12.12: Agricultural Applications of Genetically Modified Organisms

As discussed in Section 7.6 of Chapter 7, genes composed of deoxyribonucleic acid, DNA, located in the nuclei of cells direct cell reproduction and synthesis of proteins and generally direct the organism activities. Plant scientists are now able to modify DNA by processes called *recombinant DNA technology*. (This technology is also being applied to a lesser extent to animals.) Recombinant DNA technology normally involves taking a single characteristic from one organism— the ability to produce a bacterially synthesized insecticide, for example — and splicing it into another organism. By so doing, for example, corn and cotton have been genetically engineered to produce their own insecticide. Plants produced by this method are called **transgenic** plants. During the 1970s, the ability to manipulate DNA through genetic engineering became a reality, and during the 1990s, it became the basis of a major industry. This technology promises some exciting developments in agriculture and, indeed, is leading to a "second green revolution." Direct manipulation of DNA can greatly accelerate the process of plant breeding to give plants that aremuch more productive, resistant to disease, and tolerant to adverse conditions. In the future, entirely new kinds of plants may even be engineered.

Plants are particularly amenable to recombinant DNA manipulation. In part this is because huge numbers of plant cells can be grown in appropriate media and mutants can be selected from billions of cells that have desired properties, such as virus resistance. Individual plant cells are capable of generating whole plants, so cells with desired qualities can be selected and allowed to grow into plants which may have the qualities desired. Ideally, this accomplishes in weeks what conventional plant breeding techniques would require decades to do.

Transgenic crops have many detractors, and demonstrations have broken out and test plots of crops destroyed by people opposed to what they call "Frankenfoods." Opposition has been especially strong in Europe, and the European Commission, the executive body of the European Union, has disallowed a number of transgenic crops. Despite these concerns, transgenic crops are growing in importance and they have become widely utilized in highly populated countries, particularly China, where they are seen as a means of feeding very large populations.

The Major Transgenic Crops and their Characteristics

The two characteristics most commonly developed in transgenic crops is tolerance for herbicides that kill competing weeds and resistance to pests, especially insects, but including microbial pests (viruses) as well. In the earlier years of transgenic crop plantings most of the crops had traits for only one of these characteristics, but in more recent years so-called stacked varieties with two or more characteristics have become more common and now comprise the fastest growing sector of transgenic crops. As of 2008, the land areas planted to transgenic crops in the eight leading countries were the following (millions of hectares in parentheses): United States (62.5), Argentina (21.0), Brazil (15.8), India (7.6), Canada (7.6), China (3.8), Paraguay (2.7), and South Africa (1.8 million hectares). The most common biotech crops are the following (hectares planted in 2008 in parentheses): Soybeans (65.8), maize (corn, 37.5), cotton (15.5), and canola (5.9). Herbicide tolerance has been the predominant biotech trait with 79 million hectares (of a global total of 125 million hectares), next were stacked traits (27 million hectares), then insect resistance (19 million hectares).

In 2010 Monsanto and Dow Agrosciences introduced stacked transgenic corn with 8 traits including resistance to insects above and below the soil as well as tolerance of some common herbicides. It is claimed that this variety will reduce the refuge area for corn planting from 20% to 5%. (The refuge is a fraction of the area of a crop that is planted to non-transgenic crops to generate enough insecticide-susceptible insects to dilute the resistant ones that eventually develop in the transgenic areas. The rationale for this approach is that insects growing in refuge areas without any incentive to develop resistance will crossbreed with resistant strains, preventing them from becoming dominant.) In addition to pest resistance and tolerance to herbicides, future stacked transgenic crops are expected to have characteristics such as drought resistance, high omega-3 lipid production in soybeans and elevated levels of pro-Vitamin A in Golden Rice.

The disruption of natural ecosystems by cultivation of land and planting agricultural crops provides an excellent opportunity for opportunistic plants — weeds — to grow in competition with the desired crops. To combat weeds, farmers use large quantities of a variety of herbicides. The heavy use of herbicides poses a set of challenging problems. In many cases, to be effective without causing undue environmental damage, herbicides must be applied in specified ways and at particular times. Collateral damage to crop plants, environmental harm, and poor biodegradation leading to accumulation of herbicide residues and contamination of water supplies are all problems with herbicides. A number of these problems can be diminished by planting transgenic crops that are resistant to particular herbicides discussed above. The most common such plants are those resistant to Monsanto's Roundup herbicide (glyphosate, structural formula shown in Section 12.1).

This widely used compound is a broad-spectrum herbicide, meaning that it kills most plants that it contacts. One of its advantages from an environmental standpoint is that it rapidly breaks down to harmless products in soil, minimizing its environmental impact and problems with residue carry-over. By using "Roundup Ready" crops, of which by far the most common are transgenic soybeans, the herbicide can be applied directly to the crop, killing competing weeds. Application when the crop plants are relatively small, but after weeds have had a chance to start growing, kills weeds and enables the crop to get a head start. After the crop has developed significant size, it deters the growth of competing weeds by shade that deprives the weeds of sunlight.

Aside from weeds, the other major class of pests that afflict crops consists of a variety of insects. Two of the most harmful of these are the European corn borer and the cotton bollworm, which cost millions of dollars in damage and control measures each year and can even threaten an entire year's crop production. Even before transgenic crops were available, *Bacillus thuringiensis* (Bt) was used to control insects. This soil-dwelling bacterium produces a protein called delta-endotoxin. Ingested by insects, delta-endotoxin partially digests the intestinal walls of insects causing ion imbalance, paralyzing the system, and eventually killing the insects. Fortunately, the toxin does not affect mammals or birds. Bt has been a popular insecticide because as a natural product it degrades readily and has gained the acceptance often accorded to "natural" materials(many of which are deadly).

Genetic engineering techniques have enabled transplanting genes into field crops that produce Bt. This is an ideal circumstance in that the crop being protected is generating its own insecticide, and the insecticide is not spread over a wide area. There are several varieties of insecticidal Bt, each produced by a unique gene. Several insecticidal pests are well controlled by transgenic Bt. In addition to the European corn borer mentioned above, these include the Southwestern corn borer and corn earworm. Cotton varieties that produce Bt are resistant to cotton bollworm. Bt-producing tobacco resists the tobacco budworm. Potato varieties have been developed that produce Bt to kill the Colorado potato beetle, although this crop has been limited because of concerns regarding Bt in the potato product consumed directly by humans. Although human digestive systems are not affected adversely by Bt, there is concern over its being an allergen because of its proteinaceous nature.

Virus resistance in transgenic crops has concentrated on papaya. This tropical fruit is an excellent source of Vitamins A and C and is an important nutritional plant in tropical regions. The papaya ringspot virus is a devastating pest for papaya, and transgenic varieties resistant to this virus are now grown in Hawaii. One concern with virus-resistant transgenic crops is the possibility of transfer of genes responsible for the resistance to wild relatives of the plants that are regarded as weeds, but are now kept in check by the viruses. For example, it is possible that virus-resistant genes in transgenic squash may transfer to competing gourds, which would crowd out the squash grown for food.

Future Crops

The early years of transgenic crops can be rather well summarized by soybeans, corn, and cotton resistant to herbicides and insects. In retrospect, these crops will almost certainly seem rather crude and unsophisticated. In part, this lack of sophistication is due to the fact that the genes producing the desired qualities are largely expressed by all tissues of the plants and throughout their growth cycle, giving rise to problems such as the Bt-contaminated corn pollen that may threaten Monarch butterflies or Bt-containing potatoes that may not be suitable for human consumption. It is anticipated that increasingly sophisticated techniques will overcome these kinds of problems and will lead to much improved crop varieties in the future.

There are many potential green chemistry aspects from genetic engineering of agricultural crops. One promising possibility is to increase the efficiency of photosynthesis, which is only a few tenths of a percent in most plants. Doubling this efficiency should be possible with recombinant DNA techniques, which might significantly increase the production of food and biomass by plants. For example, with some of the more productive plant species, such as fast-growing hybrid poplar trees and sugarcane, biomass is competitive with fossil fuels as an energy source. A genetically engineered increase in photosynthesis efficiency could enable biomass to economically replace expensive petroleum and natural gas for fuel and raw material. A second possibility with genetic engineering is the development of the ability to support nitrogen-fixing bacteria on plant roots in plants that cannot do so now. If corn, rice, wheat, and cotton could be developed with this capability it could save enormous amounts of energy and natural gas (a source of elemental hydrogen) now consumed to make ammonia synthetically.

A wide range of other transgenic crops are under development. One widely publicized crop is"golden rice" which incorporates β-carotene in the grain, which is therefore yellow, rather than the normal white color of rice. The human body processesβ-carotene to Vitamin A, the lack of which impairs vision and increases susceptibility to maladies including respiratory diseases, measles, and diarrhea. Since rice is the main diet staple in many Asian countries, the widespread distribution of golden rice could substantially improve health. As an example of the intricacies of transgenic crops, two of the genes used to breed golden rice were taken from daffodil and one from a bacterium! Some investigators contend that humans cannot consume enough of this rice to provide a significant amount of Vitamin A.

As of 2010, transgenic alfalfa and sugar beets resistant to glyphosate herbicide were being promoted for agricultural use. Alfalfa is a nutritious forage crop for animal feed, a legume that grows synergistically with nitrogen-fixing *Rhizobium* bacteria growing in nodules attached to its roots. In 2010 the U.S. Supreme Court overturned a lower court decision that had prevented widespread distribution of these crops because of the possibility that their glyphosate-resistant qualities might spread to other plants and violate restrictions on foods designated as “organic” and that some countries have put in place against all transgenic food.

Work continues on improved transgenic oilseed crops. The one getting the most attention is canola, the source of canola oil. Efforts are underway to modify the distribution of oils in canola to improve the nutritional value of the oil. Another possibility is increased Vitamin E content in transgenic canola. Sunflower, another source of vegetable oils, is the subject of research designed to produce improved transgenic varieties. Herbicide tolerance and resistance to white mold are among the properties that are being developed in transgenic sunflowers.

Decaffeinated coffee and tea have become important beverages. Unfortunately, the processes that remove caffeine from coffee beans and tea leaves also remove flavor, and some such processes use organic solvents that may leave undesirable residues. The genes that produce caffeine in coffee and tea leaves have now been identified, and it is possible that they may be removed or turned off in the plants to produce coffee beans and tea leaves that give full-flavored products without the caffeine. Additional efforts are underway to genetically engineer coffee trees in which all the beans ripen at once, thereby eliminating the multiple harvests that are now required because of the beans ripening at different times.

Although turf grass for lawns would not be regarded as an essential crop, enormous amounts of water and fertilizers are consumed in maintaining lawns and grass on golf courses and other locations. Healthy grass certainly contributes to the “green” esthetics of a community. Furthermore, herbicides, insecticides, and fungicides applied to turf grass leave residues that can be environmentally harmful. So the development of improved transgenic varieties of grass and other groundcover crops can be quite useful. There are many desirable properties that can benefit grass. Included are tolerances for adverse conditions of water and temperature, especially resistance to heat and drought. Disease and insect resistance are desirable. Reduced growth rates can mean less mowing, saving energy. For grass used on waterways constructed to drain excess rain runoff from terraced areas (see Figure 11.6) a tough, erosion-resistant sod composed of masses of grass roots is very desirable. Research is underway to breed transgenic varieties of grass with some of these properties. Also, grass is being genetically engineered for immunity to the effects of Roundup herbicide (see above), which is environmentally more benign than some of the herbicides such as 2,4-D currently used on grass.

An interesting possibility for transgenic foods is to produce foods that contain vaccines against disease. This is possible because genes produce proteins that resemble the proteins in infectious agents, causing the body to produce antibodies to such agents. Diseases for which such vaccines may be possible include cholera, hepatitis B, and various kinds of diarrhea. The leading candidate as a carrier for such vaccines is the banana. This is because children generally like bananas and this fruit is readily grown in some of the tropical regions where the need for vaccines is the greatest.

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