Genetically Modified Planet: Environmental Impacts of Genetically Engineered Plants

C. Neal Stewart, Jr.

OXFORD UNIVERSITY PRESS

Genetically Modified Planet

This page intentionally left blank

Genetically Modified Planet

Environmental Impacts of Genetically Engineered Plants

C. Neal Stewart, Jr.

OXFORD
UNIVERSITY PRESS
2004

OXFORD
UNIVERSITY PRESS

Oxford New York
Auckland Bangkok Buenos Aires Cape Town Chennai
Dar es Salaam Delhi Hong Kong Istanbul Karachi Kolkata
Kuala Lumpur Madrid Melbourne Mexico City Mumbai Nairobi
São Paulo Shanghai Taipei Tokyo Toronto

Published by Oxford University Press, Inc.
198 Madison Avenue, New York, New York 10016
www.oup.com

Library of Congress Cataloging-in-Publication Data
Stewart, C. Neal.
Genetically modified planet : environmental impacts of genetically
engineered plants / C. Neal Stewart, Jr.
p. cm.
Includes bibliographical references
ISBN 0-19-515745-1
1. Transgenic plants. 2. Plant genetic engineering. 3. Transgenic
plants—Ecology. 4. Plant genetic engineering—Environmental aspects.
I. Title.
SB123.57 .S74 2004
631.5'233—dc22 2003021371

9 8 7 6 5 4 3 2 1

Printed in the United States of America
on acid-free paper

To my wife, Susan Stewart, for her love, support, kindness, and patience.

This page intentionally left blank

Preface

This book is the natural outgrowth of several previous writing projects, including book chapters, review papers, and journal articles, public and professional presentations, and an undergraduate class I taught on the risks and benefits of biotechnology. In the midst of my course, I realized how much dubious information about biotechnology the typical freshman had accumulated in his or her brief lifetime. It became apparent that a book written for a general audience on the science of the environmental impacts of genetically modified plants was needed. In the process of writing this book, I have learned much about the science and even more (I hope) about communicating the subject to nonscientists. I've learned firsthand that it truly is easier to write to my peers using shop jargon than to effectively communicate to the people who are, perhaps, most concerned about the ramifications of science and technology. And that truly is the purpose of this book: to communicate and demystify biotechnology to the degree that the reader can go beyond newspaper headlines to critically examine the issues. There is power in the understanding of relative risks and benefits of any technology. There is certainly value in better understanding agriculture—to go beyond the supermarket to visit the source of where our food comes from—and examining the role of genetics in farming. If this book accomplishes nothing else, I'll be satisfied to know that people have a better grasp of how agriculture really works as a result of reading it.

Many people have enabled the writing of this book. The members of my lab crew always amaze me with their hard work and insights. Without these talented people, I would have had neither the knowledge nor the time to write such a book. Specifically, Matt Halfhill has performed much of the actual ecological biosafety research in my lab, with the aid of several other scientists. I also want to thank Matt for his critical reading of the manuscript. Thanks to my principal collaborators in this field, John All, Paul Raymer, and Suzanne Warwick, who have been instrumental in helping me see the big picture of agriculture, along with my postdoctoral mentor, Wayne Parrott, who encouraged my entrance into this intriguing area of research. Likewise, I have benefited from stimulating interactions from other collaborators in the field, including Angharad Gatehouse, Angelika Hilbeck, Guy Poppy, and Tanja Schuler. The area of biotechnological biosafety has many sides, though, and conversations with people such as Tom Nickson, Detlef Bartsch, Debby Sheely, Jeremy Sweet, Fred Gould, Greg Warren, Anna Hope, Mark Sears, and C.S. Prakash have also definitely shaped my opinions.

Several people were instrumental in the shaping and wordsmithing of this book. I am indebted to Kirk Jensen, former executive editor at Oxford University Press, for his guidance and editing, and Sarah Wheaton for her help on the book proposal. I am grateful to John Rauschenberg, Heather Hartman, and the Oxford staff. Sandy Kitts at the University of Tennessee was kind enough to render several illustrations. Amy Yancey Jenkins designed the cover, and Susan Stewart, Reggie Millwood, Mentewab Ayalew, and Nathan Stewart provided drawings for illustrations. In addition, Reggie runs my lab day-to-day, and his diligence and trustworthiness have been critical in my time of sequestration on this project. I am especially thankful to Susan Stewart, who played a vital role in the final revisions of several chapters. The writing of this book (time, support, and information) was facilitated by a research leave provided by the University of North Carolina at Greensboro; the USDA Biotechnology Risk Assessment Research Grants Program; the support of the Racheff Chair of Excellence endowment; and the support of staff and administrators of the University of Tennessee Department of Plant Sciences and the University of Tennessee Institute of Agriculture. Finally, I am indebted to my parents, Charles Stewart, Sr., and Jane Stewart, as well as to my good friend Richard Fredrickson, who were quite instrumental in helping foster in me a love of nature, which is the reason I became a scientist in the first place.

All opinions and errors are my own and do not necessarily reflect the opinions of the University of Tennessee or any of the above people or institutions. To God be the glory.

Contents

Genetically Modified Planet

This page intentionally left blank

Introduction

Catastrophic Calamities and Clucking Cacophonies

A recent conversation with a major beneficiary of agricultural biotechnology revealed the depth of the American commitment to planting genetically modified (GM) crops. The proponent, a farmer in western Tennessee, explained why GM varieties are popular. "In the field, enemy number one is weeds. Roundup Ready soybeans help me control weeds easier with fewer chemicals." The soybeans he planted have an additional bacterial gene that allows them to thrive when fields are sprayed with the chemical glyphosate, the active ingredient in the herbicide Roundup. Only the weeds die. The farmer continued to explain why Roundup Ready soybeans top the list of GM crops grown on American soil: "If weeds can be controlled early in the season, the soybeans form a canopy that shades out weeds. Before these GM soybeans became available I was having to use several herbicides and tillage to keep ahead of weeds." GM soybeans have significantly facilitated reduced tillage practices, and low-till and no-till farming result in less soil erosion. When asked about real-life benefits, the farmer stated, "The bottom line for me is that I can make more money because I spend less for herbicide applications. I get good yields with these beans, plus my soil stays on the farm instead of going down the [Mississippi] River."

Biotechnological crops are indeed popular with farmers. In the United States in 2003, GM crops composed approximately one-third of the corn acreage and three-quarters of areas planted in cotton and soybeans. Most of the corn and cotton crops had a single gene addition that enabled them to produce their own insecticidal proteins; the plants now kill insect pests without pesticides. Insect-resistant biotech cotton has eliminated the need to spray millions of gallons of synthetic chemical insecticides, a huge, direct environmental benefit.

Farmers in several other countries have also embraced GM crops. In Canada, more than 70% of the canola crop consists of herbicide-tolerant varieties. Argentina and China have extensive acreage planted in transgenic crops.

Although GM plants are not very controversial in North and South America and China, they are controversial in other places, particularly in Europe. A number of vocal activists believe that GM crops may be harmful to the environment. They believe that biotechnology is inherently dangerous and that the new plants have not been sufficiently tested to assure environmental safety. One vehement opponent is Dr. Mae-Wan Ho, a reader at the Open University in England. She has declared, "Genetic-engineering biotechnology . . . will spell the end of humanity as we know it and of the world at large."[1] This statement represents an extreme viewpoint. While most anti-GM activists don't subscribe to a doomsday prediction, there are plenty of people who share Ho's general misgivings about the safety of agricultural biotechnology. But science can answer the biosafety questions.

For the sake of argument, let's say that Ho is correct and GM plants will have a significant negative impact on the world. Ecological disaster would certainly emerge first in the United States, where GM crops are most popular. In America, millions of acres have been planted with engineered crops (tables 1.1 and 1.2). Since the first GM plants were grown in the field experimentally in 1988, an estimated 38 trillion GM plants have been grown in American soil; the plants were modified for dozens of traits with hundreds of different transgenes (table 1.3). More than 99.9% have been grown under deregulated conditions, indicating that American regulatory authorities are convinced that GM plants are safe. Ecological disaster has, thus far, remained at bay.

At one end of the spectrum, proponents of biotechnology argue that GM plants are as safe as conventionally bred crops. At the other end, Ho and a montage of activists decry danger. Who's right?

There are real and perceived environmental risks associated with GM plants. Unfortunately, the perceived risks have often been greatly elevated in their stature. Although some of these erstwhile dangers might have nuggets of truth, others are nothing more than dreamy arguments. Nonetheless, I will address them all, in the context of weighing risks against

Table 1.1. Typical numbers of plants grown per acre in the United States

Crop	Plants per acre
Corn	24,000
Cotton	40,000
Soybean	120,000
Canola	350,000
Potato	40,000

These figures are drawn from consultations with agronomists.

benefits and the dangers of accepting a form of technology against hazards of rejecting it. Although benefits of any methodology or invention might be enormous, if it is inherently and "fatally" hazardous, acceptance of the technology is precarious at best. A prime example is nuclear energy, which promised to produce abundant, cheap energy. It did not take many "small" nuclear disasters for the public to decry future construction of nuclear reactors. Yet we regularly employ risky technology. The difference between what we take for granted and what we worry about often boils down to familiarity and perceived necessity. There are multiple risks of crashing and bodily injury in automobile travel; however, automobile travel is generally considered safe. There are safety issues

Table 1.2. Estimates of acres (in millions) of GM crops in the United States

	Year								
Crop	pre-1996	1996	1997	1998	1999	2000	2001	2002	2003
Corn				19.6	28.3	19.9	19.8	24.5	24.5
Cotton				5.8	7	9.3	11.1	10.1	10.1
Soybean				27	35	40.2	51.3	54.0	54.0
Canola				0.4	0.5	0.9	0.8	0.8	0.7
Potato				0.06	0.06				
All (mainly soy and corn) before 1997	1	6	18						

The USDA National Agricultural Statistics Service (NASS) and Biotechnology Industry Organization (BIO) make estimates of the yearly acreages of GM crops grown in the United States.

Table 1.3. Numbers of GM plants grown in the United States (in millions)

	Year									
Crop	Pre-1996	1996	1997	1998	1999	2000	2001	2002	2003	Totals
Corn				470,400	679,200	477,600	475,200	588,000	588,000	3,278,400
Cotton				232,000	280,000	372,000	444,000	404,000	404,000	2,136,000
Soybean				3,240,000	4,200,000	4,824,000	6,156,000	6,480,000	6,480,000	31,380,000
Canola				140,000	175,000	315,000	280,000	280,000	245,000	1,435,000
Potato				2400	2400	0	0	0	0	4800
Totals	80,000	480,000	1,440,000	4,294,800	5,511,600	5,848,600	7,092,700	7,489,500	7,489,500	38,234,200

Numbers were derived by multiplying the appropriate figures from tables 1.1 and 1.2.

associated with eating: food poisoning, allergies, and diseases associated with poor choices. Despite risks of vomiting, anaphylactic shock, and growing morbidly fat, though, most people would agree that food consumption is safe. Risk management for these and other familiar technologies is approached with a degree of scientific objectivity. It is my hope that scientists and the general public will likewise attain an objective analysis for the ecology of GM plants. One goal of this book is to demystify agricultural biotechnology and place it in a more familiar context.

I will not cover GM food safety issues in this book. Testing for toxic compounds and allergenicity is more straightforward than ecological study. Animal feeding experiments can pinpoint the acute toxicity of a novel food, and there are numerous predictors for determining whether a modified consumable will cause food allergies.

Ecological biosafety is a more complex science. Nature is a big place, and ecological interactions are far from being completely understood. In many ways, the precise introduction of single genes into plants and the analysis of their new ecological interactions can provide an excellent toolkit to better understand fundamental biology. But here we are interested in how research increases our understanding about the biosafety of GM plants.

Certain risks appear repeatedly in the scientific literature and popular press, each presenting drastic outcomes. I will explore the likelihood of environmental calamity for each of several issues. One concern is that insect pests might develop resistance to a transgenic, plant-produced pesticide and become more difficult to control. A second is that gene flow might occur between GM crops and weeds to produce superweeds of extraordinary competitive ability. A third risk is that viral transgenes in plants could recombine with existing viruses to produce superviruses.

In recent years, these and other fears have been spun into hot news stories. One of the better-known reports focused on GM corn and the monarch butterfly; early indications of a potential side effect were translated into a dramatic ecological tragedy for public consumption. In the monarch butterfly case and in other instances, actual empirical knowledge never arrived in newspapers and TV news. We want to be able to untangle the science from publicity.

The prevalent belief among skeptics is that once GM plants are released into the environment, the plants or genes can never be recalled. Once the banana is out of the peel, it is impossible to put it back. Is the cultivation of 38 trillion GM plants a huge, uncontrolled American experiment with potentially devastating consequences? Are the prognostications of dire ecological consequences reasonable warnings or Luddite ravings? Are GM plants simply an extension of conventional agriculture, or are we irreversibly treading on Mother Nature?

My study of GM plants began in 1993, and my interest was generated by the scientific possibility that certain plant–transgene combinations might carry significant and unique environmental risks. Since these beginnings I have changed from being a biosafety skeptic to a cautious optimist and a proponent of biotechnology. Still, I remain a strict advocate and practitioner of biosafety research, in favor of appropriate regulatory frameworks for the sake of environmental protection. I now believe that GM technology will not destroy the earth, but may well make the world a safer, cleaner, and greener place in which to live. I am a practicing plant ecologist and molecular biologist—an oddball in the world of biology. It is not common for a single scientist to both produce GM plants and study their ecology, as the type and scale of the research done in these two areas are usually quite different. Ecologists study organisms interacting with other organisms and with their environments. The spatial scale of interest typically spans somewhere between several square meters to square kilometers and beyond. The ecological timeline is usually months, years, decades, or longer. On the other hand, molecular biology is performed at the submicroscopic to whole-organism level, and experiments generally run from minutes to days. The two areas are rarely married, but to understand fully the interactions between a GM plant and its environment in the real world, along with the role of GM plants, a dialogue between molecular biology and ecology is extremely helpful and perhaps fundamentally essential. Molecular biology and ecology intersect at the synthetic field of research known as biotechnology risk assessment research, the ecology of transgenic plants.

My interest in the biosafety of GM plants was spurred by a study published in 1993 that described experiments in which herbicide-tolerant GM plants were grown in the field and found to be completely ecologically benign.[2] These early experiments intrigued me. The trait the transgene provided, herbicide tolerance, would not be expected to provide an increase in fitness or competition to its host—and it didn't. But the responsible British group used a very appropriate plant: canola, an oilseed crop in the mustard family that has several wild relatives with which it can interbreed.

In 1994, I began studying what I believed to be a worst-case scenario for a simple GM crop (containing one or two novel transgenes), which is described in more depth in chapter 4. Like the 1993 study, the research used canola along with its wild relatives, but different transgenes. I thought that a worst-case transgene would be one that could be affected by natural selection outside of agriculture, a *Bacillus thuringiensis* (Bt) transgene that encodes a caterpillar-killing protein. The hypothesis tested was that harboring a Bt gene could potentially make canola a weed, or confer weedy or invasive tendencies to help its survival outside an agricultural field. In addition, the Bt transgene could be transferred through hybridization and introgression from the crop to one of its weedy wild relatives. Would the transgene make the weed even weedier? It seemed to me that the wrong transgene (one that could confer fitness-enhancing traits) in the wrong crop (one that could transfer genes to weeds) could result in an ecological disaster. In such a case, the interaction between the transgene's unique and profound effect, coupled with the ecology of the crop and weed, would possibly result in an environmental effect greater than the sum of its parts. The wrong combination could create a new kudzu, some superweed of the highest order, even worse than that exotic legume imported into the southeastern United States for erosion control that now swallows homesteads with a single-season gulp.

In the following chapters, I examine the ecological risks of several crop–transgene combinations from a scientific perspective. Of interest is how the media and others interpret scientific research as these entities influence popular opinion. We'll take a look at views postulated by those who are opposed to GM technology in general and try to reach some middle ground, at least as far as the science will allow us to go. In the end, we'll see where scientific knowledge ends and speculation begins. Into the foreseeable future scientists will continue to perform experiments pinpointing risks and benefits in order to increase our knowledge about the roles of GM plants in agriculture. This research, no doubt, will continue as long as there are GM crops.

When the risks and benefits are diverse, how do we determine the advantages and acceptability of a technology, such as biotechnology? I think the safest path is to examine several specific cases where extensive scientific knowledge is available to extrapolate to bridges we're bound to cross in the future. And we will look to the future of GM plants. Plants that will be used to clean up the environment and monitor toxins will help us address problems we have not been able to solve in any other way.

The book begins and ends with some philosophical musings intended to place biological research and developments, and, in fact, agriculture, into a framework of the existing natural world. This world is highly modified by, among other things, agriculture and its blatantly unnatural components. Will modifying agriculture with biotechnology alter nature even more than it already has? Or will biotechnology actually make agriculture more harmonic with nature? We can learn a great deal about nature, agriculture, and genetic engineering by examining existing crops and weeds. The context for genetic alterations is in the farmer's field.

2

Crops and Weeds

It's Hard to Be a Wild Thing When You're Domesticated

On the Beach au Naturale

What is natural? It is an important question for interpreting biotechnology. As I sat au naturale on a deserted beach in Australia, I pondered that question. Certainly, in that setting, it appeared that everything I was seeing was natural: sea, sand, rocks, birds, and a horizon that consisted of commingled water, sky, and clouds. On other days, I've walked trails in old-growth forests observing that this, too, seemed completely natural. In each setting there was only one glaringly unnatural thing: me! There I was, a human being, sporting clothes (sometimes), a wristwatch, money, and keys—all of which linked me to the rest of the seemingly unnatural, man-made world. I, a member of the ultimate invasive species, was a foreign trespasser in otherwise pristine environments.

There is a contrasting view of nature that is all-inclusive. Here humans are as organic as the next species and part and parcel of nature itself. All organisms adapt to their environment, seeking to maximize their resource requisition and their fitness. Humans are no different from the rest of life, and while they may have modified their environment with seemingly artificial things, they are still members of nature, along with every other organism and its environmental modifications. In this case, automobiles, airplanes, asphalt, and office buildings are all part of nature, albeit a human-modified nature, which seems to be the natural thing for humans to do! In either view, mosquitoes, poison ivy, and rabies are also natural.

I think that most people's opinion of "nature" or "natural" would line up more closely with the first viewpoint than with the second "humans-as-natural-invaders" scenario. The latter is more logical, but the first is more emotionally satisfying. In reality, it is quite difficult to differentiate between the natural and unnatural. Is it natural for a chimp to use a stick to flush a dinner of ants from a hole in the ground? Is it natural for me to catch a fish dinner from a stream using another type of tool, a rod and reel? What is the difference between chimps and humans using tools to modify their environments and acquire resources? While the fishing experience might make me feel quite connected to nature, am I really invading a natural ecosystem using a tool, quite similar to the chimp, to catch food? Does the fisherman even have a natural environment? If so, where do we go to find it? Is it natural for me to be sitting in my office and typing on a computer? If I must be typing, is that my natural environment? Many of my colleagues might assume that it is, but if I had to be typing, I'd rather be typing on a beach in Australia.

This little exercise in futility is simply to underscore the point that we really can't precisely define what is natural. Many of the things that we assume are completely natural can't logically be declared as such. Agriculture and food lie at the epicenter of claims and confusion about all things natural. A case in point is so-called natural or organic food. Nearly all of it comes from crops that are overbred and highly domesticated. "Natural" wheat crackers come from a polyploid species that is a combination of at least three other species. Wheat is the product of millennia of human intervention and innovation. The crop is grown in monocultures designed to maximize the yield of one certain plant seed at the expense of every other plant, animal, and microbe—a low-biodiversity environment. After the grain is harvested with a machine, it is shipped in a truck across the country and loaded into a mechanical crusher. The crushed wheat is then mixed with other unnatural ingredients and chemicals, cooked in a man-made oven, and cut into uniform geometrical shapes. The so-called natural wheat crackers are packaged in petroleum-derived plastic and then secondarily packaged in a box made from dead and highly treated trees. Finally, the boxes are shipped to a grocer in a truck fueled by more petroleum and stocked on shelves in a place that, once again, is designed to deliver food to humans only. The crackers are often eaten with "natural" cheese that is produced using one of the earliest-developed processes of biotechnology involving the manipulation of enzymes.

So what makes such crackers natural? Is it because the only purified chemical they may contain is sodium chloride? Or is it because the wheat was grown on a farm that used no GM crops, synthetic fertilizer, or pesticides? If the latter were the case and the farm were "organic," crops may have been sprayed with a naturally occurring bacterial pesticide, such as *Bacillus thuringiensis* (a relative of the anthrax-causing bacterium; see figure 2.1), or otherwise contaminated with fungi that produce known neurotoxins.

The fact remains that the terms "natural" and "nature" are not terms we use to describe an objective reality, but are based largely on human emotion and aesthetics. Nature is not precisely definable. That is not to say that our perceptions of nature are without value—the increasingly rare environments that have not been overtly modified by humans should be preserved. There is emotional, social, spiritual, and even economic value in their conservation. But even these so-called natural environments contain blatantly unnatural components, components that were not present in recent history. Just behind my pristine, deserted beach in Australia was a semi-managed strip of lawn and tangled bank that contained *Vinca major*, large periwinkle, a popular landscaping groundcover (figure 2.2). Also present were populations of *Raphanus raphanistrum*, the wild radish, a particularly invasive agricultural weed (figure 2.3). In addition to these two species, there were a number of other escaped ornamental plants and exotic grasses. Part of the strip was intermittently mowed, but it was

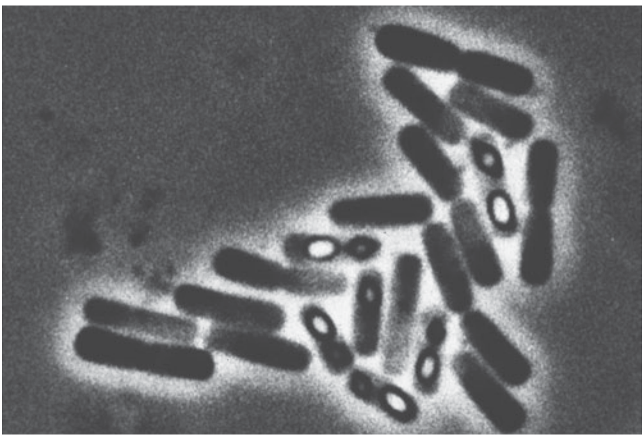

Figure 2.1. *Bacillus thuringiensis* bacteria and insecticidal crystals are used as insect control agents.

Figure 2.2. A natural-looking beach in Victoria, Australia. Note that the vegetation to the left of the central path contains horticultural and weedy plants that are not native to the continent. The bottom left contains a large patch of wild radish (*Raphanus raphanistrum*).

Figure 2.3. A prolific population of Australian wild radish on the beach.

otherwise unmanaged, and it seemed that no one had purposefully planted or maintained the bank. To most people, the plants would appear to be part of nature. To the botanical eye, though, they could be immediately recognized as exotic invaders.

Most people would enjoy seeing the small stands of wild radish with its light yellow flowers attracting a number of butterflies. Those same people would react less favorably to a monoculture of it by the beach, severely decreasing the biodiversity of other kinds of plants that could have been growing there. So exactly what are our baseline and criteria for defining natural or invasive species? Does it matter how long ago wild radish invaded the Australian coastline? Let's imagine it had been there for 20,000, 300, 20, or only 2 years. Where do we draw the line between native or natural and exotic or unnatural? These exercises are not just academic calisthenics. If the wild radish population had been there for 20,000 or even 300 years, we might rightly assume that the species had reached equilibrium, and radish would likely not displace other plants and otherwise alter stable ecosystems in the future. Twenty years may not have been long enough for population stasis to be reached. As for a plant species that suddenly appeared within the past year, it is anyone's guess what it will do. It might die out the following year, or it could become the new Australian kudzu. We want to avoid anything that could become the latter.

In actuality, wild radish has probably been along this particular strand of beach for about 15–20 years, and it is likely to continue its expansion, both in number of patches and size of patches. We can make this prediction based on its ecology. It is a nasty weed in grain crops in Australia and all other grain-growing continents; one author has called it "the nemesis of man's grain crops."[1] Most ecologists, weed scientists, and agronomists, as well as farmers and naturalists, would agree that wild radish is a problem for Australia that will only get worse. It has a prolonged vegetative phase in the spring and then starts flowering and setting seeds, continuing to do so for an extended period of time. In contrast, crops tend to flower and set seed in a linear fashion and in a short period of time. Wild radish seeds are in fruits called siliques that do not easily release their propagules. In my lab and other labs that work with this weed, researchers have invented various and sundry apparatuses to coax the seeds out of the wild radish siliques without crushing the seeds, or without driving the seed-extracting operator into a frenzy. That the seeds stay in the siliques a long time endows the species with a mechanism that staggers seed