Role of biotechnology in sustainable agriculture

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Abstract
A basic concept of sustainable agriculture includes using resources in a way that does not deplete or permanently damage systems used for plant and animal production. In early history, humans survived as hunter–gatherers and perhaps less than 1% of biomass could be used as food (Diamond, 1997). As a result, most resources in the environment were not likely to be used directly by humans. The limited availability of food also restricted population growth, helping to make the hunter–gatherer way of life sustainable. In contrast, domestication of crops and animals for food has greatly increased edible biomass, leading to dramatic population growth and the possibility that production of adequate food will lead to longterm damage to agricultural systems.

Disciplines
Agriculture | Biotechnology | Entomology | Environmental Sciences | Sustainability

Comments

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Role of biotechnology in sustainable agriculture

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A basic concept of sustainable agriculture includes using resources in a way that does not deplete or permanently damage systems used for plant and animal production. In early history, humans survived as hunter–gatherers and perhaps less than 1% of biomass could be used as food (Diamond, 1997). As a result, most resources in the environment were not likely to be used directly by humans. The limited availability of food also restricted population growth, helping to make the hunter–gatherer way of life sustainable. In contrast, domestication of crops and animals for food has greatly increased edible biomass, leading to dramatic population growth and the possibility that production of adequate food will lead to long-term damage to agricultural systems.

The high productivity of twenty-first-century agriculture is the cumulative result of periods of change called agricultural revolutions. Another revolution based on biotechnology is arguably under way. Some have called the biotechnology-based changes in agriculture the “gene revolution” because they follow the green revolution of the twentieth century, during which high-yielding crop varieties and other changes in production were spread to developing nations. The use of biotechnology in agriculture includes well-publicized techniques such as production of genetically modified (GM; alternatively called transgenic or genetically engineered [GE]) plants and animals, but also less controversial techniques (Herdt, 2006). For example, biotechnology may be used to improve or supplement conventional agricultural methods, such as when marker-assisted selection is employed to enhance traditional breeding of crops.

It is worth noting that each time agricultural methods advance, new problems related to sustainability may be resolved and created (Evans, 2003). For example, in the twentieth century the development of new synthetic insecticides delivered effective and long-lasting control of insect pests (Casida & Quistad, 1998). However, the adverse effects from uncontrolled pesticide use were brought to public attention by the book *Silent Spring* (Carson, 1962). Since the 1960s, increased regulation has considerably reduced the threat of environmental and agricultural problems stemming from overuse of pesticides. Therefore, it seems reasonable to predict that a biotech revolution will have both positive and negative effects on sustainability, and the degree to which either aspect dominates will be based on the choices society makes regarding how to use biotechnology in agriculture.

Along with changes to agriculture and society over the last century, the concept of sustainability has been popularized and expanded. Broader definitions of sustainable agriculture reveal that the concept suggested above (using resources in a
way that does not deplete or permanently damage agricultural systems) may be too simple. One representative definition suggests that sustainable agriculture “enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fiber needs; is economically viable; and enhances the quality of life for farmers and society as a whole” (American Society of Agronomy, 1989). Understanding more complex definitions can be aided by considering three common components associated with sustainable agriculture: (1) economic, (2) environmental and (3) social or community effects (Lyson, 2002). Though most agricultural practices will impact more than one of these three components, the categories are useful to organize thinking about sustainability and to emphasize the broad nature of sustainable agriculture.

20.1 Potential of biotechnology to enhance sustainability

Many specific issues relate to agricultural sustainability, but it can be argued that there are two basic challenges (Schaller, 1993). First, agriculture must be profitable for those producing plant- and animal-based food for the rest of the world. Second, agriculture must be able to produce sufficient food (quantity and quality) to support a growing global population projected to exceed 9000 million before the year 2050. However, distinctions between applications of biotechnology that address profitability and production may not be very useful for two reasons. First, because revenue from agriculture is a basic incentive for farmers to remain involved in agriculture, profit and production are related. Second, many applications of biotechnology would clearly influence both profitability and production to some degree.

The most serious threats to agricultural profitability and production are limitations or excesses of basic resources required by plants and animals (water, heat, nutrients). Even in relatively wealthy industrialized countries like the USA, the short-term impacts of drought and long-term prospects of depleted groundwater are serious agricultural and environmental problems. One approach to increase yields under drought conditions and perhaps reduce water use is the development of crops with increased drought tolerance. Genetic engineering has been used to produce drought tolerance for many major crops including rice, wheat, maize (corn) and soybean. Marker-assisted selection and genetic engineering have been used to produce crops tolerant to other stresses including high salt levels, flooding and extreme temperatures. Stress tolerance incorporated into elite crop varieties would not only increase yields in some areas, but allow the expansion of agriculture into areas currently unfit for production of certain crops. Because resistance to multiple plant stresses may be controlled by expression of a single protein, biotechnology should make breeding multiple stress tolerant plants faster and more effective than previously possible.

Complementary biotechnology approaches also are being used to increase the efficiency of agricultural production. Increasing crops’ ability to effectively use nitrogen would decrease fertilizer costs in industrialized countries and help maintain water quality by reducing the amount of nitrogen added to crops (and later leaching into groundwater). In developing nations, improved crop nitrogen use efficiency would increase yields for many farmers in developing nations who may be unable to afford synthetic fertilizer. Other biotechnology applications include modification of the nutrient content of agricultural products. Perhaps the best-known example is the beta-carotene-enriched Golden Rice, which could reduce vitamin A deficiency and save thousands of lives annually (Stein et al., 2006). Many other promising examples of biofortification (nutrient enrichment through genetic engineering or conventional breeding) of crops exist, highlighting the potential to combat malnutrition using foods that are more nutrient-rich rather than simply requiring greater amounts and more types of food. Crop nutrient enrichment is also under way for livestock production, enhancing the nutritional value of crop residues fed to farm animals.

The development of alternatives to petroleum-based fuels is one of the best-known biotechnology projects. Currently most farmers are dependent on diesel and gasoline to power agricultural equipment. This makes them reliant on a
resource that is (1) non-renewable, (2) environmentally detrimental and (3) subject to price fluctuations arguably manipulated by petroleum-exporting countries. The substitution of biologically based fuels (biofuels) such as ethanol or biodiesel may help to insulate farmers from price increases or price instability, and provide an additional source of revenue if maize, soybean or other crops are used to produce biofuels. Biotechnology is being used to more effectively produce ethanol from cellulose by the use of GM yeasts and bacteria. Similarly, genetic engineering is helping create plants that yield greater energy returns than currently available varieties. Applications of biotechnology also may allow fuels to be produced from by-products of agriculture otherwise considered waste. The benefits to the environment may increase as methods and technology related to biofuels advance. Non-food crops, including native perennial grasses, may offer the benefits of biofuels produced from maize or soybean, but with further advantages of reduced fertilizer, pesticide and energy inputs and helping to mitigate carbon dioxide emissions.

20.2 Biotechnology-based pest management and sustainability

While pest management is only one of several tools of biotechnology, transgenic management of crop pests has been the most commercially successful application of agricultural biotechnology. Herbicide-tolerance, insect-resistance and virus-resistance traits are currently available in maize, cotton, soybean, canola (oilseed rape), beets, rice, squash, papaya and alfalfa. Argentina, Brazil, Canada, China and India are among the top adopters of GM crops, though their combined GM production areas trail the leading producer of transgenic crops, the USA, which planted an estimated 54.6 million ha of the 102 million ha of global GM crops in 2006 (James, 2006).

The most successful combinations of crops and traits in the USA include insect resistance and herbicide tolerance in maize and cotton and herbicide tolerance in soybean. These traits have been commercially available since the mid-1990s with steadily increasing adoption from 2000 to 2006 (Fig. 20.1). As a result, much of the cost–benefit research on biotechnology relates to insect-resistance and herbicide-tolerance traits in maize, cotton and soybean, which have also attracted the greatest amount of scrutiny by critics of GM crops. Though some issues do not fit neatly within a single component of sustainability, the following sections further discuss what is known regarding the impact of pest management on economic, environmental and social concerns. Brookes & Barfoot (2006) provide an overview of global economic and environmental impacts of GM crops with less specific information on pest management.
Table 20.1 Estimated impacts on yield, costs and overall profitability of GM insect-resistant cotton

<table>
<thead>
<tr>
<th>Country</th>
<th>Years</th>
<th>Yield (kg/ha)</th>
<th>Seed cost</th>
<th>Insecticide cost</th>
<th>Labor</th>
<th>Profit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1999–2001</td>
<td>+19</td>
<td>+95</td>
<td>−67</td>
<td>−18</td>
<td>+340a</td>
<td>Pray et al., 2002</td>
</tr>
<tr>
<td>India</td>
<td>2002–2003</td>
<td>+53</td>
<td>+8</td>
<td>−2c</td>
<td>−</td>
<td>+54</td>
<td>Kambhampati et al., 2006</td>
</tr>
<tr>
<td>Mexico</td>
<td>1997–1998</td>
<td>+11</td>
<td>+165</td>
<td>−77</td>
<td>−</td>
<td>+12</td>
<td>Traxler et al., 2003</td>
</tr>
<tr>
<td>South Africa</td>
<td>1998–2000</td>
<td>+64</td>
<td>+89</td>
<td>−58</td>
<td>+2</td>
<td>+198</td>
<td>Bennett et al., 2006</td>
</tr>
</tbody>
</table>

a Dashes (–) indicated data not presented or collected for a study.
b Non-Bt cotton farmers produced an overall loss during this period.
c Costs of seed and insecticides combined.

20.2.1 Economic profitability

To make biotechnology-derived agriculture profitable, a combination of increased crop yield, quality or cost savings must be sufficient to offset any additional or premium costs associated with purchasing of the biotechnology-derived product. This premium for purchasing transgenic crop seed is commonly referred to as a technology fee. For transgenic pest management, a farmer is less likely to make up for the added cost when the targeted pests (insects, weeds or pathogens) are absent or only present in low numbers, or the price of the agricultural commodity is low.

In the USA, transgenic maize varieties expressing insect-active toxins derived from the soil bacterium Bacillus thuringiensis (Bt) help illustrate the sometimes complex economics of biotechnology. The first varieties of Bt maize were primarily intended to control the European corn borer (Ostrinia nubilalis). During 1998 and 1999, low maize prices and low European corn borer populations combined to make planting Bt maize an economic disadvantage (Carpenter & Gianessi, 2001). However, 1998 and 1999 were exceptionally poor economic conditions for producing Bt maize; analysis including more typical conditions for the USA (Sankula, 2006) show increased profitability for Bt-maize farmers. Research on lepidopteran-active Bt maize in Spain (Demont & Tollens, 2004) and the Philippines (Yorobe & Quicoy, 2006) also suggests farmers gain from using transgenic insect control. The overall economic benefits from reduction of insect damage and costs associated with insecticidal control (scouting, insecticide, application) are changing as new hybrids express additional Bt toxins. “Stacks,” adding Cry3Bb1 or Cry34/35Ab1 toxins, are used to protect maize from both European corn borers and corn rootworms (Diabrotica spp.) (Rice, 2004). Similarly, the use of two or more complementary Bt toxins in “pyramids” should enhance the economic value of Bt maize by improving toxicity to broader groups of lepidopteran maize pests; future adoption rates for multiple pests will also depend upon the degree to which technology fees also increase.

The other widely adopted transgenic insect-resistant crop, Bt cotton, also has economic benefits for control of lepidopteran pests. Gains may be produced by large reductions in pest damage (leading to increased yield) or expenses associated with insecticide applications, as shown for farmers in Argentina (Qaim & de Janvry, 2005), China (Pray et al., 2002), India (Kambhampati et al., 2006), Mexico (Traxler et al., 2003), South Africa (Bennett et al., 2006) and the USA (Cattaneo et al., 2006). Though the added costs of transgenic seed are considerable, a combination of benefits related to yield and production costs can combine to far exceed technology fees (Table 20.1).

The adoption and profitability of herbicide-tolerant crops present an equally interesting case. Though transgenic herbicide-tolerant crops are planted on approximately three times the area of Bt maize and cotton combined (James, 2006), markedly less information on the economic
benefits of herbicide-tolerant crops is available. For soybean, the most widely grown herbicide-tolerant crop, economic benefits have been shown in the USA (Heatherly et al., 2002) and Argentina (Qaim & Traxler, 2005). An economic analysis of transgenic glyphosate-resistant sugar beets in the USA also showed benefits from increased yield, quality and potential to decrease herbicide costs (Kniss et al., 2004). Herbicide-tolerant canola in Canada also appears to present an overall economic benefit to farmers (Stringam et al., 2003). However, some have suggested that convenience may better explain the broad and rapid farmer adoption of herbicide-tolerant crops (Economic Research Service, 2002; Stringam et al., 2003). It is also possible that grower surveys used in some studies of biotech crops do not reflect some types of economic gains (e.g. reduced labor) from growing herbicide-tolerant varieties. As noted above for Bt maize, profitability of all biotechnology-derived crops may depend on several factors including differences among years (Kambhampati et al., 2006), locations (Heatherly et al., 2002) or farmer education (Yang et al., 2005).

20.2.2 Environmental impact
Production of conventional or biotechnology-derived crops may impact agricultural fields and the surrounding environment in many different ways. Below the possible effects of GM and other biotech-derived crops are summarized with regard to (1) species abundance and diversity, (2) sustainability of pest management and (3) overall environmental health.

Effects on species abundance and diversity
Potential unintended effects of biotech crops on species abundance and diversity are often referred to as non-target effects. For GM insect-resistant crops, non-targets include any species other than the pests that an insecticidal trait is intended to control. The effects of biotechnology-derived crops on non-target species have been examined in hundreds of laboratory and field experiments. For Bt crops, the toxins generally impact only a few species closely related to target pests. Though this may effectively eliminate certain pests within a field, additional impacts on abundance and diversity are mostly limited to other species reliant on target pests, such as host-specific parasitoids. As a result, insect control with Bt crops should have far less impact on non-target species than conventional (broad-spectrum) insecticides.

Compared to conventional insecticide use, Bt crops conserve non-target species leading to greater arthropod abundance or diversity (Dively, 2005; Torres & Ruberson, 2005; Cattaneo et al., 2006) and better biological control of pests not susceptible to Bt toxins (Naranjo, 2005) (Fig. 20.2). Because many beneficial arthropods move between cropping systems (Prasifka et al., 2004a, b), conservation of non-target species in Bt fields also could improve biological pest control in nearby (non-transgenic) crops. Some research has shown unexpected adverse effects of Bt crops on non-target insects (e.g. Monarch butterfly larvae in Losey et al., 1999; predatory lacewings in Hilbeck et al., 1998), but such studies generally have been shown to be misleading or scientifically flawed (Hellmich et al., 2001; Romeis et al., 2004).

Impacts on plant biodiversity also have been considered. Because the use of GM and other herbicide-tolerant crops facilitates the use of herbicides, the abundance and diversity of weeds and weed seeds within agricultural systems will be reduced, leading to fewer herbivorous insects and birds (Chamberlain et al., 2007). However, such an effect is more accurately caused by very effective weed control rather than biotechnology-derived crops. Another concern suggests that introduction of transgenic crops has reduced the diversity (among elite lines) within crop species (Gepts & Papa, 2003), though research on cotton and soybean varieties in the USA suggests introduction of transgenic varieties produced little or no impact on genetic diversity (Bowman et al., 2003; Sneller, 2003). Further, hundreds of public-sector collections of germplasm from cultivated crops and their wild relatives exist for the purpose of preserving diversity (e.g. the National Genetic Resources Program in the USA).

Sustainability of pest management
The largest threat to sustainability for insect-resistant and herbicide-tolerant crops is the widespread evolution of resistant pest populations. As with conventional pesticide use,
increasing reliance on a single GM trait to control insect or weed pests increases the likelihood that resistant genotypes will spread.

In the USA and other countries that produce insect-resistant Bt crops, steps to delay resistance evolution in target pests are organized into insect resistance management (IRM) plans. Such IRM plans outline mandatory actions for farmers and seed companies, including the planting of non-Bt refuges (Environmental Protection Agency, 2001). Refuges provide susceptible insects to mate with any resistant individuals emerging from Bt crops, resulting in hybrid progeny that cannot survive on insect-resistant plants. Evidence from several years of resistance monitoring in Bt cotton suggests the combination of effective resistance and careful management (i.e. the high-dose/structured refuge strategy: Environmental Protection Agency, 2001) has effectively delayed resistance and provided a means of sustainable management of insect pests (Tabashnik et al., 2003, 2005). In China, Bt cotton may have improved sustainability of insecticide-based management; reductions in use of common insecticides appear to have lowered the levels of resistance in cotton bollworm (Helicoverpa armigera) (Wu et al., 2005).

There are legitimate concerns that in developing countries IRM may be more difficult. In particular, large numbers of small farms and less communication between farmers and advisors could result in ineffective use of non-Bt refuges. In such cases, the best solution may be to develop crops that utilize two or more toxins for which different adaptive mechanisms are required (i.e. pyramids). It appears this type of multiple-toxin strategy could effectively delay resistance with fewer or smaller planted refuges (Zhao et al., 2003).

Unlike GM insect resistance, sustainability of transgenic herbicide-tolerant crops is not preserved by mandatory resistance management plans. The lack of a systematic plan to delay resistance may have contributed to the spread of glyphosate-resistant weeds (Owen & Zelaya, 2005; Sandermann, 2006). However, development of resistant weeds in herbicide-tolerant crops is not a necessary result of using a biotech approach to weed control, but of an unsustainable over-reliance on a single combination of herbicide and herbicide-tolerant crop. To prevent increases in weed resistance to glyphosate and other herbicides, increasing the duration of crop and herbicide rotations should be useful. Conventional and biotechnology-derived resistance to herbicides other than glyphosate indicate producing diverse herbicide-tolerance traits for crops is scientifically realistic (Duke, 2005), but farmers may be hesitant to adopt a more complex (though perhaps more effective and sustainable) weed
management system. The cost to commercialize new products also may be unattractive to agricultural biotechnology companies (Devine, 2005).

**Overall environmental health**

In terms of environmental quality, the largest potential benefit related to pest management may come from significant reductions in the quantity of pesticides used in agriculture. Transgenic crops with resistance to insects, herbicides and plant pathogens may allow reductions in the use of pesticides whose toxic effects are a concern for humans and other vertebrate animals through acute or chronic exposure.

The level of pesticide reduction possible through biotechnology is largely dependant on crop and pest combinations. For example, without transgenic control of lepidopteran pests, cotton farmers have relied on intensive use of broad-spectrum insecticides. Since commercial use of Bt cotton began, control of lepidopteran pests has been accomplished with remarkable reductions in pesticide use by farmers in Australia (Knox et al., 2006), China (Pray et al., 2002), India (Kambhampati et al., 2006), South Africa (Morse et al., 2006) and the USA (Cattaneo et al., 2006). However, reductions in insecticide use may allow pests previously controlled by regular spraying to become more common. Dramatic reductions in pesticide use (90%) also have been recorded in China for transgenic rice varieties that include Bt or a modified cowpea trypsin inhibitor (Huang et al., 2005).

The effects of GM insect-resistance on insecticide use in maize are less clear. The first Bt-maize varieties primarily targeted the European corn borer. In the USA, insecticides are not frequently used to control O. nubilalis in field maize (see Shelton et al., 2002), meaning only modest reductions in insecticide use might be possible. However, in other areas Bt maize has provided significant environmental benefits. Control of the Asian corn borer (Ostrinia furnishalis) in the Philippines has reduced insecticide use by half (Yorobe & Quicoy, 2006). Reduced insecticide use is possible in the USA for Bt sweet corn, which receives more insecticide applications per unit area than maize produced for grain (Shelton et al., 2002). Also, the use of multiple-toxin stacks and pyramids to control other insect pests should expand the potential to reduce insecticide use with Bt maize. For example, crop rotation previously used to control corn rootworms is becoming both less effective in midwestern USA; corn rootworms have adapted to defeat a 2-year crop rotation by laying eggs on crops other than maize and exhibiting extended diapause (Levine et al., 1992; Rondon & Gray, 2004). Rotation of maize with soybean has also become less economically attractive because of increasing maize prices, causing more farmers to plant maize in consecutive years. In this instance, coleopteran-active Bt maize could prove an environmentally favorable substitute for soil insecticides.

Herbicide-tolerant GM crops also impact the environment, in part, through changes in pesticide use. Although glyphosate-resistant soybean fields received more total herbicides, glyphosate was used as a substitute for considerably more toxic herbicides (Qaim & Traxler, 2005). Similarly, the use of glyphosate in midwestern USA has increased following the introduction of transgenic glyphosate-tolerant maize and soybean. Although overall a small increase in herbicide use in soybeans appears to be due to glyphosate-tolerant soybeans, these increases may have a net environmental benefit by reducing the use of other, more persistent herbicides (Economic Research Service, 2002). In glyphosate-resistant cotton in the USA, although herbicide-tolerant varieties appeared to receive more herbicide applications, no statistically significant change could be detected (Cattaneo et al., 2006). The estimated effects of some GM insect-resistant and herbicide-tolerant crops on pesticide use are shown in Table 20.2, although data on insecticide use expressed as kilograms active ingredient (a.i.) or number of insecticide applications may not provide the best measure of environmental impacts (see Section 20.3.1, “Bt cotton in South Africa”).

Beyond possible benefits from changes in chemical weed control, herbicide-tolerant GM crops appear to have allowed for reduced use of mechanical weed control using tillage (Ammann, 2005; Young, 2006). Increased adoption of reduced- or no-tillage agriculture is beneficial to overall environmental health and agricultural sustainability by conserving water, soil and fuel. Consequently, even increases in herbicide use because
of herbicide-tolerant crops may produce an overall positive effect on the environment.

Little research is available on the environmental effects of biotechnology-derived crops with resistance to plant pathogens. However, there are likely to be significant reductions of insecticides for pathogens transmitted by insects (e.g. papaya ringspot virus: Gonsalves et al., 2007; references in Gaba et al., 2004; but see Gatch & Munkvold, 2002). Environmental benefits also seem likely from resistance to plant pathogens in cases where pesticides are currently the only effective treatment.

### 20.2.3 Social impacts

The social impacts of biotechnology-based pest management will be most direct for farmers and others who live in or near farming communities. Whether impacts on these communities are positive or not depends on whether biotechnology effectively addresses social needs, which may differ between industrialized and developing nations.

In industrialized nations like the USA, one critical need is to preserve farming as a basic lifestyle or form of employment. Over less than a century, the USA farm population has declined from over 34% to less than 2% of the total population. Even though crop yields have continued to increase, most income in farming households is now derived from non-farm sources (Lobao & Meyer, 2001). Because preservation of family farms is one key to maintaining rural communities and quality of life (Lyson & Welsh, 2005), increasing the income that farming households derive directly from farming could help to sustain rural communities. Biotechnology and its applications to pest management may help by giving farmers more choices for management of crop pests. More importantly, most of the economic gains produced by transgenic insect-resistant or herbicide-tolerant crops are retained by farmers (Falck-Zepeda et al., 2000). How significant this contribution is to preserving family farms and whether gains will be stable over the long term is difficult to predict.

In contrast, agriculture in developing countries requires more people to be directly involved in crop and animal production on small farms. Though significant, non-farm income provides a minority of income for most farming households (Food and Agriculture Organization, 1998), meaning stable yields are a key to both short- and long-term survival. Substitution of transgenic insect-control for conventional insecticides may have benefits for the health of farming families and communities (see Section 20.3.1, “Bt cotton in South Africa”), while herbicide-tolerant crops may help to improve weed control while conserving soil and water. However, because some crops and developing nations may not provide attractive markets to private biotechnology companies, strong public-sector involvement appears necessary to ensure that developing nations benefit.
from developments in biotechnology (Pingali & Raney, 2005).

20.3 Case studies: biotechnology and pest management

It is important to incorporate a broad view of how a technology may impact sustainable agriculture. In part, this is true because sustainability includes economic, environmental and social components. Positive and negative effects on each component of sustainability combine to determine the overall effect of a technology. However, even within a single component, complex relationships may exist. For example, the use of herbicide-tolerant crops may maintain soil quality by reducing mechanical weed control (and erosion), but might also lead to increased problems with insect pests previously controlled by tilling the soil. In such a case, the environmental value of soil conservation would need to be assessed against a potential increase in insecticide use to control a newly created pest problem. The case studies below highlight the results and limitations of large-scale attempts to measure the environmental effects of transgenic pest management in Africa and Europe.

20.3.1 Bt cotton in South Africa

The effects of changing pest management from a traditional insecticide-based regime to a program relying largely on biotechnology-derived cotton was studied over several years in the Republic of South Africa (Bennett et al., 2003, 2006; Morse et al., 2006). The impact of genetically engineered cotton expressing the Bt toxin Cry1Ac was evaluated, with particular emphasis given to the environmental and economic impacts. Though it can be suggested that Bt cotton does not address the adequacy of the world food supply, this argument is misleading; cotton is consumed directly (when used as cottonseed oil) and indirectly (when used as feed for cattle) by humans. More importantly, the use of cotton as a cash crop (i.e. crops grown for money rather than direct consumption) influences the ability of cotton farmers to buy food and remain profitably involved in agriculture. The studies specifically target economically disadvantaged farmers to explore the validity of concerns that GM crops could be inappropriate for use in developing countries. In an attempt to improve upon previous research, data on a large number of smallholder (small-scale) farmers were obtained from the records of a commercial seed supplier, Vunisa, which acted as the sole seed supplier and purchaser of cotton in the area. However, the validity of information provided by the company was checked against data collected by other researchers and surveys with area cotton farmers.

The economic analysis (Bennett et al., 2006) showed large financial gains for smallholders growing Bt cotton. The cost of inputs, including insecticides used for bollworms (targets of the Cry1Ac toxin), insecticides used for other pests and labor required for pesticide applications were substantially reduced for growers of Bt cotton. Though growing Bt cotton required more labor for weed control (one of two years) and harvesting (all three years), labor cost increases resulted from picking a larger cotton crop. Overall savings from reduced insecticide use and increased revenue from higher yields exceeded additional labor and seed costs associated with growing Bt cotton. To put the economic gains into context, the economic advantage realized per hectare by Bt cotton farmers was 387–715 South African Rand ($US 70–130), or approximately two to four months of relatively well-paid labor for one worker. It also appeared that gains from growing Bt were maintained during an unusually wet year when conventional cotton was produced at a financial loss. Further, farmers with less land received an equal or greater benefit compared to farmers with larger fields.

Environmental impacts of Bt cotton production were linked to overall reductions in insecticide use (Morse et al., 2006). However, data on insecticide use expressed as changes in active ingredient used can be misleading because the toxicity and persistence of any two insecticides used to control the same pest may be very different. As a result, additional methods were used to estimate environmental impacts of insecticide use. Over three years, decreases in insecticide use (kg a.i.) for Bt cotton farmers were 53%, 50% and 63%. Similar significant reductions in environmental impact were found by using methods that emphasized effects on mammals (Biocide Index) or broader
groups of organisms (Environmental Impact Quotient).

Although Bennett et al. (2003) come closest to examining the social impacts of South African Bt cotton production, Bennett et al. (2006) and Morse et al. (2006) also make significant points regarding effects of Bt cotton on the community. First, while the yields of Bt cotton producers were variable, the increases in yield and revenue seem to make smallholders better able to tolerate price fluctuations. Second, reductions in pesticide applications may have been particularly beneficial to women and children, who help with insecticide applications; accidental insecticide poisonings in the area declined considerably over the course of the study (Bennett et al., 2003). On balance, Bt cotton seems likely to improve the economic resilience and quality of life for South African farmers. However, Morse et al. (2006) note that the Bt cotton production will not be a cure-all for area farmers, and that reliance on a single company for credit, seeds, pesticides and a market for their crops makes smallholders particularly vulnerable.

20.3.2 Herbicide-tolerant crops in the United Kingdom

The possible effects of GM herbicide-tolerant crops on the environment were evaluated over three years in sugar beet, maize and canola fields in the United Kingdom (UK). These trials, often referred to as the Farm-Scale Evaluations (FSE), used split fields with farmers' conventional weed management on one half (planted to a non-GM variety) and herbicides applied to the second half (planted with a GM herbicide-tolerant cultivar). Herbicides used in the herbicide-tolerant crops included glufosinate-ammonium (maize and canola) and glyphosate (sugar beet). The environmental impacts assessed focused on potential changes in farmland biodiversity, included the abundance of weeds and arthropods. Because the FSE included controlled trials with GM crops on an almost unprecedented scale (>60 fields per crop), these trials have been among the most discussed field research on genetically modified crops.1

The results indicate the production of herbicide-tolerant sugar beet and canola reduced the abundance of butterflies, bees (sugar beet only), weeds, weed seeds and seed-feeding beetles. In herbicide-tolerant maize, no significant reductions were found for bees or butterflies and increases in the abundance of dicotyledonous weeds, weed seeds and seed-feeding beetles were seen. For herbicide-tolerant beet and maize, the abundance of springtails (many of which feed on decaying plant matter) was increased. Research on a subset of the fields in the FSE examined the effects of management on birds, finding significantly fewer granivorous birds in the herbicide-tolerant maize fields (Chamberlain et al., 2007).

Interestingly, the likelihood of adverse environmental impacts caused by increasing use of herbicide-tolerant crops in the UK are most noted by those not involved in the FSE research. In fact, the FSE researchers are careful to note that the experiments examined the effects of changes in herbicide use rather than effects directly caused by genetic modification of the crops (Firbank et al., 2003). Accordingly, Chamberlain et al. (2007) clarify that the differences in bird abundance and diversity only occurred after herbicide applications in maize. Other researchers have correctly noted the difficulty in determining clear cause-and-effect relationships for the FSE (Andow, 2003). Perhaps the most significant problem in assessing the likely impact of herbicide-tolerant crops on agriculture in the UK is that economic and social impacts were not assessed, and some possible environmental benefits were not included. Consequently, the research does not allow an overall evaluation of how herbicide-tolerant crops might affect agricultural sustainability.

20.4 Conclusions

Biotechnology has the potential to reduce the severity of many problems posed by an expanding population and limited or degraded resources. Agriculture enhanced by new technologies may be capable of producing an adequate supply of more

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1 Most of the results from the FSE were published concurrently in a 2003 issue of the Philosophical Transactions of the Royal Society of London Series B, Biological Sciences, vol. 351, no. 1342.
nutritious foods as well as biologically based fuels that use marginal land and fewer resources. With regard to pest management, biotechnology can provide improved control of pests, generally with reduced stresses on agricultural and surrounding environments.

Despite the exciting potential of biotechnology, it should not be considered a panacea for sustainability. Genetic engineering has been unable to fulfill the projections of benefits forecast in previous years. In part, benefits of biotechnology from the private sector are certainly constrained by the need to maximize profits. Further, the tools of biotechnology can be used in ways that decrease sustainability. However, there are good examples of competitive public-sector biotech products (Pray et al., 2002), successful public–private partnerships (Gonsalves et al., 2007) and responsible use of agricultural biotechnology (Tabashnik et al., 2005) that illustrate the potential of biotechnology to benefit economic, environmental and social components of sustainability.

References


cotton (Gossypium hirsutum) fields. Landscape Ecology, 19, 709–717.


