Plants, Genes, and Crop Biotechnology

Plants, Genes, and Crop Biotechnology

SECOND EDITION

Maarten J. Chrispeels & David E. Sadava

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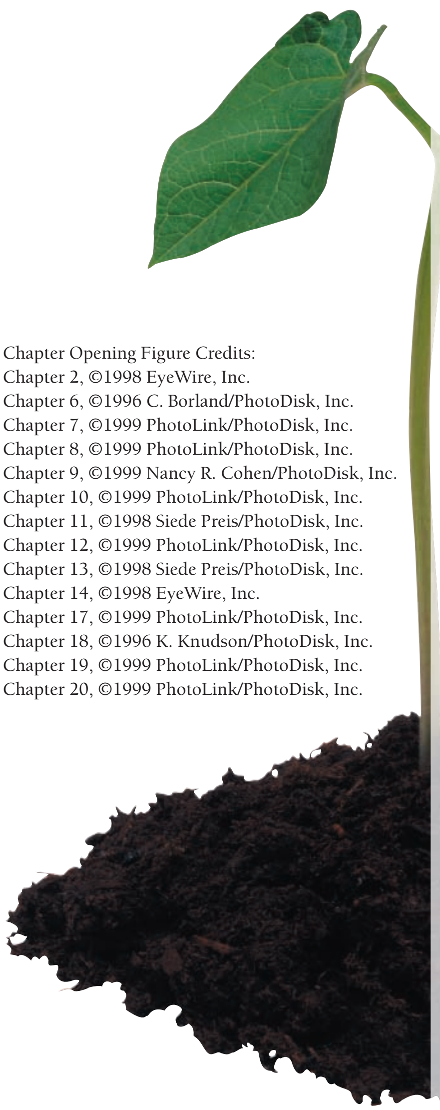

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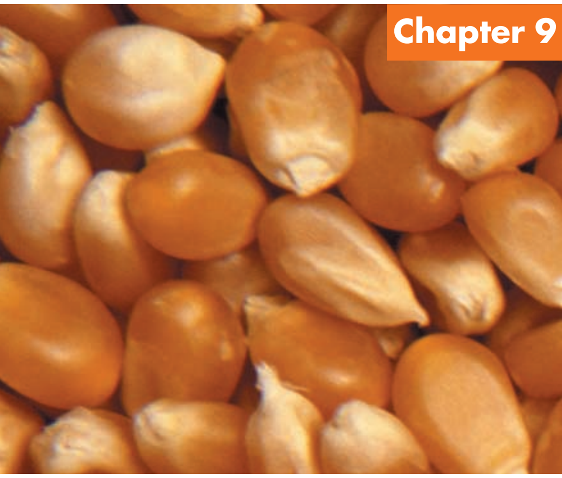

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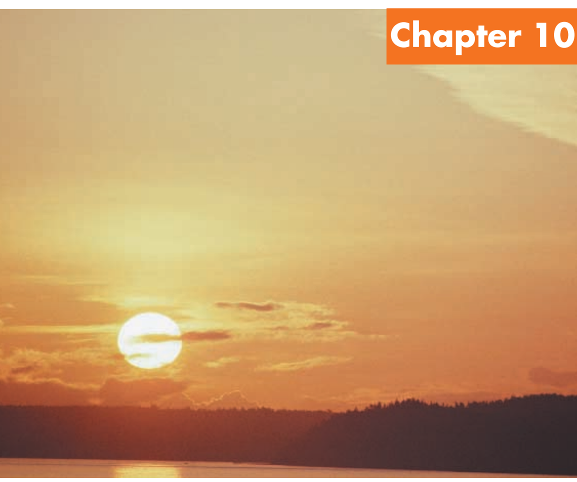

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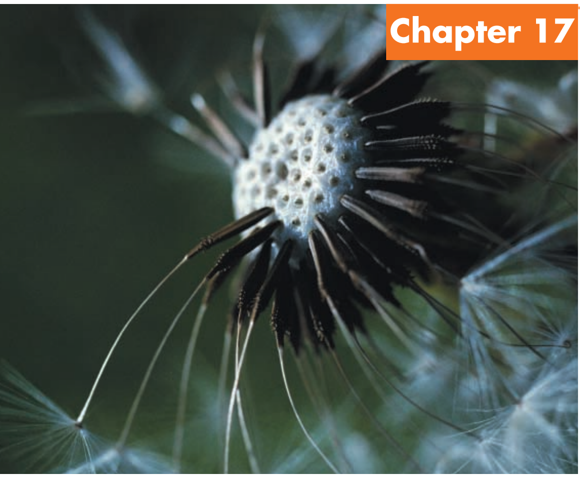

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FOREWORD

Just five decades have passed since Watson and Crick deciphered the double helix structure of DNA, the stuff of genes, and laid the groundwork for modern biotechnology. Today we know the full genetic sequence of more than sixty living organisms. The list includes human beings, over thirty important human pathogens, the photosynthetic plant *Arabidopsis thaliana,* plant pathogens, several *Archaea* from exotic environments such as ocean depths and hot springs, and nature's own genetic engineer, the bacterium *Agrobacterium tumefaciens,* which for millennia has been transferring bacterial genes into plants to create new plant traits *Agrobacterium* finds useful. Two draft sequences of the rice genome were recently published, and by the end of 2002 an international public-private partnership led by the Japanese, expects to put in the public domain the full genetic sequence of rice, the world's most important food crop and the genetic "Rosetta Stone" for all the cereals. Already the functions of many rice genes have been determined, and plant scientists throughout the world are using rice genome sequence data to improve productivity and disease resistance in rice and other crops.

In 2001, more than 5.5 million farmers worldwide planted about 52.6 million hectares of crops that were genetically manipulated (GM or transgenic crops, also called GMOs). This year the area has expanded further with India and Indonesia joining twelve other countries, including China, Mexico, South Africa, and Argentina, in approving the commercial planting of GM crops. But, agricultural biotechnology means a lot more than the creation of GM crops. It also involves the use of tissue culture to rapidly propagate disease-free seedling plants and to create new hybrids between plants that do not cross naturally, the use of sophisticated DNA-based genetic markers that allow breeders to follow and select for important traits more easily, and the use of DNA chips and other DNA-based diagnostic techniques to characterize pathogen populations for more effective deployment of resistant varieties. When we look globally we see that the real potential for public benefit from these technologies exists in developing countries where access to genetically improved crop varieties can mean the difference between hunger and a sustainable livelihood. These countries will need to draw on the best that science has to offer to help their farmers increase the productivity, nutritional value, stability of production, sustainability, and profitability of their crops. The task is to produce new crop varieties that are genetically altered to grow in poor soils and with less water, that use plant nutrients more efficiently, that can resist tropical pests and diseases—thus reducing yield losses—and that add micronutrients and essential amino acids to deficient diets. But, will this potential be realized?

Realistically, the question is no longer whether biotechnology will be used in food and agriculture, but rather how? We suspect the reason some people want to stop agricultural biotechnology, even when they understand its potential benefits, is that they do not believe those developing it will ever make the commitment to use it well and to use it equitably, and, therefore, they think biotechnology had better not be used at all. While we disagree with their conclusion, we believe they have legitimate concerns. We do need to establish more effective social and political processes to assure that biotechnology will be used wisely, that it will be made available to and used by public researchers to develop products that benefit people with limited purchasing power, and that these products will be made available for adaptation and adoption in developing countries.

While multinational corporations can help through public-private partnerships, for-profit companies will never make significant investments where there are no or limited markets. It is the international agricultural research centers of the Consultative Group on International Agricultural Research and the public agricultural research systems in larger developing countries that must assume responsibility for using these technologies to produce new crop varieties that will benefit poor farmers. These public sector agricultural research institutions need to be well supported both financially and technologically, including development of new strategies that will help them reestablish effective collaboration with advanced research institutes and universities in industrialized countries.

This second edition of *Plants, Genes, and Agriculture* with its new title *Plants, Genes, and Crop Biotechnology* provides the historical context, the global perspective, and the scientific information that students, scientists, development specialists, and knowledgeable people will find highly useful in better understanding plant genetics,the potential of agricultural biotechnology, and how biotechnology can help small-scale farmers everywhere sustainably meet their food and income requirements.

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PREFACE

We have published the second edition of *Plants, Genes, and Agriculture* with a slightly changed title to provide teachers and students of introductory courses in plant biology and crop science with a resource that will allow them to see their respective disciplines from a new vantage point. Our objective is to present an integrated view of crop biology, leading to a broad appreciation of plant biology and biotechnology in agriculture (for plant biology courses), as well as the basic biological underpinnings of crop biology and biotechnology (for crop science courses). The population explosion of the 20th century had a dramatic effect on planet Earth: huge areas with natural ecosystems rich in plant and animal life were converted to agriculture with dramatic consequences for the environment. Humanity's challenge for the new century is to double food production and to do so in a sustainable way. To achieve these twin goals, people in all walks of life need to understand what it takes to grow crops, how progress in crop production was achieved in the past, and what the role of biotechnology will be in the future.

Many people in technologically advanced countries have become more interested in the ways that their food crops are grown and how they reach the markets where they shop. This interest results in part from a greater concern for nutrition and health and from a few scandals caused by breakdowns in the regulatory processes that assure the safety of our food supply. This concern about food presents us with an opportunity to educate people about the scientific principles that underlie crop production. We, therefore, view this text as being suitable for general education courses aimed at nonscientists.

Our topic is broad, and we discuss not only the natural sciences but the social sciences as well. Among the former are plant anatomy and development, plant physiology, molecular biology, genetics, plant breeding, evolution, ecology, soil science, pest and disease control, and biotechnology. Among the latter are such aspects as the economics of farming, trade policies, price supports, the funding of research, and the economic and social benefits of biotechnology.

The first chapter of this book deals with human population growth, and the news is fairly good. When we wrote the first edition in 1994, there was no end in sight to the human population explosion. Experts now agree that, barring unforeseen events, human population will level off at about 10 billion sometime during this century. This chapter, therefore, sets the stage for the challenge: doubling food production during the same time period.

The second chapter, written by two agricultural economists, describes the changes that have taken place in agricultural production as a result of developments that accompanied the industrial revolution, and emphasizes the role that science has played in this development. The tremendous economic return of investment in agricultural research justifies our subsequent focus on the scientific basis of increased crop productivity.

Chapter 3 looks at agricultural development from a biological vantage point and emphasizes the need to reach sustainability of this important human enterprise. The fact that directly or indirectly (as animal feed) plants are the basis of human nutrition leads to a discussion of the gradual intensification of plant agriculture throughout human history. The culmination of this intensification, known as the Green Revolution, raised food production in some developing countries to the point where they became food exporters; globally, the Green Revolution allowed food production to outstrip population growth in the last half of the 20th century.

The fourth chapter discusses a most difficult issue: Why are there 800 million hungry people in a world with adequate food for all? Clearly, our market driven economic system has not produced the result that many would like: equitable distribution of that food and food sufficiency for everyone. Purchasing power is the problem, but how we go about increasing it for the poorest of this world is a major challenge.

There are several reasons why we decided to devote an entire chapter (Chapter 5) to agriculture in sub-Saharan Africa. Sub-Saharan Africa is ecologically very diverse, and in Africa, the ecological dimension of crop production is most striking. In addition, the Green Revolution bypassed sub-Saharan Africa, in part because Africa has so many agroecological zones. Africa is the world's only continent where food availability per person has declined in the past 30 years, so it provides the greatest challenge to the agricultural system. Chapters 2, 4, and 5 are new in this edition, and together with Chapters 1 and 3, they constitute a discussion of economic, sociological, and ethical aspects of feeding the world that transcend the strictly biological problem.

The second part of the book comprises the basics of plant biology, beginning with a discussion of the molecular basis of crop improvement in Chapter 6. To understand both plant breeding and genetic engineering, one must understand how genetic information (DNA) is transmitted from one generation to the next and expressed in a plant as the outward appearance, or phenotype. The principles of genetics and molecular biology can now be used to transfer genes between unrelated organisms (genetic engineering). This powerful and unprecedented technology has resulted in genetically engineered crops, here referred to as genetically manipulated (GM) crops, which are widely used in several countries. Examples of GM approaches to crop improvement are discussed in many subsequent chapters.

Plants feed people, either directly or indirectly, but what are our nutritional requirements and how do our food plants satisfy them? Do different plants and plant parts have different nutritional values? Do vegetarians have to take special precautions to eat a healthy diet? How can plants be bred to be more nutritious? Is this an area where genetic engineering can play an important role? The role of nutrients such as vitamins, minerals, or proteins is well defined, but what about the role of non-nutrients such as antioxidants in our diets? These and other questions are dealt with in Chapter 7.

People eat a variety of plant parts: seeds (bread, rice, beans), roots (carrots, cassava), tubers (potatoes), leaves (cabbage), stems (sugar cane), fruits (bananas and plantains), and even flowers (artichokes). Chapter 8 describes how these plant organs and tissues are produced from a single cell, the fertilized egg. First a seed is produced, and after it germinates the vegetative body of the plant develops. Flowers and fruits come later. This orderly sequence of events is under exquisite genetic and environmental control.

Chapter 9, a new chapter for this second edition deals with the biology and technology of seeds. Seeds are not only our most important food source, but they are also agents of plant reproduction. Companies produce elite varieties of crops and sell these to farmers primarily as seeds, often as hybrid seeds or as GM seeds. Essentially the economic value of plant breeding and biotechnology is captured in seeds.

Plant growth depends on the assimilation of carbon dioxide from the atmosphere utilizing solar energy (photosynthesis) and on the uptake of minerals from the soil and their subsequent assimilation into molecules that underlie plant structure and function. These processes are the subjects of Chapters 10 and 11, respectively. In addition to dissolved minerals, soil is also the source of water needed to maintain the transpiration stream. The productivity of crops depends heavily on managing the physical environment by adding nutrients, changing the acidity of the soil or supplying irrigation water. Barring such management, the plants experience stresses, and stress management is important for optimizing plant productivity. Conventional plant breeding and GM approaches to alleviating these stresses are also discussed.

Plant biologists usually study processes such as plant development, photosynthesis, or nutrient uptake using plants grown in isolation and without considering the interactions of these plants with other living organisms. In nature, however, plants interact directly with numerous other organisms (pests, pathogens, and symbiotic microbes, for example), and they depend indirectly on the activities of other microbes that participate in the cycling of nutrients. Nowhere are such interactions more intense than in the soil, and "life together in the underground" is the subject of Chapter 12. The soil contains a complex ecosystem in which million of species interact with one another and with the roots of plants. This ecosystem derives its energy from root exudates and decaying roots and, therefore, from photosynthesis. Many of these soil processes are vital to the sustainability of agriculture, discussed later in the volume, and Chapter 12 marks the transition to the third part of the book, dealing with agriculture.

As a human activity, agriculture began millennia ago. Chapter 13 traces its origins and spread. People saved some of the seeds they harvested for the next year's crop planting. These saved seeds captured the gradual evolution of our crops from their wild ancestors to the landraces of yesteryear and the present elite lines.

This leads to a discussion in Chapter 14 of plant breeding, the principal mechanism of crop improvement in the past and in the future. "Genetics is King" when it comes to raising crop productivity, and plant breeders use a variety of tools to genetically improve crops. Pure-line selection, back crossing, hybridization, embryo rescue of wide crosses, mutation breeding, and genetic engineering are all tools of the plant breeder. In addition, the new science of genomics is certain to speed up plant breeding considerably in the 21st century.

In the field, crop plants face stiff competition from diseases such as molds, from other plants (weeds), and from insects. Minimizing this competition is the subject of Chapters 15, 16, and 17, respectively. Diseases take their toll on the amount of the crop that the farmer harvests and genetic improvement of crops remains the best solution (Chapter 15). Because disease organisms evolve rapidly, however, this solution is never permanent and the plant breeder's work is never finished. We are making rapid progress in understanding the molecular mechanisms involved in the plant's defense mechanisms against disease organisms, and this will lead to new GM-based approaches to combat diseases.

There are many kinds of weeds, annuals and perennials, grasses and dicots; sometimes they closely resemble the crop, sometimes not. Weed control (Chapter 16) also takes several forms: manual removal (hoeing) is still very common on low-resource farms in developing countries, on organic farms in developed countries, and, when appropriate, on large farms. For many crops, chemical weed control has replaced mechanical hoeing in developed countries because it reduces labor costs. The newest refinement of weed control is to create GM crops that are resistant to certain herbicides. These crops are popular because they save the farmer money and reduce soil erosion.

Insects and other pests such as mites and nematodes can damage the parts of the plant that people want to harvest (e.g., seed weevils), or they weaken the plants so that their growth is diminished (rootworms) or the plants fall over (stem borers). Other insects such as whiteflies suck the products of photosynthesis directly from the circulatory system of the plant. As discussed in Chapter 17, because of the enormous losses sustained by farmers, insect and nematode control are of paramount importance to them. Again there are different strategies: genetic improvement of the crop as part of an integrated pest management approach is the best approach. This may be combined with biological control measures that include the release of predators or with chemical sprays that simply kill the pests. The latter method invariably results in the appearance of resistant pest strains. Genetic engineering with toxin genes from bacteria now provides a targeted approach to the killing of specific pests.

Chapter 18, "Toward a Greener Agriculture," discusses the practices that make agriculture more sustainable. These practices view agriculture as part of a natural ecosystem, and their objective is to minimize the environmental impact of crop production. Adopting sustainable practices is usually tied to government policies that may reward farmers or discourage them from doing so. Sustainable agriculture is fully compatible with GM technology. Instead of adapting the environment to the crop plant, which has been a basis of agriculture throughout history, this technology has the potential to use new genes to adapt the plant to its environment, thus minimizing ecological impact.

At one time, agriculture supplied us not only with food but also with many other products that society needs. Many of these other products are now derived artificially, from petroleum or other industrial sources. For example, think of the replacement of cotton with synthetic fibers. This changeover was paralleled by the development of the chemical industry. Could (or should?) agriculture once again be used to produce the chemical feedstocks that industry needs, and what would be the impact of this on land utilization and on food production? Could plants be used to produce pharmaceuticals and vaccines? These fascinating questions are pursued in Chapter 19.

The final chapter in this book concerns the myths that have sprung up around GM crops. Groups opposed to this technology have introduced emotionally charged terms such as "genetic pollution" and "superweeds" into the discussion. Public polls conducted by reputable agencies have found that a substantial number of people believe that eating genetically engineered plants will cause their own DNA to be mutated. This chapter discusses some of these myths and forthrightly addresses some of the as yet unsolved problems associated with the adoption of GM crops.

We wish to thank the many people who made this second edition possible. First of all, the contributing authors of the chapters whose names are at the chapter headings responded enthusiastically to our call to update the first edition. This is as much their book as it is ours. Second, we are grateful to all the people who generously sent us photographs for inclusion in the book. Assembling the artwork from the far corners of the globe turned out to be a most arduous task, and we are thankful for all the help we received. We hope that they have all been acknowledged but fear that our record keeping is less than perfect. We received feedback from teachers, especially from Larry Grabau of the University of Kentucky, and from a number of colleagues who reviewed the chapters for accuracy. We are extremely grateful to our administrative assistant Milda Simonaitis who, for an entire year, worked tirelessly with the authors and with the publisher to help us go from concept to finished product. We are very thankful to Linda Purrington, the Golux, for making the writing styles of the various authors more uniform and polishing some of the rough edges when the writing was, well…, less than fluent.

Maarten Chrispeels would like to express his appreciation not only to his agricultural mentors, first at the School of Agriculture in Ghent, Belgium (1955–1960) and then at the University of Illinois (1960–1964) but also to his father Felix Chrispeels who imbued him with a love for cultivating the soil and caring for plants. David Sadava was inspired by his university teachers of plant biology, Margaret McCully and Frank Wightman.

We are especially thankful for the professionalism of the staff of Jones and Bartlett, including Louis Bruno, Anne Spencer, Kristin Ohlin, Stephen Weaver, and Dean DeChambeau. We hope that this book will help our fellow teachers design courses that will inspire a new generation of students to enter the basic and applied sciences that help feed the world.

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