Controversies in Science and Technology

From Maize to Menopause

Edited by

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Introduction of Transgenic Crops in Centers of Origin and Domestication

Paul Gepts

In 2003, farmers worldwide planted transgenic crops over about sixty-five million hectares, or 5 percent of total arable land area (James 2003; Food and Agriculture Organization 2004), Most transgenic crops are grown in four countries, the United States, Argentina, Canada, and China. The United States and Argentina together account for nearly 90 percent of transgenic production, with Canada and China accounting for most of the remainder. In the United States, the major transgenic crops are herbicide-tolerant soybean *(Glycine max)*, lepidopteran insect-resistant cotton (mainly upland cotton, or *Gossypium hirsutum)*, and lepidopteran insect--resistant and herbicide-tolerant maize *(Zea mays);* in Argentina, herbicide-tolerant soybean; in Canada, herbicide-tolerant canola; and in China, lepidopteran-resistant cotton. The shared characteristic of these countries is that none is actually located in the center of genetic diversity and domestication of their respective transgenic crops. Cotton and maize originated in Mesoamerica (Brubaker and Wendel1994; Wilkes 2004), soybean in China (Shimamoto et al. 2000; Li et al. 2001), and oilseed rape presumably in Europe (Sauer 1993). With the exception of oilseed rape, which originated a few centuries ago (Sauer 1993) and has not been fully domesticated yet, the other crops have a history that stretches through several millennia in their respective centers of domestication.

Since Vavilov (1926),[1] it has been known that genetic diversity of crops is unequally distributed across the globe. For many crops, it is possible to identify certain areas with a high level of genetic diversity compared with other areas. Often, these areas correspond also to the center of domestication namely, the process whereby a wild plant is subjected to a selection process conducted under human influence to increase adaptation to cultivated conditions and usefulness to consumers of the harvested products such as grains, fruits, and fibers. Domestication also includes selection for adaptation to new environments, as crops were dispersed from their original centers of domestication to other regions or continents (Gepts 2004a). Many of the domestication centers are actually located in megadiversity centers. Of the seventeen megadiverse countries, at least ten belong to a center of crop domestication (Brazil, China, Colombia, Ecuador, India, Indonesia, Malaysia, Mexico, Peru, and Venezuela).

There is no a priori reason why the introduction in a center of crop domestication of a new cultivar, even a transgenic one, should be cause for alarm. However, several aspects distinguish centers of domestication from other areas where a crop is grown. The different aspects include environmental, agricultural, sociocultural, and intellectual property rights issues. In this chapter, I will discuss each of these aspects and argue that the introduction of transgenic crops into centers of domestication should proceed only with caution, if at all. Many of my examples will address the situation of maize in its homeland (now called Mexico). However, similar arguments can be used for other crops in their respective centers of origin.

Environmental Issues

Gene Flow and Genetic Diversity

The foremost environmental issue is the presence of sexually cross-compatible relatives, whether domesticated or wild. The wild types may he directly related to a crop as progenitors or they may he indirectly related as neighboring taxa. Domesticated relatives are local, farmer selected cultivars, also called landraces. Both wild and domesticated relatives fulfill important roles as reflections of sociocultural identities, production capital of farmers, and repositories of genetic diversity for plant breeders and farmers alike.

An important feature of these domesticated or wild relatives is that they generally cross readily with introduced cultivars. This feature sets the

stage for potentially extensive gene flow in domestication centers between transgenic cultivars and their relatives. On the one hand, crops have evolved to increase self-pollination, which would reduce gene flow among cropvarieties.[2] On the other hand, relatives of transgenic crops may have a more extended flowering time, thus increasing the probability of gene flow. In addition, for animal-pollinated crops, the presence of insect or other animal pollinators that have coevolved with the plant host in centers of domestication may also increase the potential for outcrossing.

Transgenic cultivars present certain issues that arc unique and differ from nontransgenic cultivars in terms of the introduction of transgenes through gene flow. It has often been stated that the transformation process does not carry any inherent risks that do not exist in conventional, sexual transfer. Therefore, the product of the gene transfer, rather than the gene transfer process itself, should be regulated. Carrying this idea to a logical conclusion suggests that certain products of classical plant breeding should also be regulated (Gepts 2002). However, there is a dearth of information about the stability of insertion and expression of transgenes in new genetic backgrounds, especially in centers of domestication where genetic backgrounds may differ considerably from those in which transgenes were originally introduced. It also remains to be seen whether and to what extent this concern extends to nontransgenic cultivars as well.

Gene flow from transgenic cultivars to native materials in centers of domestication has two potential consequences. First is a risk of accumulation of different transgenes in these native materials (called stacking), which may then serve as relays for the unwanted introduction of transgenes to other plant materials, destined fix food or organic production. This could be particularly true for pharmaceutical or industrial compounds, which are highly undesirable in the food chain. However, no foolproof methods yet exist for keeping food and nonfood uses of crops separate. Even in the current seed production systems, transgenes are contaminating nontransgenic seed stocks at a low but measurable level (Friesen, Nelson, and Van Acker 2003; Mellon and Rissler 2004). The problem is even more marked in centers of domestication because the possibilities of physical isolation are more limited, given the presence or sexually compatible relatives. Accumulation of transgenes may also lead to untested combinations of these genes in the same plant.

Second, gene flow may affect the genetic diversity of the landraces and wild relatives in a number of situations. A genetically uniform source population (such as an improved or hybrid cultivar), high and recurrent levels of migration from the source to the recipient population (i.e., landraces), short distances (depending on the flowering biology of each crop), and/or a combination of these factors can lead to a potentially severe reduction in genetic diversity of the recipient populations and even genetic assimilation (defined as the displacement of the local diversity by the incoming diversity). Transgenic cultivars would not have a monopoly of displacement of genetic diversity. Actually, the development of uniform, elite cultivars by classical breeding has reduced genetic diversity.

The key factor is the degree of uniformity of the improved cultivars. In recent decades the trend has been toward concentration of breeding activities in both the public and private sector. For example, research centers such as the International Maize and Wheat Improvement Center, the International Rice Research Institute, and the International Center for Tropical Agriculture have bred cultivars with wide adaptation that presumably can be grown over broad areas. In the United States, the seed industry has witnessed two rounds of consolidation induced by the availability of molecular biology tools and the application of intellectual property rights to living organisms and basic biological processes. Before this situation existed, breeding programs tended to be smaller and with a more local focus, which maintained a broader range of genetic diversity.

Ecosystem Effects

In addition to concerns about gene flow, it is important to consider that the environments in centers of domestication are quite different from those where transgenic cultivars are grown today, as illustrated by a brief discussion of Bt crops (transformed with the gene for the *Bacillus thuringiensis* [Bt] toxin). Not only are the pests in centers of domestication like Mexico, different, but nontarget organisms (e.g., nonpest lepidopteran and coleopteran species in the case of the Bt toxin) are also quite different. Studies have primarily been conducted in the United States and Europe. For example, following the initial observation by Losey, Rayor, and Carter (1999) of the susceptibility of the monarch butterfly to the Bt toxin, more detailed analyses were conducted (after the regulatory release of transgenic maize), which concluded that the effects of Bt on the monarch butterfly were minimal in the short term in the conditions of the Midwest (Sears et al. 2001 and references therein) but not necessarily in the long term (Scriber 20001). Similarly detailed studies are lacking in

domestication centers, so we do not know the implications for insects in these areas.

Letourneau, Hagen, and Robinson (2002) established a list of about 370 lepidopteran species associated with maize. Of these, only eleven had been examined for their susceptibility to the Bt toxin. Letourneau, Robinson, and Hagen (2003) evaluated what might happen if transgenes escaped into relatives of cotton, rapeseed, and rice by examining lists of sexually compatible relatives, host ranges of lepidopterous insects, their susceptibility to the Bt toxin, and information about the ability of these insects to limit plant growth. They concluded that data are insufficient to establish a risk of ecological release associated with the escape of transgenes among relatives of the three transgenic crops studied. An additional concern may be the effect on certain pollinating, parasitoid, and predator insects (Groot and Dicke 2002). Wolfenbarger and Phifer (2000) present a comprehensive view of the need to measure ecosystem risk and benefits resulting from the introduction of transgenic crops.

Agricultural Issues

Farmers in industrial and in traditional or subsistence agriculture (characteristic of the majority of farmers in centers of domestication) play different roles. In industrial agriculture, farmers have a more specialized role, limited to the production of crops. In contrast, in traditional agriculture, farmers play a role in conservation, development of new cultivars, and processing and consumption of crops in addition to crop production. Specifically, farmers in traditional agriculture play an active role in maintaining crop landraces (in situ conservation; Maxted, Ford-Lloyd, and Hawkes 1997). Landraces are defined as locally distributed and adapted domesticated plants, maintained by fanners. Farmers exert selection to maintain different types according to their use in different cropping systems and for different consumer uses.

Farmers are also willing to experiment by bringing in new materials, including improved bred varieties (e.g., Quiros et al. 1992; Bellon and Berthaud 2004), which then may cross with the local materials and generate new materials (process of *acriollamiento*, or creolization; Bellon and Risopoulos 2001). Farmers exchange seeds with each other, primarily with relatives but also with others in the same or neighboring villages or regions (e.g., Almekinders, Louwaars, and De Bruijn 1994; vom Brocke et al. 2003; Nkongolo 2003). Through their experimentation and selection, farmers may assure better adaptation of the planting materials to the local agroecological niches. Thus seeds are not merely an agricultural ingredient (like, for example, fertilizer or irrigation water); they are more aptly considered part of the agricultural capital of the farmer, just as land and equipment are.

Genetic diversity is a prerequisite for the development of superior cultivars by farmers and breeders alike. In addition, for farmers genetic diversity is also insurance against the vagaries of production conditions. Typically, a farmer may plant a mixture of cultivars that have different maturities and adaptations to assure some level of production. However, the continued existence of on-farm diversity is threatened by the loss of farmers through migration to cities and other countries, the spread of industrial monoculture cropping systems, and gene flow from or replacement by modern cultivars. Transgenic crops, to the extent that they are an inherent part of industrial agricultural systems, can be a driver in the potential reduction of genetic diversity. Recurrent gene flow from a uniform crop is more likely to displace native genetic diversity, as I mentioned earlier. The combination of intellectual property rights and molecular biology tools has made the development of transgenic cultivars by the private sector possible (Gepts 2004b). Concurrently, the seed industry has been consolidating, so that a few companies now dominate the seed market for several crops, such as maize and cotton. This market concentration raises the possibility that the elite domesticated gene pool will become even more depleted of genetic diversity (Gepts and Papa 2003).

To avoid such a situation in centers of domestication, the transgenic construct could be made available to breeders who could incorporate it into local varieties and thus maintain a more diverse genetic background. Such a situation exists for transgenic herbicide-resistant soybean in the United States. The glyphosate resistance transgene (used in Roundup Ready crop plants) was made available to many companies and public institutions. As a result, a large set of superior cultivars, representing the current diversity in nontransgenic North American soybean, was used to develop current herbicide-resistant cultivars (Sneller 2003). Individual breeding programs, whether public or private, run the risk of having a narrow genetic base. However, public lines originate from many independent programs and as a whole tend to be more representative of the entire range of elite genetic diversity. In addition, current public programs in-

crease diversity through the use of exotic germplasm (Sneller 2003). Exotic germplasm are plant materials that come from different countries or continents. As such, they are generally not adapted to U.S. conditions, but they carry usefu] traits such as disease or pest resistance. The long-term focus of public breeding programs allows them to use exotic germplasm to introduce these useful traits into advanced cultivars. Exchanges among breeding programs are, therefore, essential to maintaining a gene pool of elite cultivars that is as broad-based as possible.

Minimizing reductions in genetic diversity in centers of domestication because of the use of advanced cultivars, whether transgenic or not, would require a diverse group of breeding programs that actively interchange breeding lines. Plant breeding has proved to be a very successful approach that has not lost any of its power. Adoption of modern breeding methods, such as marker-assisted selection, has greatly increased the power of traditional breeding methods. For example, in the common bean, several diseases such as white mold, go]den mosaic virus, and common bacteria, once considered very difficult, if not intractable, are now amenable to genetic improvement through the use of marker-assisted selection, a broader range of germplasm, and improved screening methods (Urrea et al. 1996; Miklas et al. 2001; Kelly et al. 2003). In this respect, transgenic cultivars can make a contribution when screening has shown the native diversity to be insufficient and breeding to improve a critical trait has not worked. An example is the lack of resistance in maize to the European corn borer in the Midwest for which Bt maize provides a solution (Gepts 2002).

However, adoption of improved cultivars may be limited in certain locations. In Mexico, for example, 80 percent of the maize land is still planted with landraces rather than improved cultivars. There are several valid reasons for this limited adoption, including the varied topography (and attendant multitude of microniches), the underfunding of public breeding programs and agricultural research in general, and consumer preference, which is directed to very specific traits, such as colors, textures, cookability, and shelf-life. One solution to this problem might be to decentralize breeding programs to rural areas where farmers themselves would become more involved in the improvement of their local landraces in collaboration with plant breeders (a process also known as participatory plant breeding; Cleveland and Soleri 2002). Such an approach to plant breeding should be part of a broader goal of achieving self-sufficiency in maize production. In the case of maize in Mexico, A. Turrent (personal communication) has shown that it is possible to raise yield and total production to the point that Mexico becomes self-sufficient for its basic food crop (as well as for its nutritional complement, the common bean).

To make transgenes available-if and when necessary-to a broad section of these programs may require market segmentation for intellectual property rights. This means private companies would have to forgo their royalties for applications in developing countries in order to benefit smallholder farmers, as has been proposed for golden rice (Wai 2003). Another possibility is the public development of transgenic cultivars. The research agenda for transgenic crops should not be determined exclusively by the private sector in industrialized countries. Because the private sector primarily addresses crops with a large market and farmers who can afford to buy seeds, it may not address crops with a smaller market in countries with subsistence farmers. To put transgenic technologies fully to the test, these ought to be designed to fit the agronomic and socioeconomic conditions of smallholder fanners (Chrispeels 2000).

Intellectual Property Rights Issues

One factor driving the development of a transgenic seed industry in the United States and other industrialized countries has been the availability of intellectual property rights over living organisms (Gepts 2004b). The landmark Supreme Court decision in this area was *Diamomd v. Chakrabarty* (447 U.S. 303 [1980]), which set the stage for the award of utility patents for crop cultivars.

The United States is one of only three countries (with Australia and Japan) to award utility patents for crop cultivars. Other countries provide only plant variety protection (PVP) certificates. Utility patents must fit the criteria of novelty, inventiveness, and utility. Unlike the PVP certificates, utility patents do not allow for research exemptions or farmer's exemptions Research exemptions, as allowed by PVP certificates, allow researchers to use patented cultivars as parents in crosses to develop the next generation of improved cultivars. With a farmer's exemption, farmers could harvest patented seeds and replant them on their own land (a practice called seed saving), although they could not sell or give them away to others. Since these exemptions are not allowed by utility patents, developers of genetically modified seeds in the United States have increasingly patented those crop cultivars rather than obtaining the more flexible PVP certificates.

Although utility patents are not available for crop cultivars in most countries, transgenic constructs or methods broadly applicable to plants (i.e., not limited to a specific genotype) are patentable subject matter not only in the United States but in many other countries as well. For example, a transgenic construct carrying the Bt gene or a herbicide resistance gene can be patented. Although a more complete description of intellectual property rights on biodiversity is beyond the scope of this chapter, I do want to note that patent and plant variety protection rights are granted for a limited period (generally twenty years) and a specific place (they are limited to the country that awards them). This being said, patent rights are extremely strong-the courts generally frown on anything that might weaken these rights. For example, patent rights supersede property rights. Ignorance about a patent and lack of intent cannot be used as defense against an infringement accusation. Most surprisingly, gene flow cannot be used as a defense against infringement. Thus, if a company releases a transgenic cultivar, it is not now responsible for the inadvertent escape of transgenes to nontransgenic fields. However, a farmer can be held liable for patent infringement if the patented transgene inadvertently lands on his or her property. This has potential legal implications, especially in centers of domestication where gene flow is particularly widespread.

Although intellectual property rights are limited territorially, their existence nevertheless creates a series of challenges. First, industrialized countries have pushed less-developed countries (where most centers of domestication are located) to adopt intellectual property rights legislation through such mechanisms as the Trade-Related Intellectual Property (TRIPS) agreement, administered by the World Trade Organization (WTO). By joining the WTO, a country commits to the development and enforcement of intellectual property rights legislation. Specifically with regard to crop cultivars, the TRIPS agreement requires countries to provide protection for these cultivars, although not necessarily patenting. The system most often proposed is similar to plant variety protection. Transgenic constructs are still subject to patenting.

The stipulations of intellectual property rights for crop cultivars arc in direct conflict with practices of many farmers in centers or domestication. In traditional agriculture, seed stocks are readily exchanged and arc a public good shared by individuals in communities. This contrasts with individual inventorship and assignment to companies or institutions in industrialized countries. Landraces have been handed down as heirlooms for generations (Zimmerer 1996; Louette and Smale 2000; Perales, Brush, and Qualset 2003), a practice that also makes identification of in-lividual inventors difficult, if not impossible. Furthermore, many landraces are actually mixtures of genotypes and not pure lines, which would herefore not fit the criteria for plant variety protection. Among the stan-lard practices of farmers are to exchange seed materials and let cross-pollination recombine different genotypes, not only in cross-pollinated species but also in self-pollinated species such as the common bean (Bellon and Risopoulos 2001; Perales, Brush, and Qualset 2003; D. Zizumbo and P. Colunga GarcíaMarín, personal communication). In other words, in raditional agriculture, gene flow is a widely accepted feature or practice, whereas in industrialized agriculture it is to be avoided in order to avoid egal troubles related to intellectual property rights or contamination of the seed stock or grains. Thus introduction of Western intellectual property ights legislation in developing countries creates the possibility that local or ndigenous farmers in centers of domestication could be subjected to legal action by the patent holder.

A further consideration is traditional knowledge associated with land-aces. Traditional knowledge refers to information held by local or indige-nous people, in this case with regard to biodiversity (Brush and Stabinsky 1996). Traditional knowledge is an inherent part of biodiversity and a re-source in its own right. For example, Fabricant and Farnsworth (2001) de-ermined that 80 percent of plant-based drugs in Western medicine have had an ethnomedical (i.e., non-western) use identical or related to the current use of the active elements of the plant. With regard to crops, tra-litional knowledge encompasses information about their agronomic or culinary characteristics. Traditional knowledge is an essential aspect of an ndigenous group's cultural survival; it has been developed through generations of intimate contact with the biological materials (Mauro and Hardison 2000). Traditional knowledge is not, however, limited to the knowledge of indigenous people but encompasses knowledge (and asso-ciated heirloom varieties) of local, nonindigenous communities in modern societies as well (e.g., Bérard and Marchenay 1996).

Thus indigenous societies or local farmer groups often practice an in-ormal system of innovation and information dissemination, which does not fit well into a Western-style intellectual property rights system, nor loes the latter offer rewards for past efforts in innovation and conservation hat serve as a foundation for the existence of biodiversity in general and crop biodiversity in centers of diversity in particular. The distinct fea-

tures of the use and conservation of biodiversity in developing countries have led to a call for a separate legal system that recognizes the contribu-tioms of indigenous or local communities. When dealing with crop land-races, this legal system refers to farmers' rights. However, little progress has been made in developing an enforceable legal framework to support farmers' rights in practice (Gepts 2004b).

Cultural Issues

The long and intimate coexistence of people and crops in centers of domestication is reflected in an extensive cultural presence of the crops among the people, indigenous or not, living in these centers. Maize, for example, has multiple food uses in Mexico, its center of domestication (e.g., Kennedy 2003). Its husks are used as wrapping for dishes, its stalks and leaves as forage, and so on. Mexican Spanish contains an abundance of words derived from pre-Hispanic languages. These words are closely related to the preparation and consumption of maize and attest to the long cultural history of the crop in its center of domestication (Salvador 1997). The importance of basic food crops in their center of domestication is re flected also in their inclusion in creation beliefs. The Popol Vuh (Tedlock 1996), the creation story of the Quiche Maya, relates how, after several failed attempts based on different starting materials, Heart of Sky successfully made humans out of maize. Similar observations can be made for other crops in their respective centers of domestication, such as wheat in southwestern Asia and rice in eastern Asia.

This long-term, close association between people and their respective crops in centers of domestication explains some of their behavior, which at first may seem incomprehensible to outsiders. For example, cultivation of maize in Mexico sometimes takes place despite the lack of economic incentives and returns (Perales, Brush, and Qualset 2003). Rather, non-economic motives such as consumer preferences (color, flavor, cooking quality, shelf life before and after cooking) and cultural identity play an important part as well. Breeding programs, whether they involve trans-genic techniques or not, should take these preferences into account. It is not sufficient to consider productivity alone (yield potential, tolerance to abiotic stresses, resistance to biotic stresses). In addition, continued culti-vation of maize, a major food crop, can be justified as insurance in the face of uncertain market conditions, which are characterized by uncertain employment and fluctuating prices, induced in part by international trade agreements.

Emphasis on qualities appreciated by the consumer, in addition to those of importance to the producer, may also be a strategy to assure both the conservation of genetic resources and revenues to the fanner. The European Union has, for example, developed specific designations, such "protected geographic indication" or "protected designation of origin," which could protect local genetic resources and makc their product better known. About five hundred cheese, meat, fruit, and vegetable products are registered as protected geographic indications or protected designations of origin. It remains to be determined whether such attempts at maintaining agricultural and culinary traditions are compatible with the use of transgenic cultivars.

Human and Animal Health Issues

It is beyond the scope of this chapter to address issues related to human and animal health. However, several arguments suggest that these issues need to be addressed in the context of centers of domestication. For example, the genetic composition of human consumers, and therefore the intrinsic reactions to different components included in foodstuffs, may diffcr hom those existing in developed countries such the United States, where transgenic cnltivars have been tested initially. Because some crops are staple crops in centers of domestication, the exposure may vary from that experienced hy human populations in the United States or other countries.

Conclusions

Several issues, including environmental, agronomic, and intellectual property rights, suggest that the introduction of transgenic crops in their respective centers of domestication requires specific attention beyond that devoted to these crops outside the centers of domestication.

A dearth of experimental data often hampers the evaluation of potential risks associated with the introduction of transgenic crops in centers of diversity. Such studies need to he conducted before the introduction of transgenes in domestication centers.

Given several issues that have been raised here, those who want to

introduce transgenic cultivars into a center of genetic diversity and domestication ought to be required to prove that they are safe and can be controlled. There may well be cases in which other approaches, whether genetic or not, will solve the problem while circumventing the issues raised by transgenic cultivars. In turn, these other approaches should also be subjected to comparative risk-benefit analyses.

Delaying or denying the introduction of transgenic crops in centers of origin does not amount to denying the benefits of genetic improvement to the people of these centers. In most cases, classical plant breeding provides a functional alternative that has stood the test of time, although in some limited cases its environmental and human health effects may also need to be monitored.

Transgenic cultivars could playa role if they are specifically designed to address constraints faced by smallholder farmers and fit into the agronomic, environmental, public health, and consumer preferences characteristic of their centers of domestication.

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Notes

1. Nikolai Vavilov (1887-1943), the former director of the All-Union Institute of Plant Industry in St. Petersburg, Russia, was a prominent Russian crop geographer who led countless explorations in Eurasia, Africa, and the Americas. Based on these explorations, he formulated, among others, the theory of the centers of origin of cultivated plants (19926).

2. Plants are characterized by three major reproductive systems. In selfing species (also known as autogamous, or self-pollinating, species), the pollen of a flower is involved in fertilization of the ovules of the same flower. In outcrossing species (also known as allogamous species), pollen is transferred to flowers of other individuals, generally by wind or animals (such as insects or birds). One should keep in mind that the reproductive system of plants may vary to a certain degree. For example, selfing species will generally exhibit some degree of outcrossing, and vice versa for outcrossing species. The transfer of genes, either by pollen or seed, to a new population or location is called gene flow.

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