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Farming a Toxin To Protect Crops, Pollinators and People

Genetically modified crops that produce the pest-killing toxin Bt increase yields and reduce the use of noxious chemical insecticides. But like any powerful tool, they must be used responsibly

By Ferris Jabr | Tuesday, September 3, 2013 | 13 comments

The familiar teardrop eggplant, with its deep purple luster, is but one member of a large and diverse botanical family. Some eggplants are long, lean and pendulous, like smooth-skinned cucumbers. From a distance, ripening kumba eggplants are indistinguishable from miniature pumpkins. And oblong white cultivars that look like they were plucked from beneath chickens and ostriches explain the etymology of “eggplant."

Image: Paranoid, via Wikimedia Commons

Nowhere is the entire spectrum of eggplant shapes and colors more apparent or celebrated than India—the vegetable's birthplace and its second-largest producer worldwide. India grows more than a dozen cultivars of eggplant—or brinjals, as they are known locally—and is home to many wild eggplant relatives as well. Equally multifarious diseases and pests routinely ravage this abundance, but one does more damage than any other. Every year Indian farmers lose around half of their crops to the eggplant fruit and shoot borer—a moth whose larvae eat their way through brinjals in Africa and Asia. In really bad years the larvae may destroy 90 percent of crops.

To combat this vermin, farmers in India slather brinjals in organophosphates and other chemical pesticides that are known to linger in the environment, kill all kinds of beneficial insects and make people sick even at low doses—the kinds of chemicals the U.S. and many other developed countries have banned or restricted. Such applications are often ineffective because the larvae remain concealed and protected within the eggplant itself. Any surviving brinjals are coated with a thick white film of insecticide residue as much as 500 times the maximum permissible level. "The amount of pesticides sprayed on brinjal, cauliflower and cabbage is amazing—frightening," says P. Ananda Kumar, director of the Institute of Biotechnology at Acharya N.G. Ranga Agricultural University in Hyderabad, India. "If you saw it you would you never ever touch a vegetable in India."

Starting in the mid 1990s, Kumar and other scientists working for both universities and biotechnology companies in India—including Mahyco, a seed company partially owned by Monsanto—began devising a way to deter the fruit and shoot borer and dramatically increase eggplant yields without using so many noxious insecticides. They would still rely on a toxin to kill the larvae, but instead of synthetic chemicals they would use poisonous proteins produced by a common soil bacterium called *Bacillus thuringiensis* (Bt)—toxins organic farmers had safely used as a form of biological pesticide since the 1920s. Rather than formulating a spray or powder, though, the researchers were going to borrow the bacterium’s toxin-making gene and insert it into the eggplant’s DNA so the plant could produce Bt toxin on its own. The resulting Bt eggplants would kill only the fruit and shoot borer and possibly closely related species, leaving other insects and creatures unharmed.

Mahyco succeeded in creating Bt eggplant seeds and, in collaboration with Cornell University and the U.S. Agency for International Development, gave them to several Indian universities, where researchers began to breed them with local brinjal varieties. The plan was to sell the insect-resistant offspring to rural farmers for very little money or dispense them for free. By 2009 different teams of scientists had produced several types of Bt brinjals and extensively tested them to make sure they were not poisonous to people or animals and that wild eggplant relatives would not become less diverse or too unruly if they exchanged pollen with genetically modified (GM) strains. In October 2009, based on the recommendations of expert committees, the Indian government approved Bt brinjal for commercialization.

But Indian Environment and Forests Minister Jairam Ramesh intervened. Thousands of angry and alarming faxes and e-mails from Greenpeace and other anti-GM organizations flooded Ramesh's office. Several scientists known to oppose genetic modification urged Ramesh to ban Bt brinjal. And farmers riled up by the opposition protested in the streets. Opponents argued that, despite the safety testing—and despite the fact that farmers in India had grown Bt cotton since 2002 with great success—Bt brinjals endangered people's health and the environment. In February 2009 Ramesh imposed a moratorium on the release of Bt brinjals until India arrived at a "political, scientific and societal consensus" about their safety and benefits.

What many consider a disastrous imbroglio continues to stew in India. "Most of the concerns raised are devoid of any logic and not based on any proper scientific analysis," Kumar says. "Science has taken a backseat to politics." Elsewhere, after nearly 20 years of growing Bt corn, cotton and soybeans around the world and almost 100 years of using Bt sprays, researchers have reached a consensus about many of Bt's advantages and risks. At this point, the evidence overwhelmingly demonstrates that Bt toxins are some of the safest and most selective insecticides ever used. Claims that Bt crops poison people are simply not true. When properly managed, Bt crops increase yields and make croplands far friendlier for insect populations as a whole by reducing the use of broad-spectrum chemical insecticides that kill indiscriminately. Fewer chemical sprays also translate to cleaner grains, legumes and vegetables mixed into processed foods and sold whole in the produce aisle.

Bt crops are not entirely benign, however, nor are they a panacea. Despite the unparalleled specificity of Bt toxins, recent studies indicate that in a few rare cases they may inadvertently kill butterflies, ladybugs and other harmless or helpful insects, although so far there is no solid evidence that they poison bees. Even more concerning, agricultural pests can, will and have become resistant to Bt crops, just as they inevitably develop immunity to any form of pest control. If biotech companies prematurely release new Bt varieties without proper testing or farmers do not take adequate precautions when growing them, Bt crops ultimately fail and, ironically, encourage the use of chemical pesticides they were meant to replace. Most recently, some farmers in the Midwestern U.S. have realized that one kind of Bt corn no longer repels voracious root-chomping beetle larvae.

"Genetic engineering can be a powerful tool and provide opportunities for managing insects we have never had before, potentially with far less harmful environmental impact and certainly less threat to human health," says entomologist Kenneth Ostlie of the University of Minnesota. "The true challenge is good stewardship."

Serendipity in the soil

B. thuringiensis is a ubiquitous bacterium that lives primarily in the soil as well as in water, on plants and in grain silos. In times of stress—when nutrition is scarce, for example—*B. thuringiensis* forms an endospore: a resilient, dehydrated version of its former self. Such spores are seriously durable, especially when protected from the elements; one group of scientists managed to revive 250-million-year-old *Bacillus* spores embedded in salt. During the sporulation process, the microbe also produces a diamond-shaped crystal packed with poisonous proteins known as cry toxins. The evolutionary advantage of these crystals remains something of a mystery, but they seem to help the bacteria infect various insects and continue their reproductive cycle within the bugs' bodies. In fact, *B. thuringiensis* conducts most its conjugal activity inside the larvae of moths, beetles, mosquitoes and other insects, rather than in the soil.

In the wild, caterpillars and other larva munching on a plant teeming with *B. thuringiensis* will ingest spores and toxic crystals. Juan Luis Jurat-Fuentes of University of Tennessee and other entomologists have spent years studying what happens next in detail. Once inside the alkaline environment of the insect's intestines, the cry toxins in the crystal separate from one another, bind to proteins embedded in gut cells and create pores that burst the cells. The insect's hemolymph—its equivalent of blood—flows into its intestine and its gut juices seep into its body cavity, which alters the overall pH and impels the spores to germinate. In turn, the reanimated spores release a concoction of chemicals that further predisposes the insect to infection. Within hours all the internal chemical chaos disrupts communication between neurons and paralyzes the insect. Several hours or days later—consumed by a severe infection of *B. thuringiensis* and other opportunistic bacteria—the insect dies and the microbes use its decaying tissues as energy for a frenzied orgy.

People have been manipulating *B. thuringiensis* for their own purposes for nearly 100 years. In 1901 Japanese scientist Shigetane Ishiwata discovered that a particular strain of bacteria was killing large numbers of silkworms. He named the bacterium *Bacillus sotto*. Ten years later, Ernst Berliner rediscovered this same species of bacteria on a dead moth in a flour mill in the German state Thuringia; he gave the species the name that stuck: *Bacillus thuringiensis*. An easily duplicated living creature that killed insect pests without endangering other animals or people was an incredibly serendipitous find. But no one it in the early 1900s could have foreseen the extent to which this microscopic organism would eventually transform agriculture around the world.

Farmers began to use Bt spores and crystals as a biological pesticide as early as the 1920s. France produced the first commercial Bt insecticide, Sporine, in 1938. And the U.S. started manufacturing such sprays in 1958. By 1977, scientists had identified 13 Bt subspecies that made different kinds of crystals, all toxic to different types of moth larvae. Soon enough researchers isolated Bt strains that specifically killed flies, mosquitoes and beetles. Scientists have now catalogued more than 80 subspecies of *B. thuringiensis* and more than 200 distinct cry toxins. In most cases each subspecies and the crystals it produces evolved to kill only one or two insect species, even within the same insect family. *B. thuringiensis* subspecies tolworthi, for example, easily slays fall armyworm caterpillars (*Spodoptera frugiperda*), but is not nearly as lethal to larvae of the oriental leafworm moth (*Spodoptera litura*), which is in the same genus (the taxonomic level just above species).

In the 1980s, as crop pests developed increasing resistance to synthetic pesticides, more and more growers turned to Bt, which became especially popular among organic famers. In addition to their selective lethality, the bacterial toxins degraded in sunlight and washed away in rain, rather than contaminating wild habitat and sources of drinking water. This transience was both appealing and problematic for farmers, however, forcing them to reapply Bt sprays as often as every three days. And Bt formulations contained more than just spores and crystals; they were also full of synthetic chemicals that helped the bacteria spread over and stick to plants. Some of those chemicals were known to poison rodents and other mammals. The rapidly advancing technology of genetic engineering promised a cleaner and more precise way to use Bt. If it worked, farmers would never have to spray Bt in liquid form again; in fact, they could spend far less time and money on typical pesticides in general.

Scientists have several sophisticated tools for modifying plant DNA. Often, they recruit a rather unique and almost uncannily convenient microbe known as *agrobacterium tumefaciens*, which evolved to inject genetic material into plants to aid infection. In 1987 Plant Genetic Systems in Belgium isolated a gene encoding a cry toxin from one subspecies of *B. thuringiensis* and used *agrobacterium* to insert it into the genome of embryonic tobacco plants, creating the very first Bt plant life. That was just the beginning. Biotech companies in several different countries continued to improve this technique. Less than 10 years later, in 1996, the U.S. commercialized Bt corn and cotton. Farmers across the country readily adopted Bt crops because of their obvious benefits. "There's no question that Bt allowed us to grow and harvest more corn," says David Linn of Correctionville, Iowa, who has been farming his whole life. He explains that, before working with Bt corn, he would painstakingly search his fields for the eggs of a pest known as corn borer, trying to figure out when to spray chemical pesticides; the chemicals kill the newly hatched larvae only during a short window of time before they tunnel into the corn and out of reach. He often lost as many as 30 bushels of corn per acre to borers. "Bt corn meant not driving through fields, not spraying toxic chemicals, not using up fuel," he says. "It makes things a whole lot simpler when Bt is in the corn."

As of 2013, 76 percent of the corn grown in the U.S. and 75 percent of the cotton are Bt varieties. In 1996, 1.7 million hectares of genetically engineered crops were grown worldwide (a single hectare is about the size of the grass lawn in the middle of a standard athletic track). By 2012, the number had increased to more than 170 million hectares, at least 58 million of which were plants that produce Bt toxin.

A taste of our own poison

Some opponents of Bt crops and genetic engineering in general contend that government scientists and researchers at universities have not conducted long-term studies, or any studies, on the health risks of GM foods—that such experiments simply do not exist. Even a cursory search of the research literature refutes these claims. The independent nonprofit educational organization Biology Fortified, Inc., hosts a growing online database of 600 GM plant safety studies. Manufacturers have tested every GM food on the U.S. market to make sure they are not toxic and do not cause allergies and began selling such foods only after the U.S. Food and Drug Administration reviewed and approved the results of those tests. It's in the manufacturers' best interest to do so: After all, if something goes wrong after a company markets a GM product, there will be serious legal and financial repercussions.

Scientists at universities with no stakes in the biotech industry have also questioned and rigorously evaluated the risks of *B.*

thuringiensis and its toxins ever since farmers started using Bt sprays in the 1920s. Numerous laboratory and field tests have concluded that Bt is not toxic to fish, birds, mammals or people, even at doses thousands of times greater than what a person or animal would ever encounter outside the lab. Over the years researchers have injected or piped billions of Bt spores and toxic crystals directly into the skin, lungs, blood, stomachs and brains of mice, rats, cows, pigs, hens and quails; time and again the animals survived the experiments with few, if any, ill effects. The same is true for rats that ate one billion Bt spores a day for two years as well as for three successive generations of rats fed Bt corn. Joel Siegel, now at the U.S. Department of Agriculture, spent more than 10 years investigating the toxicity of Bt. "My conclusion was this was a very safe product," he says. "You could probably eat a pound of it and nothing would happen to you."

In the 1950s volunteers for an experiment that today's ethical committees would probably never approve did in fact eat Bt. Each day for five days 18 people ingested one gram of a Bt spray called Thuricide—containing approximately three billion *Bacillus* spores and crystals—and inhaled 100 milligrams of the insecticide. Detailed physical examinations, blood tests and x-rays on the sixth day and five weeks later revealed no unusual or harmful changes. Although no one has ever developed a serious illness or died from ingesting *B. thuringiensis* or Bt crops, research suggests that a small percentage of people routinely or accidentally exposed to plumes or splashes of commercial Bt sprays have suffered skin rashes and irritated eyes. When they work as intended, Bt crops eliminate this danger and reduce workers' exposure to pesticides in general. Bt crops also indirectly improve human health. More than half of corn grown worldwide is infected with fusarium fungi, which sneak into the plants via tunnels formed by boring insects and, once established, produce toxins that damage the kidney, liver, nerves and cardiovascular system if ingested in high doses. Bt crops that kill such insects have 90 percent fewer fungal toxins than conventional crops.

A small minority of anti-GM scientists say that a handful of worrisome studies counter the decades of research demonstrating that Bt is not poisonous to people. In each case the greater scientific community has thoroughly criticized and often outright rejected the supposedly alarming studies because they were flawed, invalid and sometimes masked ulterior motives.

Gilles-Eric Séralini of the University of Caen Lower Normandy in France has published several highly controversial studies purporting that GM plants cause tumors, kidney failure and other maladies in rodents, sometimes killing them, and that Bt toxins harm human cells. Numerous scientists and scientific organizations—including those with no ties to the biotech industry—have excoriated Séralini's experiments, stressing their defects: they have generally lacked the necessary statistical power to rule out illness due to chance; some studies used short-lived, lab-bred rats that are prone to tumors; the experiments using naked cells in petri dishes in no way reflected how the human body comes into contact with Bt; and the studies were often vague on important details or excluded them altogether.

"The authors' conclusions cannot be regarded as scientifically sound," pronounced the exceedingly cautious European Food Safety Authority in a statement summarizing independent evaluations of Séralini's work by Belgium, Denmark, France, Germany, Italy and the Netherlands. Séralini founded the Committee of Research and Independent Information on Genetic Engineering (CRIIGEN) because he regarded safety studies of GM food as inadequate; he has received funding from anti-GM organizations, such as Greenpeace; and he has offered journalists a preview of his upcoming publications only if they agreed not to discuss the research with any other scientists—a strategy science writer Carl Zimmer called "a rancid, corrupt way to report about science." Many journalists agreed anyway.

In other instances the media has exaggerated or essentially manufactured apprehension about Bt toxins. In 2011, a Canadian study claimed to find evidence of a cry toxin—Cry1Ab—circulating in the blood and umbilical cords of pregnant women. Although the study itself hardly mentioned health risks, alarming headlines proliferated. In truth, there was never any cause for concern. Some cry toxins —indeed many different proteins we eat—may in fact survive the journey from intestines to blood more or less whole, but it is by no means an easy feat. First of all, cooking and industrial processing break down and inactivate most cry toxins. The vast majority of food ingredients made from Bt corn and soybeans are mixed into highly processed products like cereals and cooking oils, although some U.S. farmers grow a single variety of Bt sweet corn for the produce aisle (which, presumably, most people would eat cooked). Secondly, cry toxins evolved to work in the high pH environment of the insect gut; our much more acidic low pH stomachs easily destroy them (which has been demonstrated in animal studies and confirmed with experiments using imitation stomach acid). And, if a cry toxin did get past the stomach and intestines into the blood, it would have no way to bind to our cells; it evolved to attach to insect cells that have very different surface proteins. Finally, any rogue cry toxins circulating in our blood are not necessarily from Bt crops. In fact, a far more likely source is organic food that has been treated with Bt sprays or any food with soil residues containing *B. thuringiensis*. Most of us eat small amounts of Bt every day.

Even if cry toxins in our food do not enter the bloodstream, our gut bacteria could grab Bt genes and start pumping out toxins, some researchers and GM opponents have proposed. This is biologically feasible, but highly unlikely. Many bacteria are famous for their ability to sponge up DNA from their surroundings and exchange genes with other bacteria and even with organisms from different kingdoms of life, such as plants. In Japan some people's gut bacteria stole a gene for digesting seaweed from ocean bacteria on raw seaweed the people ate. Perhaps our gut bacteria could pick up the Bt gene from Bt corn. Perhaps, but they have had a similiar opportunity for millions of years because people have always eaten food with some traces of *B. thuringiensis*-laced soil. And there is no reason our intestinal companions would pilfer genes from GM food specifically, rather than from foods of all kinds and the many bacteria they harbor. Plus, if the microbes in our intestines did manage to acquire the Bt gene, they do not necessarily have the right cellular equipment to make the toxin; and even if they made the toxin, it would be harmless to human cells.

Despite the prodigious evidence of Bt's safety, some people still worry about unanticipated illness and worst-case scenarios. A decade-old ruckus surrounding one particular type of Bt maize illustrates that the government can swiftly retract any GM products that slip past safety regulations. In 1998 the U.S. Environmental Protection Agency approved an Aventis (now Bayer) CropScience variety of Bt corn known as StarLink for use in animal feed, but did not allow farmers to grow it for human consumption. Tests indicated that the cry toxin (Cry9C) produced by StarLink plants did not degrade as easily in the human gut as other toxins and might cause allergies, even though it did not match the molecular structure of any known allergens.

In September 2000 a coalition of anti-GM groups discovered StarLink DNA in Kraft's taco shells in Washington, D.C., grocery stores. Evidently, some growers were not strictly segregating StarLink corn from other varieties; the chaotic journey from field to supermarket aisle probably contributed to the muddle as well. In the first-ever recall of a GM food, Kraft, Taco Bell and other food companies yanked millions of dollars' worth of taco shells off the shelves and out of restaurants. More than 30 people reported ostensible allergic reactions to StarLink, but after evaluating blood samples the FDA and U.S. Centers for Disease Control and Prevention found no evidence of true allergies. By November, however, the FDA had recalled another 300 corn-based products and the EPA began regularly screening the food supply for StarLink. Remnants of StarLink have been "virtually nonexistent since 2003," the EPA says on its Web site; the organization is so confident in its disappearance that is has stopped screening.

Collateral damage

How Bt crops threaten insect ecosystems and the environment is much less straightforward than whether they are safe enough to include in our diet. The massive mat of monoculture rolled across the U.S.—vast adjacent fields, each consisting of a single crop—is a relatively new kind of man-made ecosystem that has replaced much more diverse wild habitat. Long before GM plants of any kind, farmland displaced many native species. Still, cropfields are abuzz with life, some of which has evolved to survive on the farm. Overall, Bt crops around the world have been a boon for all kinds of insects and arthropods because this highly selective form of pest control has greatly diminished the use of chemical pesticides that kill buggy friend and foe alike. Bt crops reduced insecticide applications in the U.S. by 56 million kilograms between 1996 and 2011, according to one estimate. A recent experiment examined insect populations in 36 different sites in northern China using data collected between 1990 and 2010. Widespread adoption of Bt cotton buoyed the numbers of ladybugs, spiders and lacewings—all of which eat pests like aphids and do not harm crops.

Some Bt toxins may poison insects other than agricultural pests, but so far this danger seems to be negligible, especially when contrasted with the most likely alternative: the carnage of synthetic insecticides. In a small but widely publicized 1999 study, 44 percent of monarch butterfly larvae that ate milkweed leaves dusted with Bt corn pollen died. Monarch caterpillars feed exclusively on milkweed, and butterflies lay their eggs on milkweed plants growing near and within cornfields throughout the summer, when corn pollen abounds. Many scientists quickly pointed out serious flaws in the study, however, such as the fact that it did not quantify the amount of ingested pollen. Other teams of researchers performed more careful follow-up experiments and concluded that some forms of Bt pollen are harmful to monarchs in concentrations greater than 1,000 grains for every square centimeter of milkweed leaf; only 170 grains per square centimeter, on average, coat milkweed growing among cornfields. Pollen from one of the earliest strains of Bt corn, however—Bt 176—was toxic to butterflies at just 10 grains per square centimeter. A few years later Bt 176 had been largely phased out of the U.S. market.

Accumulating evidence indicates that in a few rare instances, researchers may have overlooked how Bt crops threaten other benign bugs. In a recently published three-year study, researchers found fewer ladybugs among plots of Bt corn than in fields of nonengineered corn—and insects living in the former died sooner on average. Bt corn, however, was still much less harmful to ladybugs than chemical pesticides. As for honeybees and native bee species, studies have consistently failed to find any evidence that Bt toxins hurt the pollinators.

Far more worrying to farmers—and ultimately to ecologists as well—is how quickly destructive insects become impervious to Bt crops. "Any entomologist would be stupid to say you're not going to get resistance," says Brian Federici, an entomologist and Bt expert at the University of California, Riverside. Whenever farmers fight pests the same way over and over again, pests adapt and outwit that strategy. Consider one of the oldest methods of pest control: crop rotation. By growing different kinds of plants in the same field each season farmers can disrupt insects' life cycles. Corn rootworm beetles lay their eggs on corn in the fall so that when their white larvae hatch in the spring they can feast on the plants' roots. But if larvae find themselves surrounded by soybeans instead, they will have nothing to eat. Several species of corn rootworm eventually caught onto this trick. Some have evolved delayed hatching, emerging a year two later than usual, when a farmer is more likely to be growing corn again. Others have adapted by laying their eggs among soybeans instead of corn, since a soybean field will probably be a cornfield the following season.

Farmers will always be in an evolutionary arms race with pests regardless of whether they grow organic, use chemical pesticides or choose Bt crops. Where Bt crops have the advantage, however, is in delaying pest resistance for longer periods of time than any other pest-control strategy—if they are carefully engineered and grown responsibly. Bt crops are most effective when farmers and biotech engineers satisfy two key conditions. First, researchers must make the crop extremely lethal to the target pest, ideally killing 99.99 percent of any invaders. That way if some insects do evolve immunity, they will likely have two copies of the genetic mutation that made them immune; any pest with a single copy of the gene would not have been strong enough to survive. Second, farmers are supposed to grow Bt crops alongside “refuge areas”—blocks or strips of conventional crops where pests can prosper. As a consequence, the few pests that evolve resistance among the Bt crops will mate with the much more numerous susceptible insects in the refuges, diluting the genetic mutations responsible for their immunity and producing offspring that are vulnerable to Bt crops.

This is not a foolproof scheme, but when both biotech companies and farmers follow the rules, it works extremely well. In 1996, when Bt corn and cotton were first commercialized in the U.S., some researchers predicted that pests would evolve resistance within three to five years. In most cases this forecast was far too pessimistic. Farmers in the U.S. have been growing Bt corn designed to slay the European corn borer for 17 years without any evidence of resistance whatsoever. In contrast, when Bt crops do not kill a high enough proportion of insects or farmers do not devote enough land to refuges, Bt can become nearly as costly to farmers and the environment as chemical insecticides.

The EPA requires farmers to grow refuges alongside most, but not all, Bt crops. In general, entomologists recommend refuges comprising between 20 and 50 percent of a given field. In some cases, however, the EPA has lowered its refuge requirements to as little as 5 percent of total acreage. And "for some pests, such as cotton bollworm, refuge requirements have been abolished in large areas because Monsanto produced data suggesting natural refuges would be abundant enough," explains Yves Carrière of the University of Arizona. "Personally, I think it's a risky decision." Data suggests that U.S. farmers have become less compliant with the EPA's regulations over the years; after all, a refuge area will probably endure more pest damage and produce a smaller harvest.

At least three kinds of pests around the world have developed some level of resistance to Bt: one in Puerto Rico, one in the continental U.S. and one in South Africa. Carrière and his colleague Bruce Tabashnik think two other pests in the southeastern U.S. and India may have become less vulnerable to Bt as well, although other researchers disagree. Considering that Bt crops target 13 major pests—and more than 50 different pests overall—that's an excellent track record. Still, despite the general preparedness of farmers and scientists, a few pests evolved resistance to Bt toxin with unexpected swiftness.

The most recent and alarming example in the U.S. is corn rootworm, the story of which is documented in studies by Aaron Gassmann of Iowa State University and his colleagues. The first Bt crops designed to kill rootworm hit the market in 2003. Given the ongoing success with other Bt crops at the time, most researchers thought the pests would evolve resistance in 15 to 20 years. By 2009, however, some farmers in Iowa, Minnesota, Nebraska and other states spotted pockets of Bt corn that had fallen over—a classic sign of root damage. Whereas Bt corn tailored to destroy European corn borer kills 99.9 percent or more of pests, Bt corn engineered to eradicate rootworm is less reliably lethal, killing 85 to 98 percent of the larvae. Biotech companies and the EPA nonetheless figured that the benefits outweighed the risks.

It seems they miscalculated. Unbeknownst to researchers, rootworm populations already had relatively common variants of genes for resistance to cry toxins, explains the University of Minnesota's Ostlie. Perhaps they evolved those genes in response to the ubiquitous presence of *B. thuringiensis* itself. Planting Bt corn only multiplied the frequency of resistance genes by creating an environment in which larvae carrying such genes had the best chance of surviving, mating and laying eggs. And any farmers failing to plant refuge areas made things worse. Some farmers whose Bt crops have succumbed to rootworm have now resorted to chemical insecticides. A similar but even worse situation unfolded in Puerto Rico, where man-made refuges were practically nonexistent and fall armyworm became impervious to Bt corn just three years after the crop's introduction in 2003. By 2007, seed companies had voluntarily pulled that variety of Bt corn from the Puerto Rican market.

In India and other developing countries rural farmers may not know about refuge requirements, if they exist at all; others will outright ignore them because they do not have the space or cannot afford to devote any land to vegetables that will probably become a buffet for bugs. Since introducing Bt cotton in 2002 India has become the second-largest producer of cotton in the world, after China. So far cotton pests are not worryingly resistant. One explanation is that India's farmlands are generally more diverse than those in the U.S., varying greatly within and between districts; the hodgepodge of different crops creates natural refuges. Many researchers argue that concerns about pest resistance should not stand between GM crops like Bt brinjals and the rural farmers that sorely need them. "The general idea is to get the plants out there, monitor changes in pest susceptibility and modify as we go along," says Anthony Shelton of Cornell University, who develops insect management strategies for vegetable crops and has worked extensively on Bt brinjals in India.

To address increasing pest resistance, Monsanto, Syngenta and other biotech companies have started selling seed mixes of 5 to 10 percent conventional corn or cotton and 90 to 95 percent Bt crop. When using such a "refuge in a bag," farmers do not have to go to the trouble of designating sections of their land as refuges; the conventional crops and Bt crops automatically intermingle wherever growers plant the seed mix. Such planting should be especially effective at delaying resistance in species like rootworm, the adult beetles of which tend to mate with nearby insects rather than traveling to a different part of a field. A mosaic of Bt plants and typical crops makes it difficult, however, for farmers to treat only damaged plants with pesticides. Biotech companies have another solution: they are expanding their inventory of "pyramid" Bt crops engineered with two or more toxins against the same bug. Even adding one more toxic protein to a Bt crop makes it far more difficult for pests to acquire immunity because they must not only evolve multiple genetic mutations but also inherit enough copies of each of those mutations to survive. Of course, if an insect has already evolved resistance to one of two toxins a plant makes, there's really only a single hurdle left.

Promiscuous pollen

In parallel to steering insect evolution, Bt crops may also alter other plants in unintended ways by mating with them. Because of differences in the shapes and sizes of pollen grains and the floral pads to which they stick, most plants can only pollinate their own species and closely related ones. Whether genetically engineered or not, many crops pollinated by insects or the wind inevtiably exchange genes packaged inside pollen grains with nearby fields of the same crop—including those owned by different farmers. Cotton and soybean flowers can pollinate themselves without much assistance; their pollen is generally not windborne, but it will hitch a ride with insects when they are around. Corn pollen, however, can travel half a mile in a few minutes in a moderate wind, despite being relatively large and heavy. Most likely, insects and gusts of wind have already scattered genes meant to stay within Bt cornfields—and other genetically engineered crops—among receptive neighbors. With an assist from people and modern transportation, such transactions seem to have surreptitiously crossed country borders as well.

In the fall of 2000, David Quist, then at the University of California, Berkeley, discovered genes from Bt crops in corn growing in the mountains of Oaxaca, Mexico—where GM crops were not approved. Farmers in Mexico may have planted imported GM corn kernels that were intended only for animal feed; once grown, they could have spread their genes to nearby cornfields. Other scientists questioned Quists's results, however, and pointed out inadequacies in the way he tested for introduced genes. In 2003 Allison Snow of The Ohio State University and her colleagues collected kernels from 870 corn plants in 125 Oaxaca fields and searched them for genes from GM crops. They found none. But in two later experiments, Elena Alvarez-Buylla of the National Autonomous University of Mexico and her team scrutinized corn in Oaxaca and discovered the same genetic sequences Quist originally uncovered. “I think it’s inevitable that GM corn has gotten into Mexico and will continue to cross borders,” Snow says. She thinks the incidence is very rare, though, explaining the discrepancies between her studies and later surveys.

Whether such cross-pollination is beneficial or harmful depends entirely on the plants and genes in question and whether you look at the situation from a plant or person’s perspective. In one of Snow’s studies, the offspring of Bt sunflowers and their wild counterparts deterred caterpillars much more effectively than typical sunflowers and produced an average of 55 percent more seeds. That would be fantastic for wild sunflowers but horrifying for farmers in the Midwest who regard the pervasive seed-spewers as weeds that compete with their crops. In the U.S., corn, cotton and soybean have few if any closely related native species, so the chances of Bt genes finding their way into wild cousins are small. In contrast, were Bt brinjal commercialized in India, it could spread the Bt gene among the many different types of wild and cultivated eggplants. Such promiscuity would probably benefit most domesticated cultivars and would be unlikely to give wild weedy eggplant relatives a large enough survival advantage to make them a nuisance. Wild brinjal cousins are already far hardier than the eggplants farmers grow to eat. “Cultivated eggplants are pretty much wimps—they are watered, fertilized and protected,” Shelton says.

For the past four years, much more resilient eggplants have been poised to join corn, cotton and soybeans as the major Bt crops grown worldwide. All the available evidence—including research in India itself—confirms the safety of Bt crops for human consumption and demonstrates that their advantages vastly outweigh their risks. "If you take a global perspective, are things better since Bt crops? Absolutely, yes," says Tabashnik of the University of Arizona. "Now the question is: how can we optimize the use of these crops to maximize benefits?" Yet the moratorium Minister Ramesh originally imposed on Bt eggplants in 2009 stands stalwart with no signs of crumbling anytime soon, even though a new minister took his place. Gorgeous, healthy Bt brinjals exist, but they are trapped in the fenced-off fields of organizations that intended them for the public. "The past three years have been a very, very rough ride," Kumar says. "Environmental lobbies, anti-GM lobbies and anti-biotech lobbies are having a field day, going largely unopposed. Scientists do not speak much and, if they do, they do not speak in loud tones."

On August 23 India’s Supreme Court was scheduled to meet and review a report by the latest expert committee tasked with assessing the safety of Bt brinjals. In the days before the meeting, Kumar tried to stay optimistic, but he knew that, in all likelihood, nothing would change. Indeed, for vague reasons, the report was “not available to the government counsel.” So the eggplant fruit and shoot borer will continue to worm its way into the majority of cultivated brinjals; farmers will keep soaking their crops in pesticides; and, instead of transforming eggplant farming across India to the benefit of millions of people, insects and the environment alike, the plants that could change everything will remain under indefinite house arrest.