in some plants with conventional breeding methods, but the process is more efficient and effective with gene-splicing techniques. Varieties of canola, corn, cotton, flax, rice, and sugar beet have all been bioengineered to tolerate herbicides, but by far the most popular herbicide-tolerant crop plant is Monsanto's Roundup Ready soybean. Planted on over 70 percent of all soybean acres in the United States, this variety is resistant to Monsanto's proprietary glyphosate herbicide, Roundup.

Farmers growing glyphosate-tolerant soybeans have realized herbicide cost savings and a significant reduction in the number of soybean herbicide treatments, although yields have not increased. The exact change in herbicide use varies among regions and growers, ranging from increases of as much as seven percent to reductions of up to 40 percent. Overall, the adoption of Roundup Ready soybeans has led to a modest net reduction in herbicide use. Nevertheless, adoption of those varieties accelerated a shift from relatively more harmful herbicides to glyphosate, which is generally considered an "environmentally friendly" chemical because it degrades quickly and has an extremely low toxicity.

Similarly, adoption of herbicide-tolerant cotton varieties has shown a shift from more toxic herbicides to glyphosate and other less toxic ones, as well as a reduction in overall herbicide use of between 20 and 50 percent. And herbicide-tolerant canola varieties in Canada led to a 29 percent reduction in total herbicide use.

Perhaps an even more important benefit is that the use of herbicide-tolerant crops facilitates the adoption of conservation tillage practices. The loosening of soil and consequent erosion from wind and water is reduced by up to 90 percent compared with plowing. That is a little-appreciated, but very important, environmental benefit because eroded topsoil can be a troublesome pollutant. Erosion removes more than 12 tons of topsoil per hectare from U.S. cropland annually. When it runs off farm fields, soil can be transported to lakes, ponds, and waterways where the sediment muddies water, damages aquatic habitat, interferes with navigational and recreational uses, and requires periodic dredging.

Farmers like conservation tillage, but it is considerably less practical without the use of herbicides for weed control. And because growers do not need to worry about damaging their crop, the adoption of herbicide-tolerant varieties is a perfect compliment to conservation tillage systems. Since the 1996 introduction of Roundup Ready soybeans, conservation tillage acreage in the United States has increased by 35 percent. And, while many growers of conventional varieties are adopting those tillage practices, U.S. farmers growing herbicide-tolerant soybeans are 25 percent more likely to practice conservation tillage than farmers growing conventional varieties.

Super-weeds The primary concern among environmentalists regarding bioengineered herbicide-tolerant crops is that the trait could be transferred to wild plants through cross-pollination, creating so-called "super-weeds" that might out-compete other wild plants and become invasive. As with conventionally bred plants, there is some chance that genes from biotech varieties could "out-cross" with wild plants, but only in regions where there are wild species related closely enough to the biotech plants for ordinary sexual reproduction — canola and wheat in North America or rice in Asia, for example. Nevertheless, out-crossing is only problematic when the genes in question could enhance the weeds' ability to survive better in the wild. Because we do not normally spray herbicides on wilderness areas, however, the herbicide tolerance trait would not give the wild plant any selective advantage relative to other species. Thus, while the transfer of a gene for herbicide tolerance into a wild relative could create a nuisance for farmers, it is unlikely to have any impact on native biodiversity.

Even in the event that herbicide tolerance genes were transferred to a weed species, it is unlikely to be genuinely problematic, even for farmers. Genetic tolerance to herbicides is highly specific. In fields, farmers could still control herbicide-tolerant weeds by using a different herbicide. Indeed, herbicide-tolerant canola plants have been produced with conventional breeding and have been commercially available in North America for more than 20 years. No unmanageable weed problems have been reported as a result of their use, even though several sexually compatible wild relatives often grow very close to canola fields, and though canola is a highly promiscuous out-crosser.

EFFICIENT FERTILIZERS

Just as with pesticides and herbicides, the overuse of nitrogen, potassium, and phosphorous fertilizers and the presence of large amounts of animal manures can have negative environmental impacts. Runoff from fertilizers or manures into streams and lakes can cause excessive growth of aquatic plant life and deplete the availability of absorbed oxygen needed by other organisms. Despite such problems, fertilizers are an important part of food production. "It is fantasy," notes agricultural economist Tom DeGregori, "to suggest that we can grow crops and feed the world's population without some form of crop protection and soil nutrient renewal." In many cases, even newly cleared lands need supplemental nitrogen, potassium, and phosphorous to improve soil quality. Many crop plants will not grow to full maturity in alkaline soils unless phosphorous fertilizer is added, and will not grow to full maturity in acidic soils unless phosphorous or lime is added.

Nearly 30 million tons of phosphorous fertilizer is applied every year to farm fields around the world. Even then, as much as 80 percent of what is applied remains unavailable to plants in much of the world's arable land. More than two-thirds of global land area is naturally acidic or alkaline, so phosphorous forms compounds with elemental aluminum, iron, calcium, and magnesium in the soil. And because such large amounts of those mineral additives go unused by plants, runoff becomes a significant pollution problem.

Scientists at the Center for Research and Advanced Studies in Irapuato, Mexico have bioengineered corn, tobacco, and papaya plants with a gene from the bacterium *Pseudomonas aeruginosa* to secrete citric acid from their roots, which unbinds the phosphorous from other elements and makes it available to the plants. The engineered varieties yield more leaf and fruit than conventional plants when grown in acid soils with no added phosphorous, and they require substantially less phosphorous fertilizer to reach optimal growth. Research is now underway to modify other crop plants such as rice and sorghum in the same way. And a similar discovery has resulted in bioengineered rice and corn varieties that grow better in alkaline soils. Once they are commercialized, such plants could reduce the use of soluble mineral fertilizer by as much as 50 percent and improve crop yields dramatically in the tropical regions where acidic and alkaline soils are most prevalent.

THE ORGANIC ALTERNATIVE

As we have seen, biotechnology already is contributing to improved environmental stewardship. However, many critics of biotechnology argue that the choice between bioengineered crop varieties and greater agricultural chemical use is a false dichotomy. Organic and other "natural" farming advocates believe that intensive agriculture, which relies upon heavy use of synthetic and other "off-farm" inputs, devastates soil health, makes for unhealthy food of poor quality and taste, and has serious detrimental impact on the surrounding environment.

Yet claims that organic farming is a nearer and dearer friend to the environment are difficult to substantiate because organic practices merely trade some environmental threats for others. For example, organic farms do not use synthetic chemicals, but they do still need to control pests, weeds, and pathogens. Instead of synthetic pesticides, organic farmers use mineral- or plant-derived chemicals — including copper sulfate, pyrethrum, ryania, and sabadilla — to control insects and plant diseases. Yet, ounce for ounce, most of those chemicals are at least as toxic or carcinogenic as many of the newest synthetic chemical pesticides. Pyrethrum, for example, has been classified as a "likely human carcinogen" by a U.S. Environmental Protection Agency scientific panel.

Next, instead of soluble nitrogen, potassium, and phosphorous fertilizers, organic farmers rely on animal manure and so-called "green manures" such as legume nitrogen fixation or organic plant matter to restore soil nutrients. However, plowing legume crops and animal wastes into the soil leads to nitrate leaching into groundwater and streams at rates similar to conventional soluble fertilizers. And once animal manures and legume crops are broken down in the soil, the chemical properties of the remaining nitrogen are identical to those of soluble mineral fertilizers that are prohibited in organic farming.

Also, because organic farmers must control weeds by using frequent mechanical tillage (or else sacrifice yields), organic agriculture contributes to topsoil erosion and disturbs worms and other soil invertebrates. Compared with modern conservation tillage practices, organic weed control is much more environmentally damaging.

Finally, productivity from organic farming and ranching is substantially lower than from conventional intensive agriculture. Organic farming generates yields that are at least five to 10 percent lower than conventional crop production and as much as 30 to 40 percent lower for important staple crops such as potatoes, wheat, and rye. Organic livestock productivity is approximately 10 to 20 percent lower than conventional husbandry. Even those yield drags can be misleading because soil nutrient replacement on organic farms requires lands to be fallowed with nitrogen-fixing plants such as clover or alfalfa for two or three years in every five or six. Conventional farming that incorporates soluble mineral fertilizers does not need to fallow land. Thus, conventional farms can achieve total yields per acre that are as much as 40 to 100 percent greater than organic farms. Alternatively, they can match the yields of organic farms with only 50 to 70 percent of the land.

THE IMPORTANCE OF PRODUCTIVITY

The importance of agricultural productivity for ecological stewardship and habitat conservation should be evident. The loss and fragmentation of native habitats caused by agricultural development, along with the conversion of both wilderness areas and agricultural lands into residential areas, are widely recognized as among the most serious threats to biodiversity. According to a recent report published by Future Harvest and IUCN/The World Conservation Union, "reducing habitat destruction by increasing agricultural productivity and sustainability" is one of the six most effective ways to preserve wildlife biodiversity.

Over the past 50 years, the world's population doubled from three billion to six billion, and it is expected to grow by an additional three billion in the next half-century. Fortunately, over the past five decades, the development of better plant varieties and animal breeds, and the production and better use of herbicides, pesticides, fertilizers, and other agronomic technologies — collectively known as the "Green Revolution" — dramatically increased per-acre agricultural yields. That is perhaps the most remarkable environmental success story in history.

From 1961 to 1993, the earth's population increased 80 percent, but cropland increased only eight percent, all while per-capita food supplies rose. Higher food demand was met almost totally by increasing per-acre yields. Had that not been the case and agricultural productivity in 1993 remained at the 1961 level, producing the same amount of food would have required increasing the amount of cropland and grazing land by 80 percent or more. In other words, an additional 27 percent of the world's land area (excluding Antarctica) would have had to come into agricultural use. Surely, that would be an environmental nightmare far greater than any of those imagined by opponents of agricultural technology.

Still, similar yield increases will be necessary in the twenty-first century if the projected population is to be fed with an equally light impact on the environment. The projected increase in food demand can be supplied in one of two ways: increasing the land area dedicated to agriculture or increasing agricultural productivity. Though the ability of conventional technology to increase agricultural productivity over the past few decades has been impressive, it is not guaranteed to continue. Annual increases in agricultural productivity have been declining in recent years. Cereal yields per hectare rose 2.2 percent per year in the late 1960s and 1970s, but only 1.5 percent per year in the 1980s and early 1990s, and as little as just 1.0 percent by the end of the '90s. Consequently, some scientists believe new breakthroughs will have to come from bioengineering techniques. Fortunately, biotechnology is much more flexible, precise, and powerful than those earlier methods of genetic manipulation, and rapid productivity gains of five, 10, and even 25 percent in individual varieties from a single added trait are not unrealistic.

As important as pest and weed control and soil nutrients are to crop productivity, controlling the destructive forces of nature do not end there. Plant pathogens such as viruses, bacteria, and fungi cause billions of dollars in crop losses worldwide. Already, virus-resistant varieties of potato, papaya, squash, and melon have been approved for commercial cultivation, and varieties of citrus fruits, peanuts, tomatoes, and tobacco have all been engineered and are awaiting commercialization.

A more difficult challenge has been engineering resistance to a range of bacterial and fungal pathogens, though some successes have already been had. Extremes in temperature, periods of drought, and impure water are also significant factors that limit the productivity of crop plants. Researchers in Brazil have bioengineered tobacco plants to over-express a gene that reduces dehydration during periods of drought. Other researchers have identified plant genes that will help crops better survive bouts with extreme heat and with soils affected by excess mineral salinization. Scientists at the University of Toronto and the University of California, Davis have engineered tomatoes and other plants that are so tolerant to salt that they not only grow in salty soil, they can also be irrigated with brackish water with only a modest negative effect on plant growth. Those improvements and many others, made possible only with recombinant DNA techniques, will go a long way toward improving the yield potential of the world's most important crops.

CONCLUSION

Because of the complexity of plant transformation, many of the promised benefits of biotechnology are still many years away. But the biggest threat bioengineered plants face is overly restrictive policies based on the false notion that there is something inherently dangerous about biotechnology. Of course, not all the products of gene-splicing will prove to be better than the best conventional ones. Some will have inferior agronomic properties; others may express traits that pose genuine environmental or human health risks. But to gauge the value of individual applications or agricultural biotechnology as a whole, we have to place their risks and benefits into a broader context that does not ignore the risks posed by conventional and organic production practices or our ability to manage those risks responsibly. Yet that is exactly how advocates of increased regulation would have us examine them: without reference to the place biotechnology occupies in the broader spectrum of plant modification and other agricultural practices.

Numerous attempts have been made in recent years to increase the regulatory burden borne by the products of biotechnology — through both agency rulemaking and congressional legislation. All of those attempts have two things in common: They require regulators to consider only the risks of bioengineered crops and not their benefits, and they hold gene-splicing to a standard of safety that could not possibly be met by non-biotech products and practices. Heightened regulation of certain high-risk plant varieties may indeed be warranted. But the appropriate level of oversight cannot be achieved simply by singling out bioengineered varieties for differential treatment. When biotechnology is evaluated on a level playing field, farmers, consumers, and regulators will find that it outshines its competitors. R

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