"Ronald and Adamchak's clear, rational approach is refreshing, and the balance they present is sorely needed in our increasingly polarized world."—*Science*

TOMORROW'S TABLE

Organic Farming, Genetics, and the Future of Food

PAMELA C. RONALD & RAOUL W. ADAMCHAK

Second Edition

OXFORD
UNIVERSITY PRESS

Oxford University Press is a department of the University of Oxford. It furthers the University's objective of excellence in research, scholarship, and education by publishing worldwide. Oxford is a registered trade mark of Oxford University Press in the UK and certain other countries.

Published in the United States of America by Oxford University Press
198 Madison Avenue, New York, NY 10016, United States of America.

First Edition published in 2008 (hardback)
First Edition published in 2010 (paperback)
Second Edition published in 2018

Library of Congress Cataloging-in-Publication Data
Names: Ronald, Pamela C., author. | Adamchak, Raoul W., 1953– author.
Title: Tomorrow's table : organic farming, genetics, and the future of food /
Pamela C. Ronald, Raoul W. Adamchak.
Description: Second edition. | New York, NY, United States of America : Oxford University Press, 2018. |
Includes bibliographical references and index.
Identifiers: LCCN 2017026975 | ISBN 9780199342082
Subjects: LCSH: Food—Biotechnology. | Organic farming. | Genetically modified foods. |
Genetic engineering.
Classification: LCC TP248.65.F66 R66 2017 | DDC 664/.024—dc23
LC record available at https://lccn.loc.gov/2017026975

1 3 5 7 9 8 6 4 2

Printed by WebCom, Inc., Canada

Contents

Eleven

Who Owns the Seed?

Raoul

I finish work at the farm at 1:30 PM, pick a few vegetables, hop in my car, and head home for lunch. As I turn into our gravel driveway, the car tires crackle, and my stomach growls. I have not eaten anything since breakfast, and I'm hungry. I gather my tea mug and a bag with kale and tomatoes, grab my sweater, and head to the mailbox.

I check the mail every day with a sense of anticipation, hoping for checks and invitations but receiving bills, catalogs, and PennySaver mailers instead. The selection today is mostly junk: a credit card offer, a local coupon book, catalogs, and—wait a second—jackpot! Here is something even better than checks or invitations: this year's new Johnny's Selected Seeds catalog.

Stuffing the mail under my arm, I head into the house and dump everything on the island in the kitchen. Moments later, I find myself sitting in a comfortable chair in the living room with the Johnny's seed catalog. All thoughts of food have vanished, and I am not aware of how I got here. My brain has shifted all its attention to the seeds, the plants, and their traits.

Johnny's Selected Seeds is my source for most of the vegetable seeds for my various organic farming operations. I like Johnny's. The owners cater to organic vegetable farms of all sizes. They sell a lot of seed from other companies and also have developed some of their own varieties. The company's focus seems to be on the more innovative varieties that are early, uniform, and disease resistant. Years of plant breeding research go into developing a new variety. I see from the prices of the hottest varieties that the seed companies that developed them are trying to make back their investment and then some. This seems fair because companies need to make a profit to stay in business, and I wonder how they protect their varieties from being copied by other companies, farmers, or seed savers. I also wonder if I can afford to buy the seed.

Johnny's owners, Rob Johnston and Janika Eckert, are featured on the catalog cover holding a basket full of long, red peppers. It's unusual to picture the owners on the cover of a seed catalog because the vegetables are the stars. Perhaps this is an effort to show how these two are accessible and proud of their product, but it also looks like they are there to protect their latest variety from anyone who might want to steal their seed.

As I browse methodically through the catalog, I cannot help noticing that most of the new varieties are hybrids—pricey hybrids. A hybrid is the offspring from parent plants of the same species but different varieties; the resulting offspring carry one half of the genes from each parent. It sounds simple, but the process of hybridization takes time and effort. A breeder starts by creating two inbred parent lines over many years. To do this, the breeder allows each plant to self-pollinate for many generations until the plant attains genetic uniformity and does not segregate for new traits in the next generation. The breeder then cross-pollinates plants from these inbred lines by placing the pollen (i.e., male gamete) from the parent of one line onto the pistil (i.e., the part carrying the female gamete) from the parent of the other line (see Box 4.1 in Chapter 4). For some reason that is not entirely clear, in some plants, the cross-pollination of inbred parents results in offspring with *hybrid vigor*, which typically means higher yield. Unfortunately, if the farmer replants seeds that the hybrid itself produces, the plants that grow from these seeds are not the same as the hybrid parent—they do not breed true. Instead, the offspring plants include a varied assortment of types because each of the new seedlings inherits an unpredictable mix of genes from the hybrid parent. From the seed company's point of view, this is great. Each year, the hybrid seeds have to be created anew by the seed company. They are expensive for that reason, but most organic growers buy them because the hybrid vigor, uniformity, disease resistance, yield, and sometimes taste are deemed to be worth the extra cost. Most farmers are unwilling to create their own inbred lines by cross-pollination each year. Few have the time to be both a breeder and a farmer. In any case, Johnny's sells many wonderful hybrids: Packman broccoli, Nelson carrots, Ambrosia melons, Big Beef tomatoes. These are my favorites, but the list goes on and on.

G. H. Shull created the first documented, intentional hybrid in field corn in 1909 at Cold Spring Harbor, New York. I do not know whether Mr. Shull realized what he had done for the seed industry. From his writings, it seems he knew that making hybrid seed would be more expensive because it took more time, but he was not sure whether the increase in yield would cover the extra cost of the seed.[1]

It took a while for the idea of hybridization to gain popularity. At first, it was viewed as impractical and too complex, and farmers resented having to buy new seed each year. In 1930, only 1% of the corn crop consisted of hybrid varieties. After several years of drought, however, when hybrids responded better than the traditional varieties, their use rapidly increased. By 1940, 30% of US corn was hybrid. By 1970, hybrids accounted for 96% of the US corn crop.[2]

Today, farmers can buy hybrid seed for popular vegetable crops such as tomatoes, broccoli, melons, peppers, and sweet corn. With the ascent of hybrids, seed companies control the supply of the most widely used varieties, and the seed is much more expensive, albeit commensurately higher yielding, than other types of seed (see Box 4.1 in Chapter 4). In 1920, corn yields were approximately 20 bushels per acre. Today, growers of hybrid corn harvest more than 170 bushels per acre.[3] In a 2014 corn-growing competition, more than 500 bushels per acre were harvested.[4]

Many of the seed companies producing hybrids are large corporations. Similar to the trend in the organic food industry, corporations have been buying seed companies. In January 2005, Monsanto bought Seminis, which had previously purchased Peto Seed and Asgrow Seed. Monsanto now competes for a large segment of the US vegetable seed market. The company that developed genetically engineered corn, cotton, and soybeans now also controls many of the hybrid vegetable varieties organic growers like to grow.

Not all the varieties in the catalog are hybrids. When a parent plant is fertilized by another plant of the same genetically stable population, it is called *open pollination* (OP). The offspring of these parents have traits that very closely resemble those of the parents, and seed can be saved from one generation to the next. Before the invention of hybrids, farmers planted open-pollinated varieties, selected the best, and saved seed from them to plant the next season. Through selection, farmers could direct the evolution of plants for their own ends. An example is tomatoes, which are naturally self-pollinating with a low percentage of out-crossing. The farmer plants a particular variety, then chooses the largest, crack-free, and tastiest ones and saves the seeds. As the farmer continues to select for these chosen traits, the genetic mix of the tomatoes becomes slightly more uniform each year. After many generations, the tomatoes may become a little larger, have fewer cracks, and taste better, but these improvements are limited. If a particular variety only has genes to produce a 5-ounce fruit, the tomato is not going to get much bigger than that unless there is a genetic variant somewhere in the population.

Plant breeders trying to improve a particular open-pollinated variety cross-fertilize it with other varieties within the same species that may have useful traits. After the cross is made and the plant produces seed, the breeder plants the seed and selects for plants that contain the desired trait. The breeder then tries to stabilize the selection so that it breeds true in succeeding generations. The process takes years. At the student farm, we are part of the Organic Seed Partnership, which is funded by the US Department of Agriculture. The group's goal is to develop vegetable varieties that are well adapted to organic production. Some of the varieties we are testing on the farm are ones that university plant breeders, particularly Molly Jahn, Professor of Plant Breeding from Cornell University, have created through crosses. When I asked Matt Falise, a vegetable breeder in the Department of Plant Breeding and Genetics at Cornell, who helps organize the OSP, how long it takes to develop a new open-pollinated variety, he estimated about 8 years. Molly suggests it could take between 3 and 30 years.

Anyone can save seeds from open-pollinated plants, and many companies, organizations, and home gardeners do just that. Groups such as Seed Savers Exchange specialize in saving open-pollinated varieties that may have been passed down by somebody's grandmother or discontinued by a seed company because another variety was developed that was considered an improvement. Many of these older varieties are called *heirlooms*.

I continue browsing through the catalog and get stuck on the heirloom tomato page. The heirlooms most commonly grown around here are tomatoes. Johnny's offers quite a few, including Brandywine, Striped German, Cherokee Purple, and Pruden's Purple. These heirloom varieties usually taste better or are more exotic looking than the hybrid red slicers, but they soften easily, are lower yielding, crack readily, and are susceptible to many diseases. Local organic growers like to grow the heirloom varieties because they sell at $20 to $30 for a 10-pound box, compared with $15 to $25 for 20 pounds of hybrid red slicers.

The most popular heirlooms, such as the Brandywine tomato (which many consider the best tasting), are offered by almost all of the seed catalogs I have. The Territorial Seed Company catalog understates a not-so-endearing trait, "Not a heavy yielding tomato," which probably explains why for many years it was not commercially available. Although a fair amount of Brandywine seed is once again being sold, it is probably not as profitable for the seed producer or the seed company. Johnny's sells it for $11 for 1000 seeds.[5] Compare this with my favorite, the high-yielding, crack-free hybrid Big Beef. Johnny's is selling the same amount of seed for it at $38.45.[6] It does take more work to produce the hybrid, but is it really three times more?

If you want some perspective on heirloom vegetable varieties, find a reprint of *The Vegetable Garden,* written by M.M. Vilmorin-Andrieux and published in 1885. The book has illustrations, descriptions, and growing practices of garden vegetables of France in 1885. It provides a baseline with which to compare today's vegetables with those from 125 years ago. Vilmorin states that for broccoli, "Instead of producing a head the same year in which the plants are sown, it usually does not do so until early in the following spring."[7] Modern broccolis have come a long way since then, with some varieties producing heads within 60 days. On top of that, the broccoli plants described in Vilmorin's book are white headed instead of green! Carrots at the time were sometimes orange but more often red, yellow, or white. Some of the heirloom varieties we use at the student farm, such as Early Nantes carrots, Egyptian beets, and Jersey Wakefield cabbages, are listed in the book. However, most of the varieties I have never heard of, and some of the vegetables seem like they are from a different planet. I wonder where all the genes have gone that coded for these different colors and shapes.

Steve Tanksley and Susan McCouch, geneticists at Cornell University, estimate that modern tomato and rice varieties contain only a fraction of all the possible gene variants present in their wild relatives. Over the years, many of these traits were selected against through domestication and breeding.[8] I imagine that this has happened to virtually all other improved vegetables as well.

Reading Vilmorin's book, I get the sense that humans are driven to breed plants and to come up with something new and better. Ironically, this has meant that diversity is reduced because conventional breeding techniques discard the plants not exhibiting desired traits. As a result, potentially useful genes that encode for traits that cannot easily be seen, tasted, or smelled are lost. Lost genes can be recovered only by going back to the wild ancestors of our crop species and landraces that have been conserved by traditional farmers throughout the world. This is quite difficult to do without help from modern genetic techniques.

Are the beautiful and tasty heirloom varieties protected and owned exclusively by a particular company? No. Organic seed companies such as Seeds of Change have programs to improve the quality of heirloom varieties by growing many individuals of a particular variety and selecting for those that exhibit the best traits. We have done several variety trials for Seeds of Change at the student farm, and I have had a chance to grow and taste many wonderful open-pollinated varieties that are as good as or better than hybrids. Imperial eggplant, Crimson Sweet watermelon, Orange CA Wonder pepper, Kurota carrots, Early Green broccoli, and Viroflay spinach are all very satisfying to grow and eat. However, there is no mechanism for preventing growers, companies, or home gardeners from reproducing and saving (or selling) the seed. For a newly created open-pollinated variety (not an heirloom), the situation is different.

As I leaf through the pages of the Johnny's catalog, I notice another icon used with open-pollinated varieties: PVP. Checking the Key to Vegetable Symbols, I see that PVP is defined as "plant variety protection—unauthorized marketing of seeds prohibited." The PVP Act was enacted in December 1970 to provide intellectual property right (i.e., legal entitlement) protection to developers of new open-pollinated varieties that are propagated by seed.[9] The act was toughened in 1994 to prohibit the sale of farm-saved seed without permission of the variety's owners, and the length of protection was extended to 20 years. Under the PVP Act, farmers may save the seeds of PVP varieties for use on their own fields but they are not allowed to sell them.[9] The purpose of PVP is to encourage the development of new nonhybrid varieties by allowing breeders to recoup money spent on development. I looked at the PVP website, which lists all of the protected open-pollinated varieties, and was amazed by their number and diversity.[10] Although there is some debate over the effectiveness of the PVP Act in protecting the new open-pollinated varieties, there is no doubt that seed companies think it is better than nothing. However, it is not cheap to register a variety. In 2005, the cost was $5150, enough to keep backyard gardeners out of the variety protection business. In an email, the owner of Johnny's Selected Seeds, Rob Johnston, explained the value of PVP:

> We have PVP on several of our own varieties, and we sell many more PVP'd varieties bred by (and PVP'd by) others. Although PVP still allows farmers or gardeners to save seeds for their own use, PVP disallows the variety to be used as a parent in a hybrid and disallows its unauthorized production and marketing. A PVP label acts as a kind of no-trespassing sign, and potential pirates usually avoid the variety. However, if there is a violation, the holder of the PVP has to do the prosecuting. We've never had to pursue anyone.
>
> Hybrids are inherently protected by the fact that the originator maintains the parents and has a monopoly on the seed supply. Some companies, however, PVP parents of hybrids, to prevent one or both from being stolen and used. For the record, I prefer the respect method of protecting intellectual property

> to the legal method (e.g., PVP). If we find that some seed company has stolen one of our varieties, I like to think that I could call them and get them to stop (R. Johnston, personal communication, 2006).

I am about three fourths of the way through the catalog and dazzled by the pictures of plump hybrids and beautiful open-pollinated vegetable varieties, but when I start adding up the bill for my choices, I get into triple digits very quickly. I start to think that maybe we should just grow and save our own seed at the student farm.

Over the past 10 years, we have saved seed from basil, tomatoes, parsley, chard, Stutz supreme melon, arugula, cilantro, onions, watermelons, garlic, and potatoes. In the educational sense, it is fine to save seed. To see your favorite vegetable mature, flower, and make seed is experiential learning at its best. In the farming sense, however, saving seed is often a pain in the neck.

Last year at the farm, my students and I decided to save arugula seed. To get seed from arugula (one of the easiest crops), we needed to leave it in the ground for a couple of months longer than we would have if we had just harvested it for greens. More months in the ground meant more irrigating and weeding, and the bed space being used by the arugula could have been planted with something else. When the arugula went to seed, it produced a lot. Because we did not have a combine or a mechanical seed harvester, we harvested the seed by hand. In the case of arugula, this meant stripping off dried pods of seeds and putting them into a bag. A fair amount of seed was lost as the pods broke in our hands and fell to the ground. After a couple of hours, we had a few pounds of seed mixed with quite a bit of chaff. We were lucky enough to have a simple mechanical seed winnower that more or less separated the seed from the chaff. After another couple of hours of cleaning, we ended up with less weight than we started with but much cleaner seed.

It took a couple of our students 4 or 5 hours to harvest and clean a pound of seed. Johnny's sells a pound of organic arugula seed for $26.15, but even with added tax and shipping, it meant that we were working for about $4 per hour. This does not include the cost of growing the crop. I hope that we covered those costs in the arugula we harvested and sold, but when a farmer is growing a crop just for seed, everything must be done efficiently for it to be profitable.

I recently asked Paul Holmes, a partner in Terra Firma Farms, a successful organic farm in Winters, California, if he saved any seed this year. Terra Firma grosses close to $1 million a year selling through a large community-supported agriculture (CSA) group (a subscription produce service), farmer's markets, and retail and wholesale outlets. Paul said he wanted to save some of the orange heirloom tomatoes called Valencia, for which he was having a hard time finding seed, but he had never gotten around to it. He and everyone else on the farm were too busy to save seed, which is typical of organic farms in this part of California.

In other parts of the country such as New England, New York, the Northwest, and the Midwest (maybe everywhere but California), saving seed is much more common. At a meeting of Organic Seed Partnership participants (where I was the only grower from California), I was amazed at the extent of farmer participation in on-farm variety trials and of seed saving throughout the country. Part of the explanation may be that California growers have higher land costs and therefore cannot afford the field time needed to save seed. Perhaps growing several crops year-round in an agricultural paradise makes one too busy. Another reason might be that in the New York and New England area, the OSP has a mobile seed-cleaning trailer that goes from farm to farm to facilitate seed cleaning by local growers. If this technology were available here, more growers might save seed.

The ability of growers to save seed does help to keep seed companies from getting rich selling open-pollinated varieties. If open-pollinated prices get too high, growers have an incentive to save seed. At reasonable prices, it is easier to let the seed companies provide the seed. The companies also typically do a better job of maintaining seed purity and quality. If hybrid prices get too high, growers can switch to open-pollinated plants instead and save the seeds. This can be a difficult choice if a specific trait such as disease resistance, size, or uniformity is needed. Yields may also be reduced.

Reading about heirloom tomatoes reminds me that I'm still hungry. I would like to eat a sandwich with Brandywine tomato slices, but it's winter, so instead I settle for a couple of quesadillas with salsa and canned heirloom organic Jacob's cattle beans. I sit down to eat, with the catalog again in hand, dripping salsa on the pages.

Although Johnny's caters to organic growers, they do not sell only organic seed. The USDA National Organic Program standards state that organic growers must use organically grown seed if it is commercially available. If not, growers can use conventionally grown seed that has not been treated with any prohibited materials such as fungicides. Johnny's sells some organic seed, but many of the varieties they sell are hybrids, and most hybrids are not organically grown. Until the last couple of years, there were no organic hybrids. Johnny's recently has offered more organic hybrids, such as Red Ace beets and three hybrid sweet corn varieties. I think that organic hybrid seed will become much more common in the next 5 years. Johnny's does offer an increasingly long list of certified organic open-pollinated varieties, with many choices of lettuce, tomatoes, cucumbers, and greens available.

I continue to fill out the order form, my mind filled with all the information and intrigue that lies between the lines of the seed catalog. I value the qualities of hybrids: the higher yield, disease resistance, uniformity, and in some cases (e.g., Nelson carrots), the taste. Although the hybrid varieties are well protected and dearly priced by their developers, I am willing to cough up the money to pay for the traits I value. If the prices get too high, I will shift to open-pollinated varieties. If I get totally fed up with seed prices, I can go back to seed saving.

None of Johnny's seeds are genetically engineered. In the beginning of the catalog, there is a statement indicating that they are proud to be a member of the Safe Seed Initiative, pledging that they do "not knowingly buy or sell genetically engineered seeds or plants." They provide this explanation:

> The mechanical transfer of genetic material outside of natural reproductive methods and between genera, families, or kingdoms poses great biological risks as well as economic, political, and cultural threats. We feel that genetically engineered varieties have been insufficiently tested prior to public release. More research and testing is necessary to further assess the potential risks of genetically engineered seeds.[11]

As I read this, two thoughts come to mind. First, it is odd that the Safe Seed Initiative is concerned about genetically engineered varieties but not varieties grown using pesticides, because the misuse of pesticides is an ongoing problem. In 2012, there were 992 confirmed pesticide injuries in California.[12] As far as I can tell, there were no reported injuries due to genetically engineered varieties in California, the United States, or the world. Although genetically engineered herbicide-resistant crops and crops containing Bt have other issues for organic farmers (see Box 8.3 in Chapter 8) and would not have been my first choices as crops to engineer, they have not physically injured anyone since they were first planted in 1996.[13] They also have not escaped into the wild or created superweeds, and Bt crops have reduced insecticide applications. If the Safe Seed Initiative is concerned about biological risk, why are they not more concerned about pesticide use? If so, It would make sense to advocate for the sale of seeds that require fewer pesticide sprays.

There are only two commercially available genetically engineered vegetable species. Asgrow Vegetable Seeds (now owned by Monsanto) has a few yellow summer squash and zucchini varieties (same species) that are resistant to zucchini yellow mosaic virus, watermelon mottle virus, and cucumber mosaic virus. Syngenta markets a genetically engineered sweet corn that has a Bt gene to control corn earworm and the European corn borer (see Fig. 5.1 in Chapter 5). Because there are only two, Johnny's and other seed companies are not giving up much by avoiding genetically engineered varieties. However, if Johnny's were to drop all the varieties grown with pesticides (i.e., most of the hybrids and a good share of the open-pollinated plants), many varieties would become unavailable.

Second, I notice that the Safe Seed Initiative has clumped all genetically engineered varieties together and has not analyzed each one on a case-by-case basis. To me, this is throwing the baby out with the bath water. Genetically engineered plants on the market confer a range of benefits, including some that fit well with our criteria for a sustainable agriculture (see Box P.3 in the Preface).

It seems to me that the Safe Seed Initiative's policy on genetic engineering slows the development of varieties that could facilitate ecological farming. What if a tomato plant is genetically engineered with another tomato gene? That is the same sort of genetic transfer that occurs with open-pollinated plants in nature or that could be done by plant breeders using traditional methods. The advantage of genetic engineering instead of traditional plant breeding is that only one gene is introduced—the gene that expresses the desired trait—and less time is required. For example, to produce a Brandywine tomato that is resistant to nematodes, you could put the nematode-resistant gene from Red Sun tomato (also sold by Johnny's) into Brandywine. With the addition of only one gene, the heirloom Brandywine would retain all of its tastiness. These tomatoes would not pose any negative economic, political, cultural, ecological, or health threats. If other tomato genes could be put into Brandywine to increase the yield, make it resistant to diseases, eliminate cracking, and make it just a little firmer, you would have a heck of tomato. At a future time, would Johnny's sell the seed? Would organic growers grow it, and would consumers eat it? That may depend on who owns the genes.

Twelve

Who Owns The Genes?

The Seed Industry: Accelerating or Impeding Innovation?

Pam

> The world's next superpower will be determined not just by which country has the most military might but also, and more importantly, by its mastery of the technology required to produce large quantities of food.
>
> Ted Genoways, *New Republic*[1]

In 2012, FBI agents tasked with flushing out international corporate espionage made a startling announcement. Chinese nationals employed by the Chinese seed company, Kings Nower, were caught with "seeds under development by Monsanto, DuPont Pioneer, and LG Seeds."[2] Further investigation revealed that the seeds were likely patented genetic stocks, valued as parents for producing high-yielding hybrid seed. Prosecutors allege that the seed was valued at more than $500 million.[2]

In other words, Chinese nationals were accused of attempting to steal an accumulated 70+ years of corn breeding. The seed resulting from that breeding carries genes encoding valuable traits such as high yield and resistance to diseases, pests, and stresses. This treasure can easily fit into a pocket. Anyone possessing this seed can use genetic engineering or other genetic approaches to further improve its performance.

As this story shows, the global seed trade is a serious business and genetic advances are a critical component in the increasingly high national security stakes of feeding the world. Advances in sustainable agriculture rely in part on our ability to innovate and share agricultural technologies.

In the fall of 2014, I visited Monsanto's research laboratory in St Louis. I was curious about the technologies Monsanto is using to develop high-yielding lines coveted by China. To many consumers, this company has been cast a villain, the face of industrial agriculture. According to its opponents, Monsanto pressures farmers to buy expensive seeds that they do not need.[3] They worry that Monsanto's large share of the seed market and patents limits farmers' choice on the seed they buy. I wanted to find out if this image is accurate.

After I signed in, Janice Person, a former journalist who now serves as Monsanto's engagement director, chatted with me as we walk upstairs. Her job, she told me with a grin, was to "help people better understand stuff." We entered a large room where a giant robot was busy at work, clicking and clanking.

"This is our famous corn chipper," she said pointing to a set of seeds, arrayed in a small plastic dish; each seed was separated from the others. The robot picked up an individual seed and chipped off a piece without damaging the embryo, then the piece was transferred to another plate, where its DNA is extracted and analyzed for its genetic fingerprint. The information gathered through this process helps Monsanto breeders sort through millions of seeds very quickly. Seeds that carry a combination of traits predicted to increase yield or other agronomic properties are planted in the field. Those that are lacking the right combination of genes are discarded or shelved for later use.

As a scientist, I was impressed. In my laboratory, things are much slower. It is not possible for us to survey the entire genome so quickly. We must first plant the rice seed, grow it in the greenhouse, clip off a leaf, and extract the DNA. Our technologies limit us to screening for the presence of a single gene at a time—a snail's pace compared with the automated process of Monsanto's robots. The mechanization allows them to quickly screen the whole genome (i.e., the entire collection of 32,000 genes) to identify traits of potential interest. Breeders can select seeds that are predicted to grow well in a particular environment before planting them, saving time, labor, and greenhouse space. In contrast conventional breeding requires planting the entire lot, then looking for the few individuals with beneficial traits. Breeders using conventional methods often retain fewer than one of every thousand or more plants they grow.

This type of automated genetic fingerprinting is one of the technologies that Monsanto and several other large seed companies are using to generate high-yielding seed. The results are stunning. Today, American farmers average about 160 bushels of corn per acre each year, compared with 60 in Brazil and 27 in sub-Saharan Africa (22 if South Africa is excluded).[4] Chinese farmers average 96 bushels per acre.[5] Although many factors in addition to seed quality affect yield these numbers reinforce Monsanto's fundamental message—that higher productivity, not a return to the methods of the past, is likely to be the true source of agricultural and environmental sustainability. They argue that making each acre as productive as possible will help to meet global food demands and reduce the pressure to bring more land into production.

Through a combination of mergers, Monsanto has accumulated the intellectual property portfolios (i.e., patented technologies, genes, and seed varieties) that has allowed them to expand their share of the seed market.[6,7] As a result, Monsanto is now the world's largest seed company and expects to double its profits by 2019.[8] The potential downside to this success however, is that according to the American Antitrust Institute, an independent competition watchdog, Monsanto's technologies and market power hinder competition, potentially slowing innovation in seed and adversely affecting prices, quality, and choices for farmers.[9,10]

Not everyone agrees with the American Antitrust Institute. According to Dan Sumner, Distinguished Professor of Agricultural and Resource Economics at UC Davis, "the evidence of the net effect of seed and trait ownership versus the vigor of the markets is unclear. It is also not clear that bigger seed companies are obviously bad. Economies of scale in research and sharing of genetic materials with big companies may be better for the economy and for farmers than lots of little companies. I do not disagree with the concern that Monsanto's market power could potentially reduce choices for farmers, but the answer is not obvious." In contrast to commodity crops, such as corn where Monsanto has the majority market share, a diverse number of companies produce and sell vegetable seeds. Greater competition in the vegetable seed industry means greater benefits for farmers.

Whatever your views on Monsanto's business practices, it is clear that many countries are following its example and are now fostering their own seed companies. For example, emerging industrial economies such as China view the seed business and seed biotechnology as a nascent field of innovation in which they intend to compete.[11] In 2013, I visited my friend and colleague Professor Xing Wang Deng in the office of his seed company, Frontier Laboratories, in Beijing, China, to learn more.

"We are developing high-yielding varieties of corn and other crops that will rival the productivity of seeds produced by multi-national companies," Xing

Wang told me. "We are competing for a share of Monsanto's seed market." According to Nathanael Johnson, journalist at the environmental magazine *Grist*, the lower yields obtained by Chinese farmers compared with US farmers indicate that there is a lot of room for genetic improvement.[12]

Agricultural official Han Jun agrees: "We cannot lag behind others in the GMO research. Our GMO market should not be saturated by foreign brands."[13] I have little doubt that Xing Wang and his colleagues will be successful. Chinese scientists have a long track record of innovative breeding and have pioneered the development and use of rice hybrids, which yield 20% more than conventional rice varieties.[14] The annual yield increase is enough to feed 60 million people.

Chinese researchers are also leaders in isolating individual genes and entire pathways that govern important traits such as tolerance to drought and efficiency in nitrogen uptake. These are big challenges for breeders. If Chinese scientists are successful in creating a thriving Chinese seed industry and can produce seed that will grow well in China's diverse farming environments, it will be a boon to the Chinese economy and will help Chinese farmers produce more food on less land. In 2016, Chinese officials announced a $450 billion dollar investment to improve the country's farms over the next 4 years.[12] This investment in scientific research benefits agricultural science around the world. According to Dan Sumner, "The planet depends on China's science. This is not just for Chinese consumers but for all of us."

China has changed dramatically since my first visit in 1993. Gone are the Mao suits and the threadbare dormitories that packed four students and a hot plate into a tiny room. Today, Beijing and the major east coast cities are a bustle of brightness and sound—men and women dressed in colorful fashions, massive shopping malls blasting the music of the US rock band One Republic, and Red Bull advertised on umbrellas in the courtyards of Buddhist temples. Instead of millions of people commuting to work on bicycles, the streets are clogged with cars. The large cities have food available on every corner—not only the traditional favorites of roasted salted cabbage, braised ferns, fried mushrooms, barley tea, and steamed dumplings, but hamburgers, French fries, donuts, soft drinks, and candy.

Despite these signs of wealth, the government of China grapples with a mammoth task—feeding its 1.4 billion people, equivalent to almost a fifth of the world's population. To do this, they either must produce food in the country or import food from other countries. Of the 3.7 million square miles of land in China (slightly larger than the land mass of the United States), only 15% is suitable for cultivation (in the United States, about 50% of the land is suitable for farming).[15] This means that China's 300 million farmers must be efficient; to be self-sufficient, they must feed more people on less land than the 3.2 million farmers in the United States.[16] As the population grows, this is an increasingly difficult task.

China is no longer able to meet the country's growing demand for grains, soybeans, and other crops by producing these crops inside the country. China has become a huge importer of food commodities and products as well as a large exporter. Exporting food might seem counterproductive if what they are trying to do is feed their own people, but although China is not self-sufficient, it is no different from most countries that trade food. Its exports help to feed Japan, Korea, and many other countries and is an important part of the national income.

The threats to China's food security are similar to those affecting other countries around the globe. For example, fresh water is increasingly scarce as China's main aquifers become depleted. In neighboring Vietnam, with another 100 million people, according to a 2016 United Nations report, "Water scarcity and climate change are imperiling key crops—rice, cassava, corn, coffee, and cashew nuts. Since the end of 2015, water levels in the Mekong River delta have been at their lowest since records began almost 100 years ago; as of mid-March 2016, almost a million people in central and southern Vietnam lacked access to fresh drinking water."[17]

Having grown up in a community of subsistence rice farmers, Xing Wang is intimately aware of the agricultural challenges confronting growers. He and I were graduate students at UC Berkeley together. During one class, he described his journey from Guanping, a tiny village in China's Hunan Province, to one of the world's premier research institutions. As a child, he walked miles to the nearest school, weaving his way through terraced hillsides of rice paddies. When he was admitted to Beijing University, the families in his village pitched in funds to make it possible for him to afford tuition. The day he left home, he walked 15 miles to the bus stop, and then traveled by bus for 12 hours to catch a train to Beijing. Three and a half days after leaving home, he arrived in the city and began his studies.

In 2013, Xing Wang was elected to the US National Academy of Sciences in recognition of his highly regarded scientific expertise. A few years later, Xing

Wang found that he was so interested in Chinese agricultural problems that he was compelled to go home and offer his expertise in solving those problems. He now serves as founding dean of Beijing University's School of Advanced Agriculture Sciences.

On a walk through the laboratories of his startup company, Xing Wang told me that he wants to build on his experience in plant genetics to help breeders produce high-yielding seed for farmers.[18] If they are able to harvest food more efficiently, they will be able to better feed their families and to sell more grain, making a profit that they can use to send their children to school. Xing Wang is using highly precise genetic tools to engineer the genomes of rice and wheat for this purpose.

Xing Wang believes that high-yielding crops are essential if China is going to be able to grapple with greenhouse gas emissions and pollution. Over the past 300 centuries, the conversion to cropland of 20% of Chinese forests and 40% of its grasslands has triggered massive greenhouse gas emissions.[19] More recently, China's demand for energy and food and the use of outdated coal-burning technologies have created smog that smothers major cities, prompting regular red alerts because of the poor air quality.[20,21] Smog already claims the lives of 1.6 million Chinese each year, or more than 4000 people each day.[22–24]

Until a few years ago, China was able to feed itself, although at an enormous environmental cost. High-volume applications of pesticides, fertilizer, and irrigation water have left soils polluted, salty, and depleted of nutrients while also straining limited water and energy resources. The situation is expected to get worse. "Temperature increases and precipitation decreases could slash China's net yields of rice, wheat, and corn by 13% over the next 35 years," according to an analysis by scientists at Beijing University's Center for Climate Research.[2,25]

Demand for imported corn is expected to surge from about 5 million tons to 20 million tons in just 10 years.[2] Facing a lack of food for animals, China has already increased imports of genetically engineered soybean and corn from the United States.[26] In 2014, China imported about 5% of its food.[27]

Even though there is increasing demand for food, fewer people are available to farm. The youth of China are increasingly drawn to higher-paying jobs in the thriving eastern cities. This migration and urbanization, encouraged by the government, means that the few who are left behind in the village do most of the farming. Some of these are the elderly, with no better choices available.[28] Some who remain are making informed choices about inputs and farming practices, thereby increasing productivity for their families and country.

To enhance long-term food security, locally and globally, China's leaders are redoubling investment in science and technology programs, bolstering basic research, and supporting the development of seed companies. Chinese seed companies have been tasked with establishing the country as a major contributor in international scientific circles, boosting economic competitiveness in world markets, and modernizing the Chinese agricultural sector.[27] One of the goals is to consolidate many of the country's thousands of seed companies into major corporations that will link basic research to large-scale production of seed just like Monsanto.[2] The research of Xing Wang, a global agricultural player with farm-boy roots, is contributing to achieving these goals.

Increasingly in China, as has been the case in the United States for many years, seed companies are developing high-yielding hybrids. Farmers like the traits conferred by hybrids, and this increases demand among high-income farmers who can afford them. However, small-scale farmers (i.e., those who manage 5 hectares or less or who are constrained in terms of capital and labor) typically prefer open-pollinated seeds because they can save the seed and eliminate the cost of purchasing new seed each growing season.

This means that the global seed industry needs to figure out ways to produce high-yielding hybrids and seed stocks (which typically yield more food on a given plot of land) as well as low-cost open-pollinated seeds that can sustain small-scale farmers. The challenge is to accelerate innovation for all farmers, not only those who can afford higher priced seed.

For much of the history of agriculture, plants self-pollinated or cross-pollinated, and seeds were shared. About 40 years ago, plant variety protection and utility patents began to proliferate, contributing to the establishment of the modern seed industry. Today, most plant breeders rely on income from selling their varieties. The Plant Variety Protection (PVP) Act enabled breeders to restrict others from marketing a variety they have developed. However, the PVP Act does permit further breeding with that variety. In contrast, a utility patent prohibits further breeding. Many vegetable seed sold by companies such as Johnny's selected seed is protected by PVP (e.g. lettuce). Hybrids, (e.g. most corn varieties) are protected by PVP or utility patents.

In a landmark decision allowing utility patenting of a living organism for the first time, the US Supreme Court ruled in 1980 (*Diamond v. Chakrabarty*) that a genetically engineered strain of bacteria that could break down crude oil was a proper subject matter for patent protection under the patent statute.[29] The same year, to promote technology transfer and product development in the United States, the Bayh-Dole Act gave universities and other publicly funded research institutions the right to obtain patents on, and commercialize, inventions made under government research grants.[30] According to William Tracy, Chair in Plant Breeding for Organic Agriculture at the University of Wisconsin, "The most important contributor to the modern seed industry was the development of hybrids and associated trade secrets (the inbreds). This is why the modern seed industry is based on corn. And why wheat, which can be protected by both PVP (often) and utility patents (rarely), is still mainly bred by the public sector. Also, why big companies want to turn wheat into a hybrid crop."

One of the benefits of plant variety protection and utility patents is that they grant inventors exclusive rights to use the technology for a set period of time before it becomes public. In this way, patents create an incentive to invest in research and development. According to a National Academy of Sciences 2016 report, "In the specific cases of agricultural crop R&D, the application of patent protection to GE crops means that firms can secure a return on their research investments in GE seeds and thus have an incentive to apply their resources to more agricultural crop research and innovation."[31]

Patents can sometimes spur the process of discovery and development of socially beneficial products. In 2013, the US Supreme Court addressed the validity of gene patents without resolving ethical or moral concerns. The Court ruled that naturally isolated DNA is not patentable.[32] In other words, DNA of a wild flower seed you collect is not patentable. It also ruled that genes that have been isolated and engineered into crops or used for making drugs could continue to be patented. For example, the Bt gene isolated from DNA of a bacteria and then engineered into a plant is patentable.

Despite these benefits, there is intense debate about the ethics of patenting genes and seeds. Some people see all biological material as a public good or a gift from nature or, more accurately, as handed down or improved by many generations of farmers and breeders and therefore something that cannot be owned by an individual or company. A public good is available to people without payment, and its use by one person does not make it unusable by others.

Public goods are traditionally associated with the public sector (i.e., university and government laboratories) and private goods with the private sector (i.e., industry).[31] Genetically improved crops can exist as private or public goods, depending on what kind of intellectual property restrictions developers use to limit access to the germplasm (Boxes 12.1 through 12.3).

BOX 12.1 **Patents on CRISPR-Cas9, The Novel Genome-Editing Technology**

The ways in which patents and intellectual property are handled and owned affect the ability of breeders to access those technologies for commercial use. For instance, consider patent landscape around CRISPR/Cas9, the novel genome-editing technology. The seed giant DuPont Pioneer entered a strategic alliance with genome-engineering company Caribou Biosciences in 2015 that outlined a strategy for the companies to share intellectual property rights for CRISPR/Cas9 applications in plants.[33] As part of the agreement, DuPont and Caribou cross-licensed their respective patent portfolios, with DuPont receiving exclusive intellectual property rights for CRISPR/Cas9 technology applications in major row crops, and nonexclusive rights in other agricultural and industrial bioscience applications. In addition, the alliance between DuPont and Caribou involves a multi-year research collaboration with scientists from the two organizations focused on enhancing the breadth, versatility, and efficiency of the core CRISPR/Cas9 toolkit. DuPont also made a minority equity investment in Caribou to further strengthen the working relationship.

If the technology is made freely available for basic research (which is currently the case) and if the licensing fees for commercial applications are low, it could accelerate innovation. However, if the technology is licensed at a high cost or not licensed at all, it would impede innovation.

To address these concerns, DuPont Pioneer has launched an Open Innovation initiative[34] to establish collaborations, develop innovative technologies and deploy new crop varieties. Chosen collaborators can receive access to germplasm and the most advanced enabling and analytical technologies or services controlled by the company.[35]

As an example of the DuPont Pioneer open innovation model, the company formed a public/private partnership with the International Maize and Wheat Improvement Center (CIMMYT) to jointly develop improved crops using CRISPR-Cas9 technology to address the needs of smallholder farmers around the world. A range of potential product targets are under consideration by the newly formed Pioneer-CIMMYT Steering Committee. The first project will apply CRISPR/Cas9 to address the devastating maize lethal necrosis disease in Sub-Saharan Africa.

BOX 12.2 Access to Genes and Germplasm for Public Breeding Efforts

Germplasm is the term used to describe the combination of genes in a seed that gives each plant its unique properties. An issue of concern for public-sector geneticists and agronomists is the question of access to the full range of germplasm for conducting experiments (e.g., historical germplasm yield trials to understand and quantify genetic progress) and for testing new opportunities to improve crops through conventional and biotech methods. Limited access stifles public-sector innovation.

Corn is a good example. Most large companies apply for utility patents on their new varieties; that is, they patent the combination of genes they have created. This *utility patent* prohibits other breeders from using the proprietary variety as a parent for further breeding. Other breeders are free to try to reconstruct the variety by starting with the publicly available seed stocks in collections such as the American Type Culture Collection.[36] However, without knowledge about how the variety was made, it would take a public breeder many years to reconstruct it. This is one of the reasons that most European countries do not allow patenting of plant varieties. Instead, they use the Plant Variety Protection Act (PVPA) of 1970, which allows further breeding. Monsanto and other seed companies are against this research exemption. They argue that it discourages commercial investment and innovation because, with a plant variety protection exemption, other companies can recreate the varieties in just a couple years. They want to protect their investment. After patenting started in the 1980s, investment in seed companies also took off, and seed development became very profitable. Before patents were in place, soybeans sold for $5 to –$10 per bag. Today, seed can sell for $30 to $40 per bag. At the same time, funds for public breeding efforts decreased. University breeders and hobby breeders often cannot compete because they lack the capital required for advanced breeding (e.g., the Monsanto gene chipper). Utility patents have been a boon to large seed companies, but public breeding has been neglected and limited.

In my experience, researchers at public institutions can access a diverse variety of germplasm to advance basic knowledge on how plants function. In my 25 years as a rice geneticist, overly restrictive patents have never impeded my research. Patent restrictions are largely irrelevant until an invention goes commercial or is needed for a humanitarian application (e.g. Golden Rice). For example, my colleagues and I obtained several important rice varieties from the International Rice Research Institute (IRRI), isolated genes that conferred important traits (e.g., disease resistance, flood tolerance), and then worked with public breeders and institutions to make the genes and varieties available to farmers. The situation is somewhat different for researchers who study corn, a highly profitable crop because it is typically sold as a hybrid. Although academic scientists can collaborate with seed companies to study their proprietary corn germplasm, it often is just as easy to use older seed for their studies-after 20 years, the proprietary protection expires. According to my colleague Jeff Ross-Ibarra, UC Davis, "For basic research, we can use the older seed and still make important discoveries."

Although most of the corn grown by farmers in the United States is hybrid and proprietary, there remains a robust community of public breeders who are developing open-pollinated sweet corn varieties that farmers can replant every year. For example, University of Wisconsin at Madison agronomy professor Bill Tracy has created a new variety of sweet corn that is open pollinated. The seed of open-pollinated varieties can be saved and planted from year to year to produce the same plant.[37]

If too much global germplasm becomes tied up with for-profit seed companies that are not willing to license the valuable genetic stocks at reasonable prices, the ability of small companies to develop new seed varieties would be restricted. This provides an incentive for stealing rather than collaboration. The term *stealth seeds* refers to stealing or trading seeds to avoid payment of licensing fees or other constraints. The Bowman vs. Monsanto Supreme court case (Box 12.3) and the story of the Chinese nationals (this chapter) reflects this outcome. Other countries have experienced similar situations. In Brazil, there was widespread smuggling of herbicide-tolerant soybeans from Argentina[38,39] before they were legally commercialized. Similarly, in India, counterfeit Bt cotton was passed around widely before its sale was made legal.[40,41]

Often, patents on new technologies is less of a hindrance than the slow process with which genetically engineered crops are regulated (see Box 5.6 in Chapter 5). According to Plant Science Professor Kent Bradford, innovations in DNA sequencing and computer technologies have moved quickly because each company tries to do better than its competitors—even though most of the necessary technologies are patented. "If the regulatory system for evaluating new plant varieties were more efficient, there would be more incentive to innovate, new varieties would be released faster and humanitarian applications would not suffer," he said.

Some reform in patent regulations is needed. For example, if nonexclusive (as opposed to exclusive) licenses were available for technologies and processes important for advancing research it would encourage innovation. "In this way," say agricultural economist Matin Qaim, "companies can make more money with patented technologies in rich countries, and in poorer countries, the same technologies can be used at a lower cost."

BOX 12.3 ***Bowman v. Monsanto***

Like CDs and DVDs, seeds are readily replicated. The efforts of the music industry to retain control over their products in the face of widespread electronic copying and sharing mirrors the efforts of the seed companies to restrict farmers from replanting their proprietary seed stocks. In both cases, it is illegal for consumers to reproduce and sell the product.

In 2013, the US Supreme Court ruled that Monsanto has the right to guard the profits from their innovations.[42] Monsanto sells their herbicide-tolerant soybeans under a limited-use license that prohibits the buyer from using the seeds for more than a single season or saving any seed produced from the crop for replanting. In *Bowman v. Monsanto*, soybean farmer Verson Hugh Bowman challenged this restriction. He bought Monsanto's herbicide-tolerant soybean from a local source and then planted the seed to produce additional seed. Monsanto sued Bowman for patent infringement.[43] Justice Elena Kagan delivered the opinion of the Court, ruling against Bowman.[42] Kagan stated that Bowman could resell the patented seeds he obtained from the elevator or use them as feed, but he could not plant them and produce additional crops from the seed without the patent owner's permission.

Patenting can slow progress in breeding if the germplasm (see Box 12.2) and genes are removed from the public domain. Some people argue that all seed should be made internationally available because it gives rise to food, and food is not a commodity like smartphones. According to Kent Bradford, Professor of Plant Sciences at UC Davis, "The ability to patent 'natural' genes or traits is concerning. It limits access to germplasm and is a key issue for smaller seed companies these days. Most prefer plant breeders' rights or the plant variety protection systems, which give the breeders rights to their specific variety but do not restrict other breeders/companies from breeding that variety for further improvement. The utility patents on genes/traits stop breeding with that material, and that is a problem. Such patents limit broad access to the source germplasm." Matin Qaim, professor at the University of Göttingen, Germany agrees. He notes that "patenting contributes to industry consolidation, which is not what we want from a socioeconomic perspective." Also he says that it makes licensing negotiations very complex which benefits large companies who can afford sufficient staff to execute agreements.

Most people don't want to see a single company dominate the seed supply. However, as World Food Prize awardee Per Pinstrup-Anderson points out, lawsuits between companies will likely prevent that from happening. Almost all litigation from seed companies is between seed companies. "They sue each other all the time," UC Davis plant biologist, Chuck Gasser, told me.

The National Institutes of Health (NIH) has long recognized that the goals of commercialization of biomedical research could conflict with the broad dissemination of research findings and research tools. In 2000, the NIH established a policy for its grant recipients to promote public access to government funded research and tools.

The US Congress also amended the 1980 Bayh-Dole Act to make clear that the objectives of the patent system is to promote the utilization of inventions arising from federally supported research and development [and] to ensure that inventions made by nonprofit organizations and small-business firms are used in a manner to promote free competition and enterprise.[31]

In 1995, I received first-hand education on the issues of patenting and licensing. My laboratory team had just isolated the rice gene *Xa21,* which confers resistance to a serious bacterial disease.[44] There was tremendous international and commercial interest in using this gene to accelerate plant breeding.[45] In addition to improving crop production in rice, some scientists thought that *Xa21* would be useful for developing new means of disease control in other crops, such as the commercially important wheat, maize, and barley. Deployment of such engineered varieties could reduce the application of pesticides to the environment and reduce patent health risks to farm workers. I wanted to figure out how to further develop this technology for use in crop improvement programs and still make it freely available to less developed countries.

UC Davis filed a patent application covering the *Xa21* sequence in 1995, convinced that without a patent application on file, there would be little commercial interest or overall investment in developing the gene. The next step, licensing the invention, needed to be handled carefully. An exclusive licensing agreement with the private sector, typically preferred by companies because it can be more lucrative, would eliminate the ability of UC Davis to share this technology with other public-sector institutions, such as national and international research centers that are working on new crop varieties for poor farmers in developing countries. Because rice is the most important staple food in the developing world, improvements in rice yield have a significant impact on global food production. If the *Xa21* invention were tied up exclusively by one company, it could impede benefits for the public good.

Because I wanted to make the gene widely available and because the mission of UC Davis is to serve the public, UC Davis agreed to option use of the gene to private companies under the conditions that noncommercial researchers would also have free access *Xa21*. UC Davis and the International Rice Research Institute (IRRI) formalized this arrangement in an agreement giving the IRRI full rights to develop new rice varieties using the cloned *Xa21* gene and to freely distribute the new, improved varieties and the cloned gene to developing countries. National breeding programs could then introduce the gene into locally adapted varieties and be free to distribute the new varieties to farmers. Because the gene is passed on to the progeny, farmers could grow their own seed for the next season. The *Xa21* patent allows for the use of *Xa21* in conventional breeding.

After the exclusivity issue was resolved, I wanted to tackle another, potentially more difficult issue: compensating developing nations for their contributions to the development of new crops and drugs, such as anticancer medications and antibiotics.[46] At the time, there was growing concern that industrialized nations, which have the technology and resources to patent and develop commercial products, do not always equitably compensate developing nation providers of the source germplasm. Although conservation and use of plant biodiversity have benefited food production worldwide (Box 12.4), benefits may not have accrued to the particular country where the crop's genetic material originated.[47–49] In response to these concerns, the Convention on Biological Diversity was founded in 1993. In conjunction, the FAO International Treaty on Plant Genetic Resources established an Access and Benefit Sharing Fund to ensure that the eventual commercial value of plant genetic resources (germplasm, plants, genes or seeds) which originate in one country and are used by breeders in other countries, have a proportional benefit share back to the originating country.[50,51]

BOX 12.4 **The Value of Biological Diversity**

The value derived from biological diversity far exceeds the world's investment in conservation.[47] When plant genetic diversity has been consciously conserved, the rewards have been great. An international system of gene banks established by organizations such as the global CGIAR system, the Global Crop Diversity Trust and the US National Lab for Genetic Resource Preservation (in Ft Collins) conserves extensively collected germplasm for evaluation and use in breeding programs. This genetic conservation is critical to ensure ongoing access to plant biodiversity. The International Rice Research Institute (IRRI) Rice Germplasm Center, for example, preserves 83,000 of the estimated 120,000 rice varieties.[48] The benefits to the world community from work at international centers have been "enormous, with low-income food consumers in developing countries receiving the vast majority of those benefits. The total value of germplasm flowing through international research centers to industrialized countries benefited industrialized countries by more than $3.5 billion annually, while the benefits to developing countries for wheat and rice only were approximately $67 billion annually."[48,49]

One of the difficulties in assessing appropriate compensation is predicting that a particular gene will lead to a marketable product. A single genetic contribution by itself usually represents only a small percentage of the total value of the eventual product. This is why many people think that exclusive ownership of a variety that results from making only a small change is unacceptable. As William Tracy pointed out, "If a variety with a transgene was PVP'ed but not utility patented, I could easily use that variety in my breeding program by allowing the transgene to segregate out of the population." In other words, many people who oppose utility patenting accept PVP ownership because most of the traits remain available.

In this sense, germplasm is similar to a raw resource such as copper. A country such as Chile sells copper and is compensated for the cost. However, Chile does not expect to profit from the additional value of products made from that raw material elsewhere. Although copper is essential to the final product, much more is added to create the final value. In a similar manner, it would make sense to compensate countries that provide a genetic resource. However, if only a single component (i.e., a single gene) is present in the final product (i.e., a seed), the donor would likely not expect to receive a large fraction of the overall value.

Because there was no university precedent for germplasm compensation to source countries and there was no prior agreement governing intellectual property rights, it was not obvious what would be the most appropriate method to recognize and potentially compensate the source country, in this case Mali, for rice carrying Xa21.

I tried to work through the UC technology transfer offices to develop a mechanism to compensate Mali for its germplasm, but the staff members I spoke to were unsure of how to best make this happen. A few weeks later, I flew to the Philippines to attend a meeting to talk about the role of Xa21 in the rice immune response, with the challenge of establishing a compensation mechanism very much on my mind. Coincidentally, I found I was sharing my flight with John Barton, a courtly, intelligent, and thoughtful Professor of Law from Stanford University who had attended the same meeting. As we talked, I discovered that he was an expert on international genetic resources law and technology transfer and was quite interested in my dilemma.

By the time we got off the plane, it was clear that John was willing to help and that he was confident we could overcome the impasse. We decided that the best way to compensate Mali for their contribution would be to establish a fund (called the Genetics Resource Recognition Fund (GRRF)) dedicated to advanced study or conservation of genetic resources there.[52] It was likely to be more beneficial to the source nations than a direct financial transfer because it is usually not possible to determine who should receive compensation as the owner of a specific genetic resource.

By 2016, the *Xa21* gene had been distributed to more than 25 countries and to many researchers throughout the United States. By 2017, Xa21 has been widely used in conventional breeding programs around the world enhancing yields for farmers. Because we were careful to make *Xa21* available to less developed countries, China has been able to move forward in developing genetically engineered hybrid varieties that carry *Xa21* (Box 12.5).[53]

BOX 12.5 **Commercialization of Xa21 Rice in China**

Jia Shirong, a professor from the Chinese Academy of Agricultural Sciences in Beijing said that, after 8 years of laboratory trial and field tests, his team had applied to the government for commercial production of Xa21 rice in the central province of Anhui, an area the size of Italy. In contrast to conventional breeding, which introduces many genes at once and requires years to disentangle the genetics before the new hybrid can be useful, genetic engineering of *Xa21* introduced only this single gene. “The field performance has been excellent,” Jia told Reuters in a telephone interview. “Farmers can reduce yield losses and chemical use. Our research data showed that the transgenic rice is as safe as the traditional rice.”[53] The BIOSafety committee of the Chinese Ministry recommended Xa21 rice for commercialization late in 2004, but it was not released, possibly because of trade problems China could face in light of European consumer opposition to genetically engineered plants.[53]

Our strategy of nonexclusive licensing combined with a contribution to the GRRF was an appropriate approach for *Xa21*, benefitting both public and private domains. It does not, however, makes sense for all genes (Box 12.6). For example, after some consideration, UC Davis did not file a patent application on the *Sub1* genes (see Chapter 1) because the immediate need for this gene was primarily for rice in the developing world. The generation of a commercial product in other crops would probably require years of additional and expensive research, so it did not seem worthwhile to pursue a patent application. We concluded that the public would benefit most broadly if we rapidly placed the *Sub1* gene into the public domain.

BOX 12.6 **The Genetic Resources Recognition Fund**

In June 1996, with the help of Stanford Law Professor John Barton, the University of California at Davis established the Genetics Resource Recognition Fund (GRRF) to recognize contributions of developing nations to the success of UC Davis discoveries.[52] The GRRF was to be funded by royalty income generated from commercialization of genetic materials derived from germplasm originating in developing nations. The goals were to use GRRF funds for fellowship assistance to researchers from developing countries, for farm training projects in the home country, and for conservation of land rich in genetic diversity. The fund was designed to benefit the individuals and farming communities from the same area where the genetic resources were obtained. Students from germplasm-source countries (in this case, Mali) would have first priority. UC Davis hoped that the establishment of this program would set a precedent for universities to recognize and compensate for germplasm contributions from developing nations. We also thought that the GRRF would provide a means for scientists to patent their inventions while maintaining productive collaborations and good relations with scientists from developing countries. It would create economic incentives for continued sharing of germplasm and conservation efforts.

Although the GRRF made no effort to assess the future potential income generated from an invention, it provided a constructive solution that would be easy to implement and could be widely accepted. Because it is virtually impossible to predict the commercial success of a single invention, the GRRF ideally would be funded from many inventions. As of 2017, no commercial product had been made from the *Xa21* gene. There have been no sales, royalties, or funds to distribute. The hope is that as additional UC Davis discoveries are made and licensed to industry, some will find commercial success, and the fund will grow over time. Ideally, all future agreements between UC campuses and companies that license UC inventions would specify a contribution to this fund if the material being licensed was derived directly or indirectly from a developing country. By depositing all the royalties in one fund, the risk that one license may not be profitable would not diminish the overall effectiveness of the fund. Each country that contributes genetic resources would benefit from the fund independent of the commercial success of its particular contribution.

If breeders and geneticists do not have access to valuable germplasm because it is largely tied up in a few large seed companies, there may be fewer varieties of seed available, and the public will lose out.[54] In 2010, the US Department of Justice and the Department of Agriculture (USDA) held a series of public workshops to examine whether consolidation of the US seed industry violates antitrust laws.

One of the attendees, Director and Vice President of the American Antitrust Institute, Diana Moss, concluded that an antitrust investigation should focus on complex seed platforms composed of innovation, genetic traits, and seed markets.[9] She observed that Monsanto's share of the market for genetically engineered corn and soybeans was about 65%, and for genetically engineered cotton, it was about 45%. Moss argued that through this large market share Monsanto was actually harming innovation. To limit this harm, US authorities typically place restrictions on mergers. For example, to win the antitrust authorities' approval for two of its biggest purchases: DeKalb in 1998 and Delta and Pine Land in 2007. Monsanto had to divest US assets of its cottonseed business. Similarly, to obtain approval from antitrust regulators for their merger announced in 2015, Dow and DuPont agreed to divest certain assets. They split the new entity into three separate companies, focused on agriculture, materials, and specialty products. In 2016, US regulators approved ChemChina's acquisition of Syngenta, a giant in farm chemicals and seeds.[55] In 2016, Bayer announced an offer to buy Monsanto.[56] If the Monsanto-Bayer deal receives the required approval from regulatory agencies, these three consolidations would put a significant share of the corn seed and pesticide market into the hands of just three companies, raising concerns among US farmers and legislators about more expensive products and fewer choices.[56]

Proprietary ownership, if shared, has the potential to bolster innovation and benefit farmers. For the past decade, Monsanto has licensed its technology broadly to hundreds of firms, including some of its main competitors. These other seed companies have gone on to develop seed with additional traits that farmers value. According to Moss, this is one of the reasons that Monsanto is not as powerful as many consumers believe. It is not in sole control of the world's seed supply (although it can dictate practices to other companies, large and small, that need Monsanto technology). Because US patent law is national, researchers in other countries (e.g. China or Kenya), are not restricted in their use of US patented technology (unless the innovator has also applied for and been granted a patent in those other countries which is not the case for most genetic technologies).

Consumers who oppose the use of genetic engineering argue that the large corporations are taking advantage of farmers. However, the overwhelming level of farmer adoption of genetically engineered crops in the United States and elsewhere shows that the genetically engineered crop varieties on the market are useful to farmers. It is unlikely that experienced and skilled farmers would buy genetically engineered seeds if their farm operations did not benefit economically. If you ask a US farmer why she plants Bt seed, she will likely tell you that she prefers it to spraying chemical insecticides that can harm farm workers and the environment.[57]

In the developed world, most farmers buy seed from one of the large seed companies. There is a huge incentive for these companies to innovate because better seed means better sales. Monsanto's user contracts prohibit farmers from saving seed from the Monsanto crop and then selling it to a third party. In other words, farmers must agree to use Monsanto-purchased seed solely for planting a single commercial crop. Its violator exclusion policy denies farmers who break the terms of its licenses access to all its technology forever. When farmers buy seed every year, seed companies profit, and so do farmers (if the seed is not overly expensive), because good-quality seed of high-performing varieties is a critical component of their operations.

One of the early critiques of biotechnology was that some of the utility patents covering important enabling technologies (e.g., transforming genes into plants) were overly broad and therefore restricted innovation. However, as Kent Bradford pointed out, "Edwin Land patented his Polaroid camera technology so thoroughly that no other company could enter that space until the patent expired, yet photography continued to advance. Of course, food is different, but the concept of rewarding inventors and contributing a new product for consumers is the same. Having a limited period of exclusivity to reward inventors is what the entire patent system is about."

If the yield increases and cost savings are sufficient, even small farmers can benefit and afford seed. For example, in India, 95% of cotton farmers buy hybrid Bt cotton seeds. Because seed is usually less than 10% of total input costs in farming, better seed is often a smart investment.

In many places around the world, however, subsistence farmers cannot afford to buy expensive proprietary seed. Instead, they rely on public-sector agricultural researchers to generate seed varieties and plants that they need (e.g., cassava, rice, banana). Subsistence farmers who can improve their yield with new knowledge and technologies, are often able to sell their excess product on the market and use these funds to educate their children.

Growers of specialty crops (e.g., strawberries, apples, lettuce) also rely on research in the public domain. One of the challenges for these researchers and for subsistence farmers is that financial support for public-sector agricultural research and plant breeding has declined.[58]

The cost of guiding a genetically engineered crop through the maze of safety regulations has increased making it difficult for public-sector scientists or small companies to bring a genetically engineered crop to market (Box 12.7). Strict European Union regulations, for instance, make it difficult and expensive for public-sector scientists to carry out field tests of engineered seeds. According to Bradford, "This type of regulatory environment stifles public-sector innovation and raises the cost of releasing genetically engineered varieties. Because it costs more to release a genetically engineered variety, public-sector scientists can little afford to release such varieties."[31]

BOX 12.7 **Cost of Safety Regulation**

When Dennis Gonsalves and his team genetically engineered papaya (see Box 4.3 in Chapter 4), public scientists in the United States could afford to carry out field tests because regulatory costs were minimal. Today, genetically engineered crops face daunting regulatory burdens in the United States and abroad.[59–63] While all food crops are subject to safety assessments, genetically engineered crops are subject to additional pre market review by USDA (as an ag product), FDA (as a food) and EPA (to ensure no adverse environmental impacts) (see Box 5.6).

The current governmental regulatory regimens for genetic engineering were developed for crops that carry genes imported from distant species (e.g., bacterial Bt). However, the same rules are applied to genes whose sources and effects resemble those of conventional breeding (e.g., a rice gene into a rice plant). This "one size fits all" regulation imposes large costs (ranging from $50 to $100 million for a single trait) effectively excluding nonprofit groups from bringing crops to market. Furthermore these costs limit the application of the technology in specialty crops such as fruits, vegetables, and nuts, which are grown on only 4% of the cropping area and have little value compared with the revenue generated by corn, soybeans, or cotton.[62,63]

For example, if a university research laboratory genetically engineered a Brandywine tomato for resistance to nematodes, few organizations would be willing to pay the associated regulatory costs needed to bring the new variety to market. On the other hand, large seed or biotechnology companies, which do have the funds, might not be willing to invest them because of the small market and limited potential returns.[64]

As Steven Strauss, a professor in the Department of Forest Science at Oregon State University, explained, "If regulatory costs and hurdles were significantly reduced, it might promote genetically engineered crop development by small companies and public sector investigators. Given the widespread suspicion of the power and ethics of many large corporations and the major role that this skepticism has played in the controversy over genetically engineered crops, such 'democratization' of biotechnology might be as important as biological advances in permitting public approval of genetic engineering in agriculture."[65]

In 2016, the National Academies of Sciences, Engineering, and Medicine recommended a tiered process for regulating new crop varieties that focuses on a plant's characteristics rather than the process by which it was developed. New plant varieties that have intended or unintended novel characteristics that may present potential hazards would undergo safety testing—regardless of whether they were developed using genetic engineering or conventional breeding techniques.[31]

With regards to regulation of genome editing, plant geneticists Daniel Voytas and Caixia Gao notes that: “The time and cost savings resulting from less regulation will be important factors in how quickly agricultural biotechnology companies adopt genome engineering. Reduced government regulation will also enable genome engineering to be applied to minor crops, such as vegetables or horticultural species, which lack the profit margins necessary to pay for governmental regulatory packages.”[66]

Despite these difficulties, public-sector organizations, small seed companies, and public-sector and private-sector partnerships have been successful in developing genetically engineered crops for farmers.[67] For example, in 2015, a small Canadian company, Okanagan Specialty Fruits, received regulatory approval for sale of a genetically engineered, nonbrowning apple for consumption in Canada and the United States.[68] The apple is engineered to produce less of an enzyme that causes browning, an application of genetic engineering that is attractive to many consumers. Likewise, a collaboration between the public-sector Bangladesh Agricultural Research Institute (BARI) and International Programs of the College of Agriculture and Life Sciences at Cornell University has led to the development and approval of an insect-resistant eggplant in Bangladesh[69] (see Box 5.3 in Chapter 5 and Chapter 13).

Despite these successes, many of the public-sector innovations developed decades ago have not yet made it to market. They include disease-resistant wheat, an insect-resistant tomato, and virus-resistant fruit trees.[70] Typically, it is not patenting that restricts these innovations; it is the high cost of safety regulation. The technologies for the genetically engineered eggplant and Okanagan apple were accessible to the public sector and small business innovators, but in both of these cases, the restrictive global regulatory system slowed release. It took 15 years to obtain approval to release the Okanagan apple. Although Bangladesh permitted farmers to plant insect-resistant eggplant, farmers in neighboring India were blocked from planting the seed after nongovernmental groups petitioned the government to protest its use. Planting of insect-resistant eggplant has also been blocked in the Philippines.

Some university scientists and entrepreneurs are seeking ways to release their seed innovations directly to farmers, but few public institutions can produce and market their own varieties on a commercial scale because of the significant costs associated with production, distribution, and quality assurance. Even for crops that still rely largely on public varieties (e.g., 75% of wheat varieties), the universities license these varieties to companies that can efficiently increase and sell the seed. Despite the fact that about one fourth of the patented inventions in agricultural biotechnology are made by public-sector researchers (e.g., public universities), many of these inventions are exclusively licensed to private companies.[71] Although the business contracts sometimes restrict free distribution, the public-private partnerships can also facilitate putting seed into the hands of farmers.

Patents and safety regulations can slow release of seed by scientists working in the public domain. A prominent example is Golden Rice, which was developed initially largely with support from the Rockefeller Foundation to alleviate vitamin A deficiency in children in developing countries. Although the work was carried out in the public domain with an entirely humanitarian aim, the more than 70 patents or contractual obligations could have constrained its development.[72]

Thanks to organizational assistance from the Rockefeller Foundation, the private companies holding these patents and intellectual property rights agreed to release the technology for humanitarian purposes. Syngenta also supported the development of Golden Rice 2, which had higher levels of β-carotene.[73] A Golden Rice Humanitarian Board was established to assist with the technology transfer. Within a couple of years, the intellectual property issues were resolved. The next challenge for the inventors was to field test the new varieties in accordance with the complex web of regulatory requirements and to fend off challenges from organizations opposed to biotechnology.[74–76] Many years later, not a single child has been able to eat Golden Rice—a consequence of a successful opposition from those opposed to biotechnology as well as experimental challenges related to field testing a highly regulated crop. The cost of regulation and field testing restricted the number of varieties that could be tested in a single season, which slowed release. Breeders at the IRRI have introduced the Golden Rice trait into varieties favored by subsistence farmers in Bangladesh and the Philippines. 2016 field trials of Golden Rice in Bangladesh have yielded promising results[77] and breeders are seeking regulatory approval for commercial release.

The case of Golden Rice illustrates the need to ensure that crops developed for humanitarian purposes do not require years of negotiations, expensive lawsuits, or overly complex public/private partnerships. Ingo Potrykus, one of the inventors of Golden Rice, sees it this way: "At one time, I was much tempted to join those who fight patenting. Upon further reflection, however, I realized that the development of Golden Rice was possible only because of the existence of patents. Much of the technology that I had been using was publicly available only because the inventors, by patenting, could protect their rights. Without patents, much of this technology would have remained secret or not developed at all without incentives. To take full advantage of available knowledge to benefit the poor, it does not make sense to fight against patenting. It makes far more sense to fight for a sensible use of intellectual property rights."[72]

Gary Toenniessen piloted the Rockefeller Rice Biotechnology Program from its inception in 1985 to its completion in 2000.[78] Trained as a microbiologist, he was responsible for developing and implementing programs that would help address environmental problems associated with farming. In 2006, Gary and his colleagues at the Rockefeller Foundation joined together with the McKnight Foundation and with several of the leading agricultural universities and plant research institutes in the United States to funds the Public Intellectual Property Resource for Agriculture (PIPRA), founded by UC Davis professor, Alan Bennett.[79] The goal was to ensure that genetically engineered breakthroughs and useful technologies were available to less developed countries and small farmers growing rice and other crops. PIPRA allows universities to market their technologies to the private sector (and profit from their inventions) while retaining rights for humanitarian purposes and small crops that are vital to small-acreage farmers.[79]

Other organizations with similar missions have popped up. For example, the Open Source Seed Initiative (OSSI) at the University of Wisconsin, the Australian research institute Cambia, and the Biological Innovation for Open Society (BiOS) group are dedicated to bringing together farmers, breeders, and small seed companies to share plant genetic resources.[31] Founders of those organizations have compared innovation in seed with innovations in computer software despite the increased complexity of plant genetic resources.[31]

In 2016, the NAS reported, "There is good reason to draw comparisons with the software model. . . . {O]pen-source software is outperforming the intellectual-property protected software generated by the Microsoft Corporation, one of the largest and most powerful private companies in history. Furthermore, . . . many existing technologies could solve numerous problems and save millions of lives if intellectual-property protections were not limiting access. Giving smallholder farmers in developing countries greater control over their seeds, along with other forms of agricultural knowledge and technology, may be foundational to promoting their social welfare."[31]

The Rockefeller Foundation, under the direction of Gary, has also worked to improve food security in Africa and has helped to establish the African Agricultural Technology Foundation (AATF).[80] Because local organizations are best able to determine and develop what is relevant to the needs of their consumers, the AATF identifies African organizations that would like to use publicly available materials and links them with private institutions that could further help them to develop new crop varieties, conduct appropriate biosafety testing (which remains expensive), distribute seed to resource-poor farmers, and create local markets for excess crop production. Several international seed companies and the USDA have expressed interest in working with the AATF.[80] For example, Monsanto collaborates with the AATF to develop drought-tolerant corn for Africa, a project called Water-Efficient Maize for Africa (WEMA). In 2016, the first field trials were planted in Tanzania.[81]

According to Toenniessen, "Plant Breeders Rights was and, in my opinion, could still be an effective mechanism of protecting the intellectual property of plant breeders and seed companies without stifling the research and product development of others. The problem is with utility patents, particularly when applied to the tools for doing research and the products of research. Large, multinational seed companies provide the necessary service of delivering improved varieties to areas that would otherwise have trouble accessing them. However, local seed companies often do a much better job than big corporations in meeting the needs of farmers with limited purchasing power." William Tracy agrees, "I think most public sector breeders would agree wholeheartedly with this. Further, most don't have any problems with patenting new genes or ideas. It is utility patenting of cultivars that most object to."

The future of global agriculture is tied to how we create and share agricultural innovations. Farmers face many challenges, including the need to reduce the negative environmental impacts of food production. To foster innovation, we need policies that safeguard access to germplasm and genes for the public good and that streamline regulations that impede progress that has the potential to benefit farmers, rich and poor. We need to bolster public investment in plant biology research that provides the foundation for innovation and breeding of crops grown by subsistence farmers. We need to encourage and foster public-private partnerships, which bring new and innovative solutions to address common problems. This combination of approaches will advance food security and enhance sustainable agriculture.

Foods: Approaches to Assessing Unintended Health Effects. Washington, DC: The National Academies Press, 2004, 254 p.

23. *Hawks, B., to the National Association of State Departments of Agriculture* (letter), December 21, 2004. Available from: http://www.nasda.org/File.aspx?id=2151.
24. Walz, E., *Final Results of the 4th National Organic Farmers' Survey: Sustaining Organic Farms in a Changing Organic Marketplace*. Santa Cruz, CA: Organic Farming Research Foundation, 2003. Available from: http://ofrf.org/sites/ofrf.org/files/docs/pdf/4thsurvey_results.pdf.
25. Arias, D.M., and L.H. Rieseberg, "Gene Flow Between Cultivated and Wild Sunflowers." *Theoretical and Applied Genetics* 89, no. 6 (1994): 655–660.
26. Byrne, P.F., and S. Fromherz, "Can GM and Non-GM Crops Coexist? Setting a Precedent in Boulder County, Colorado, USA." *Food, Agriculture and Environment* 1, no. 2 (2003): 258–261.
27. National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*. Washington, DC: The National Academies Press, 2016, 420 p.
28. Larson, R., "In Banning Open Space GMO Crops, Boulder County, Colorado Votes Against Sustainability." *Genetic Literacy Project*, March 21, 2016.
29. Meltzer, E., "Sustainable Agriculture Panel Debates GMOs Forum Part of Boulder County`s Cropland Policy Development." *The Daily Camera*, Boulder, CO, November 7, 2010.
30. Snider, L., "Boulder County Agrees to Allow Some GMOs on Public Land." *The Daily Camera,* Boulder, CO, December 20, 2011. Available from: http://www.dailycamera.com/ci_19585517.
31. "Colorado's Boulder County Initiates Phase-Out of GE Crops." *OSGATA* (blog), 2016. Available from: http://www.osgata.org/2016/public-land/.

CHAPTER 11: WHO OWNS THE SEED?

1. Shull, G.H., *Bursa bursa-pastoris and Bursa heegeri Biotypes and Hybrids*. Washington, DC: Carnegie Institution of Washington, 1909, 57 p.
2. Fedoroff, N.V., and N.M. Brown, *Mendel in the Kitchen: A Scientist's View of Genetically Modified Foods*. Washington, DC: Joseph Henry Press, 2004. xiii, 370 p.
3. National Agriculture Statistics Service, *Crop Production: 2014 Summary*. Washington, DC: US Department of Agriculture, January 2015. Available from: https://www.census.gov/history/pdf/cropan15.pdf.
4. "NCGA Announces 2014 Yield Contest Winner." *National Corn Growers Association* (website), December 2014. Available from: http://ncga.com/news-and-resources/news-stories/article/2014/12/ncga-announces-2014-yield-contest-winners.
5. Johnny's Select Seeds. *Brandywine Organic Tomato Seed* (product information). 2015. Available from: http://www.johnnyseeds.com/p-7941-brandywine.aspx.
6. Johnny's Select Seeds. *Big Beef (F1) Tomato Seed* (product information). 2015. Available from: http://www.johnnyseeds.com/p-7958-big-beef.aspx.
7. Miller, W., J. Murray, and Vilmorin-Andrieux et cie., *The Vegetable Garden: Illustrations, Descriptions, and Culture of the Garden Vegetables of Cold and Temperate Climates*. English edition. London: John Murray, Albemarle Street, 1885, xvi, 620 p.

8. Tanksley, S.D., and S.R. McCouch, "Seed Banks and Molecular Maps: Unlocking Genetic Potential from the Wild." *Science* 277, no. 5329 (1997): 1063–1066.
9. Agricultural Marketing Service, *Plant Variety Protection Act and Regulations and Rules of Practice*. Washington, DC: US Department of Agriculture, 2013, 44 p.
10. Germplasm Research Information Network. *Plant Variety Protection Office: Status of Certification*. Washington, DC: US Department of Agriculture, updated March 2017. Available from: http://www.ars-grin.gov/cgi-bin/npgs/html/pvplist.pl.
11. Johnny's Selected Seeds. *2016 Catalog*, p. 2. Available from: http://www.johnnyseeds.com/about-us/about-our-seed/safe-seed-pledge.html.
12. Department of Pesticide Regulation, Worker Health and Safety Branch, *Summary of Results from the California Pesticide Illness Surveillance Program 2012*. Sacramento, CA: California Environmental Protection Agency, 2015.
13. Institute of Medicine, Committee on Identifying and Assessing Unintended Effects of Genetically Engineered Foods on Human Health, *Safety of Genetically Engineered Foods: Approaches to Assessing Unintended Health Effects*. Washington, DC: The National Academies Press, 2004, xvii, 235.

CHAPTER 12: THE SEED INDUSTRY: ACCELERATING OR IMPEDING INNOVATION?

1. Genoways, T., "Corn Wars." *The New Republic*, August 16, 2015. Available from: https://newrepublic.com/article/122441/corn-wars.
2. Talbot, D., "China's GMO Stockpile." *MIT Technology Review*, October 21, 2014. Available from: https://www.technologyreview.com/s/531721/chinas-gmo-stockpile/.
3. Anderson, L., "Why Does Everyone Hate Monsanto?" *Modern Farmer*, March 4, 2014. Available from: http://modernfarmer.com/2014/03/monsantos-good-bad-pr-problem/.
4. Doane Advisory Services, "A Comparison of World Corn Yields." *Farm Journal's AGPRO,* October 11, 2013. Available from: http://www.agprofessional.com/news/A-comparison-of-world-corn-yields-227415201.html.
5. "The Parable of the Sower." *The Economist*, November 19, 2009. Available from: http://www.economist.com/node/14904184.
6. *Roundup Ready Soybean Patent Expiration* (news release). Monsanto, 2015. Available from: http://www.monsanto.com/newsviews/pages/roundup-ready-patent-expiration.aspx. Monsanto now makes more money from seed sales than from glyphosate (Roundup), and the margin is growing rapidly because the Roundup patent has expired.
7. Toenniessen, G.H., "Opportunities for and Challenges to Plant Biotechnology Adoption in Developing Countries," in *Biotechnology: Science and Society at a Crossroad.* New York: National Agricultural Biotechnology Council, 2006, 245–261. Available from: http://nabc.cals.cornell.edu/Publications/Reports/nabc_15/15_7_3_Toennissen.pdf.
8. "Big Seed: How The Industry Turned From Small-Town Firms To Global Giants." *Morning Edition* (NPR radio program), April 6, 2016. Available from: http://www.npr.org/sections/thesalt/2016/04/06/472960018/big-seed-consolidation-is-shrinking-the-industry-even-further.
9. Mitchell, D., "Why Monsanto Always Wins." *Fortune*, June 26, 2014. Available from: http://fortune.com/2014/06/26/monsanto-gmo-crops/.

10. *American Antitrust Institute Says Compeitition in the Transgenic Seed Indsutry is Impaired by Monsanto* (news release). Washington, DC: American Antitrust Institute, October 23, 2009. Available from: http://www.antitrustinstitute.org/content/american-antitrust-institute-says-competition-transgenic-seed-industry-impaired-monsanto.
11. El-Chichakli, B., J. von Braun, C. Lang, D. Barben, and J. Philip, "Policy: Five Cornerstones of a Global Bioeconomy." *Nature* 535, no. 7611 (2016): 221–223.
12. Johnson, N., "China's $450 Billion Farm Plan Could Determine Our Fate." *Grist*, September 30, 2016.
13. "China Eyes GMO Progress Amid Crop Shrinkage." *Xinhua Insight*, February 4, 2015.
14. "Yuan Longping." *Wikipedia*, last updated March 15, 2017. Available from: https://en.wikipedia.org/wiki/Yuan_Longping.
15. "Overview," in *Land Use, Land Value & Tenure*. Washington, DC: USDA Economic Research Service, 2016. Available from: http://www.ers.usda.gov/topics/farm-economy/land-use,-land-value-tenure.aspx.
16. "Farm Demographics—U.S. Farmers by Gender, Age, Race, Ethnicity, and More," in *2012 Census Highlights*. ACH12-3, May 2014. Washington, DC: USDA Census of Agriculture, last modified October 19, 2016. Available from: https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Highlights/Farm_Demographics/.
17. Larson, C., "Mekong Megadrought Erodes Food Security." *Science*, April 6, 2016.
18. Jiao, Y., O.S. Lau, and X.W. Deng, "Light-Regulated Transcriptional Networks in Higher Plants." *Nature Reviews Genetics* 8, no. 3 (2007): 217–230.
19. Li, B., X. Fang, Y. Ye, and X. Zhang, "Carbon Emissions Induced by Cropland Expansion in Northeast China During the Past 300 Years." *Science China Earth Sciences* 57, no. 9 (2014): 2259–2268.
20. Wong, E., "Beijing Issues Red Alert over Air Pollution for the First Time." *The New York Times*, December 7, 2015. Available from: http://www.nytimes.com/2015/12/08/world/asia/beijing-pollution-red-alert.html?_r=0.
21. Guo, O., "Beijing to Raise Threshold on Red Alerts for Smog." *The New York Times*, February 22, 2016. Available from: http://www.nytimes.com/2016/02/23/world/asia/beijing-smog-alerts.html.
22. Rohde, R.A., and R.A. Muller, "Air Pollution in China: Mapping of Concentrations and Sources." *PLoS One* 10, no. 8 (2015).
23. Wong, E., "Life in a Toxic Country." *The New York Times*, August 3, 2013. Available from: http://www.nytimes.com/2013/08/04/sunday-review/life-in-a-toxic-country.html.
24. Patel, S., "In the Dirtiest Cities, Air Pollution Forces Life Changes." *The New York Times*, December 22, 2015. Available from: http://www.nytimes.com/2015/12/23/world/asia/air-pollution-china-india.html.
25. Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y. Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang, and J. Fang, "The Impacts of Climate Change on Water Resources and Agriculture in China." *Nature* 467, no. 7311 (2010): 43–51.
26. "China GMO Corn Approval Seen Spurring Recovery in U.S. Imports." *Bloomberg News*, December 18, 2014. Available from: http://www.bloomberg.com/news/articles/2014-12-18/china-gmo-corn-approval-seen-spurring-recovery-in-u-s-imports.
27. *Ibid.*

28. Karplus, V.J., and X.W. Deng, *Agricultural Biotechnology in China: Origins and Prospects*. New York: Springer-Verlag, 2008.
29. *Diamond v. Chakrabarty*, 447 U.S. 403 (1980).
30. *Bayh-Dole Act (University and Small Business Patent Procedures Act of 1980)*, 35 U.S.C, § 200 (1980).
31. National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*. Washington, DC: The National Academies Press, 2016, 420 p.
32. "Association for Molecular Pathology v. Myriad Genetics, Inc." *Wikipedia*, last updated March 13, 2017. Available from: https://en.wikipedia.org/wiki/Association_for_Molecular_Pathology_v._Myriad_Genetics,_Inc..
33. Grushkin, D., "DuPont in CRSIPR-Cas Patent Land Grab." *Natural Biotechnology* 34, no. 1 (2016): 13; Available from: http://crisprcas.pioneer.com/our-promise/.
34. Where Ideas Become Reality. Available from: https://openinnovation.pioneer.com.
35. Cool, M., (for DuPont Pioneer). "Open Innovation." Email, July 12, 2017.
36. "Corn Seeds." *American Type Culture Collection*, 2016. Available from: https://www.atcc.org/Search_Results.aspx?dsNav=Ntk:PrimarySearch%7cCorn+seeds%7c3%7c,Ny:True,Ro:0,N:1000552&searchTerms=Corn+seeds&redir=1.
37. Cullen, S., "UW-Madison Professor Gets Corny with New Seed Variety Called 'Who Gets Kissed?'" *Wisconsin State Journal*, March 29, 2015. Available from: http://host.madison.com/wsj/lifestyles/home-and-garden/uw-madison-professor-gets-corny-with-new-seed-variety-called/article_101cae50-027f-5bac-9447-0d8c51d53dbc.html.
38. Vaidyanathan, G., "A Search for Regulators and a Road Map to Deliver GM Crops to Third World Farmers." *The New York Times*, March 31, 2010. Available from: http://www.nytimes.com/cwire/2010/03/31/31climatewire-a-search-for-regulators-and-a-road-map-to-de-53658.html?pagewanted=all.
39. Elliott, R.S., "Brazil GM Soy Ban Cultivates Seed Smuggling." *Reuters News Service,* September 28, 1999. Available from: http://www.iatp.org/news/brazil-gm-soy-ban-cultivates-seed-smuggling.
40. Srimali, K., "Govt Worried over Fake Bt Seeds." *The Times of India*, June 10, 2004. Available from: http://timesofindia.indiatimes.com/city/hyderabad/Govt-worried-over-fake-Bt-seeds/articleshow/729083.cms.
41. Kulkarni, N., "Creating Awareness to Curb Sale of Fake Bt Seeds." *BioSpectrum*, April 11, 2006.
42. Barnes, R., "Supreme Court Rules for Monsanto in Case of Genetically Modified Soybeans." *The Washington Post*, May 13, 2013. Available from: https://www.washingtonpost.com/politics/supreme-court-rules-for-monsanto-in-genetically-modified-soybean-case/2013/05/13/c84d7710-bbdb-11e2-97d4-a479289a31f9_story.html.
43. "Bowman v. Monsanto Co." *Wikipedia*, last updated March 27, 2017. Available from: https://en.wikipedia.org/wiki/Bowman_v._Monsanto_Co..
44. Song, W.Y., G.L. Wang, L.L. Chen, H.S. Kim, L.Y. Pi, T. Holsten, J. Gardner, B. Wang, W.X. Zhai, L.H. Zhu, C. Fauquet, and P. Ronald, "A Receptor Kinase-Like Protein Encoded by the Rice Disease Resistance Gene, *Xa21*." *Science* 270, no. 5243 (1995): 1804–1806.

45. Blakeslee, S., "Genetic Engineering Creates Rice Resistant to Destructive Blight." *The New York Times*, December 15, 1995. Available from: http://www.nytimes.com/1995/12/15/us/genetic-engineering-creates-rice-resistant-to-destructive-blight.html.
46. Brush, S.B., "Whose Knowledge, Whose Genes, Whose Rights?," in *Valuing Local Knowledge: Indigenous People and Intellectual Property Rights*, eds. S.B. Brush and D. Stabinsky. Washington, DC: Island Press, 1996, 339 p.
47. International Rice Research Institute (IRRI). *Basic Facts About Rice*. Manila, Philippines: IRRI, 1990. Available from: http://irri.org/our-work/research/genetic-diversity/international-rice-genebank.
48. Jacoby, C.D., and C. Weiss, "Recognizing Property Rights in Traditional Biocultural Contribution." *Stanford Environmental Law Journal* 16 (1997): 74 p.
49. Smale, M., and B. Koo, "Introduction: A Taxonomy of Genebank Value," in *Biotechnology and Genetic Resource Policies: What is a Genebank Worth?*, eds. M. Smale and B. Koo (Washington, DC: International Food Policy Research Institute, 2003), 22.
50. "Convention on Biological Diversity." *Wikipedia*, last updated September 30, 2017. Available from: https://en.wikipedia.org/wiki/Convention_on_Biological_Diversity.
51. "International Treaty on Plant Genetic Resources for Food and Agriculture." *Wikipedia*, last updated December 6, 2017. Available from: https://en.wikipedia.org/wiki/International_Treaty_on_Plant_Genetic_Resources_for_Food_and_Agriculture.
52. ten Kate, K., and A. Collis, *Benefit-Sharing Case Study: The Genetic Resources Recognition Fund of the University of California, Davis*. Submission to the Executive Secretary of the Convention on Biological Diversity of the Royal Botanic Gardens, Kew, 1997, 24.
53. Nakanishi, N., "China Close to Production of 'Safe' Genetic Rice." *Reuters News Service,* March 9, 2005. Available from: http://www.cropgeneticsinnovation.org/wp-content/uploads/sites/197/2016/01/China-close-to-production-of-safe-genetic-rice.pdf.
54. Tribe, D., "Seed Biodiversity in Terms of Numbers of Commercial Varieties of Vegetable Seeds for Purchase Is Largely Unchanged over 100 Years." *GMO Pundit* (blog), June 11, 2012. Available from: http://gmopundit.blogspot.com/2012/06/seed-biodiverity-as-measured-on-in.html.
55. Bray, C., "U.S. Regulator Signs Off on ChemChina-Syngenta Deal." *The New York Times*, August 22, 2016.
56. Bunge, J., and J. Newman, "Bayer's Bid for Monsanto Faces Hurdles." *The Wall Street Journal*, May 19, 2016.
57. Hutchison, W.D., E.C. Burkness, P.D. Mitchell, R.D. Moon, T.W. Leslie, S.J. Fleischer, M. Abrahamson, K.L. Hamilton, K.L. Steffey, M.E. Gray, R.L. Hellmich, L.V. Kaster, T.E. Hunt, R.J. Wright, K. Pecinovsky, T.L. Rabaey, B.R. Flood, and E.S. Raun, "Areawide Suppression of European Corn Borer with Bt Maize Reaps Savings to Non-Bt Maize Growers." *Science* 330, no. 6001 (2010): 222–225.
58. Lane, E., *Report: Basic Science Research Is Critical for U.S. Well-Being*. Washington, DC: American Association for the Advancement of Science, April 28, 2015.
59. Alston, J., K. Bradford, and N. Kalaitzandonakes, "The Economics of Horticultural Biotechnology." *Journal of Crop Improvement* 18, no. 1–2 (2006): 413–431.

60. Bradford, K., J. Alston, and N. Kalaitzandonakes, "Regulation of Biotechnology for Specialty Crops," in *Regulating Agricultural Biotechnology: Economics and Policy*, eds. R. Just, J. Alston, and D. Zilberman. New York: Spring Publishers, 2006, 683–697.
61. Kalaitzandonakes, N., J.M. Alston, and K.J. Bradford, "Compliance Costs for Regulatory Approval of New Biotech Crops." *Nature Biotechnology* 25, no. 5 (2007): 509–511.
62. Dobres, M., "Barriers to Genetically Engineered Ornamentals: An Industry Perspective," in *Floriculture, Ornamental and Plant Biotechnology: Advances and Topical Issues*, Volume V, ed. J.A.T. da Silva (London: Global Science Books, Ltd., 2008), 1–14.
63. Miller, J.K., and K.J. Bradford, "The Regulatory Bottleneck for Biotech Specialty Crops." *Nature Biotechnology* 28, no. 10 (2010): 1012–1014.
64. Graff, G.D., D. Zilberman, and A.B. Bennett, "The Commercialization of Biotechnology Traits." *Plant Science* 179, no. 6 (2010): 635–644.
65. Strauss, S.H., "Genetic Technologies: Genomics, Genetic Engineering, and Domestication of Crops." *Science* 300, no. 5616 (2003): 61–62.
66. Voytas, D.F., and C. Gao, "Precision Genome Engineering and Agriculture: Opportunities and Regulatory Challenges." *PLoS Biology* 12, no. 6 (2014): 1–6.
67. Stein, A.J., and E. Rodriguez-Cerezo, *The Global Pipeline of New GM Crops: Implications of Asynchronous Approval for International Trade.* JRC Scientific and Technical Reports. Seville, Spain: Joint Research Centre, Institute for Prospective Technological Studies, 2009.
68. Carter, N., "Arctic® Apples Approved in Canada!" *OSF* (website). Summerland, BC, Canada: Okanagan Specialty Fruits Inc., 2015. Available from: http://www.okspecialty-fruits.com/arctic-apples-approved-in-canada/.
69. *Bt Brinjal Facts.* Ithaca, NY: Feed the Future South Asia Eggplant Improvement Partnership, April 6, 2016. Available from: https://bteggplant.wordpress.com/.
70. Fernanadez-Cornejo, J., S. Wechsler, M. Livingston, and L. Mitchell, *Genetically Engineered Crops in the United States.* USDA Economic Research Report 162. Washington, DC: US Department of Agriculture, 2014. Available from: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2503388.
71. Atkinson, R.C., R.N. Beachy, G. Conway, F.A. Cordova, M.A. Fox, K.A. Holbrook, D.F. Klessig, R.L. McCormick, P.M. McPherson, H.R. Rawlings III, R. Rapson, L.N. Vanderhoef, J.D. Wiley, and C.E. Young, "Intellectual Property Rights. Public Sector Collaboration for Agricultural IP Management." *Science* 301, no. 5630 (2003): 174–175. Note: *Agrobacterium*-mediated transformation was discovered by public sector scientists but did not become an important tool for plant transformation until scientists at the private seed companies Monsanto and Calgene optimized it. In recognition of this public-private partnership, the World Food Prize was awarded to Monsanto scientist Rob Fraley and scientists Marc van Montagu and Mary Dell Chilton.
72. Potrykus, I., "Golden Rice and Beyond." *Plant Physiology* 125, no. 3 (2001): 1157–1161.
73. Paine, J.A., C.A. Shipton, S. Chaggar, R.M. Howells, M.J. Kennedy, G. Vernon, S.Y. Wright, E. Hinchliffe, J.L. Adams, A.L. Silverstone, and R. Drake, "Improving the Nutritional Value of Golden Rice Through Increased Pro-vitamin A Content." *Nature Biotechnology* 23, no. 4 (2005): 482–487.

74. Alberts, B., R. Beachy, D. Baulcombe, G. Blobel, S. Datta, N. Fedoroff, D. Kennedy, G.S. Khush, J. Peacock, M. Rees, and P. Sharp, "Standing Up for GMOs." *Science* 341, no. 6152 (2013): 1320.
75. Grens, K., "Judge Decides on GM Rice Retraction." *The Scientist*, August 3, 2015. Available from: http://www.the-scientist.com/?articles.view/articleNo/43656/title/Judge-Decides-on-GM-Rice-Retraction/.
76. Campbell, H., "GMOs Don't Hurt Anyone, But Opposing Them Does." *Science 2.0*, August 5, 2013. Available from: http://www.science20.com/science_20/blog/gmos_dont_hurt_anyone_opposing_them_does-117782.
77. Ahmad, R., "Vitamin A Rice Now a Reality." *The Daily Star*. October 28, 2016.
78. Myers, M., *Exploring 100 Years of Food Security*. Food & Prosperity Series. New York, The Rockefeller Foundation, 2013. Available from: https://www.rockefellerfoundation.org/blog/exploring-100-years-food-security/.
79. Boetliger M., and Bennett, "Bayh-Dole: If We Knew then What We Know Now." *Natural Biotechnology* 24 (2006): 320–323.
80. *African Agricultural Technology Foundation (AATF-Africa)* (website), latest update 2017. Available from: http://aatf-africa.org/.
81. Conrow, J., "Tanzania Plants Its First GMO Research Crop." *Cornell Alliance for Science* (website), October 5, 2016.

CHAPTER 13: FEEDING THE WORLD ETHICALLY

1. Smith, B., "Don't Let Your Children Grow Up to Be Farmers." *The New York Times*, August 9, 2014. Available from: http://www.nytimes.com/2014/08/10/opinion/sunday/dont-let-your-children-grow-up-to-be-farmers.html?_r=0.
2. "The Tech Awards 2012—Accenture Sustainable Energy Award—Eco-Fuel Africa" (video). San Jose, CA: The Tech Museum of Innovation, November 15, 2012. Available from: https://www.youtube.com/watch?v=bKk-odFRgGk.
3. Peed, M., "We Have No Bananas: Can Scientists Defeat a Devastating Blight?" *The New Yorker*, January 10, 2011: 28. Available from: http://www.newyorker.com/magazine/2011/01/10/we-have-no-bananas.
4. Tripathi, L., J.N. Tripathi, A. Kiggundu, S. Korie, F. Shotkoski, and W.K. Tushemereirwe, "Field Trial of *Xanthamonas* Wilt Disease-Resistant Bananas in East Africa." *Nature Biotechnology* 32, no. 9 (2014): 868–870.
5. Tripathi, J.N., J. Lorenzen, O. Bahar, P. Ronald, and L. Tripathi, "Transgenic Expression of the Rice Xa21 Pattern-Recognition Receptor in Banana (*Musa* sp.) Confers Resistance to *Xanthomonas campestris pv. musacearum.*" *Plant Biotechnology Journal* 12, no. 6 (2014): 663–673.
6. Tripathi, L., H. Mwaka, J.N. Tripathi, and W.K. Tushemereirwe, "Expression of Sweet Pepper *hrap* Gene in Banana Enhances Resistance to *Xanthomonas campestris pv. musacearum.*" *Molecular Plant Pathology* 11, no. 6 (2010): 721–731.
7. "Johns Hopkins Global Food Ethics and Policy Program." *Johns Hopkins Berman Institute of Bioethics* (website), 2017. Available from: http://www.bioethicsinstitute.org/globalfoodethics?doing_wp_cron=1443565908.4481410980224609375000.