# PLANT BREEDING AND BIOTECHNOLOGY

## Societal Context and the Future of Agriculture

This accessible survey of modern plant breeding traces its history from the earliest experiments at the dawn of the scientific revolution in the seventeenth century to the present day and the existence of high-tech agribusiness. Denis Murphy tells the story from the perspective of a scientist working in this field, offering a rational and evidence-based insight into its development. Crop improvement is examined from both a scientific and socio-economic perspective, and the ways in which these factors interact and impact on agricultural development are discussed. In conclusion, some concerns over the future of plant breeding are highlighted, as well as potential options to enable us to meet the challenges of feeding the world in the twenty-first century. This thoroughly interdisciplinary and balanced account will serve as an essential resource for everyone involved with plant breeding research, policy and funding, as well as those wishing to engage with current debates about agriculture and its future.

DENIS J. MURPHY is Professor of Biotechnology at the University of Glamorgan, UK. His career in plant biotechnology research spans three decades, including ten years on the management team of the John Innes Centre, arguably Europe's premier research centre in plant science. He is currently highly involved with the ongoing debate on genetically modified food and crops, both locally and internationally, providing expertise and advice to numerous organisations and government agencies, as well as engaging with the general public and the media.

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521823890



First published 2007

Printed in the United Kingdom at the University Press, Cambridge

*A catalogue record for this publication is available from the British Library*

ISBN 978-0-521-82389-0 hardback
ISBN 978-0-521-53088-0 paperback

In the frozen midwinter of 1941–1942, the great metropolis of Leningrad began its epic 900-day siege by the encircling German army. Throughout the ruined city, thousands of people were dying of cold, starvation, and shellfire. In the world's oldest seed bank, at the Institute of Plant Industry, a dedicated team of breeders and curators sought to guard and preserve their priceless samples for posterity. This collection of over 160 000 plant varieties had been set up in the 1920s by Nikolai Vavilov, the doyen of twentieth century plant breeding. Hardly any food reached the biologists as they maintained their protective vigil. One by one, they succumbed to starvation, surrounded by bags of edible seeds and tubers. The oats curator L. M. Rodina died, as did rice curator D. S. Ivanov, and peanut curator A. G. Shtchukin, and seven more of their heroic colleagues, one of whom even expired at his desk, working until the end. When the city was eventually liberated in January 1944, the entire collection was intact. It has since been used to supply new edible plant varieties to millions of people around the world.

This book is dedicated to all the many heroes of plant breeding, both past and present, including: Norman Borlaug, Robert Carsky, Charles Darwin, Thomas Fairchild, Jack Harlan, Monkombu Swaminathan, Nikolai Vavilov, those brave workers from Leningrad and from other more recently threatened seed banks in Asia and Africa; and, of course, the untold generations of anonymous farmer-breeders, most of whom were women.

*It is to you that we truly owe our daily bread.*

# Contents

# Preface

This book is an evidence-based and, in places, a personal account of the development of scientific plant breeding over the past two hundred years. The work is informed by my background and experiences as a biologist who, while largely trained in the UK, has also worked extensively in the USA, Germany, Australia and, more recently, in the Far East. It is the story of how breeding evolved from an empirical endeavour, practised for millennia by farmers and amateur enthusiasts, to become the globalised corporate agribusiness enterprise of today. I was moved to write this account after spending over two decades working at the interface of academic plant science and its practical application in crop breeding. During this time I have witnessed the steady erosion of plant breeding as a worthwhile and respected aspect of plant science, especially in the public sector. One of my principal motives in writing the book is to raise the profile of plant breeding as a valued and useful profession. I also wish to highlight some of the many imbalances that now bedevil our approach to breeding, some of which have coloured today's often contentious discourse on agriculture and crop improvement in general.

There are many misapprehensions, among scientists and the general public alike, about the way that plant breeders go about their business. In particular, the supposedly revolutionary nature of the 'new' (actually now more than two decades old) technologies of genetic engineering has been exaggerated by virtually everybody involved in the debate, whether they be researchers, politicians, agbiotech companies or anti-GM (genetic manipulation) campaigners. The current fixation on this at times overhyped phenomenon is coupled with a worrying dearth of knowledge and understanding about the many other (non-transgenic) forms of plant breeding which, as I will show, can in principle be subjected to many of the same objections that are levelled against GM technologies. So, why is it that this particular aspect of plant breeding is deemed so threatening that it can elicit violence and disorder among often idealistic and well-intentioned anti-GM activists, while the same people know little of the rudiments of plant breeding in the wider sense? And it is not just anti-GM campaigners who have little knowledge of the broader socio-scientific dimensions of

plant breeding; a similar charge can be levelled against many people in the broader realms of science, politics, the media etc.

In Part I, we will begin to address these issues by discussing the basic scientific background of plant breeding. These three chapters are the only ones that focus on science per se. The remaining five parts of the book are devoted to examining the interface between science/technology and society, and the manner in which these forces have mutually influenced each other in the case of plant breeding and the production of improved crops. In this analysis, I will take it as read that science and technology are deeply embedded in the wider socio-economic milieux from which they both arise. This is particularly true in the case of plant science and its applications via various technologies to effect improvements in crop performance. As we will see, an 'improvement' is normally so defined by the improver; hence one person's improvement might even be another's curse. Science and society are respectively made up of many players, all of whom interact with and affect one another, often in subtle ways that are not always obvious to the casual observer. In the case of GM crops, the peculiar, and unusually contentious, trajectory of this technology has been determined by interactions between a host of factors including scientific discoveries (how to transfer genes), legislative measures (patenting plants), the economic environment (privatisation), political opportunism (policy based on pressure groups), ideology (policy based on belief systems), and so on. I will show how it was a particular conjunction of circumstances in the 1980s and 1990s that has led to the current, and arguably inappropriate, domination of the agbiotech/GM phenomenon in both scientific and public discourse. A key message that I wish to convey is the need to rediscover a sense of perspective in our attitude to crop improvement and to raise our gaze beyond the narrow confines of the GM debate, so that we can behold the real challenges and opportunities that confront international agriculture in the twenty-first century.

# Acknowledgements

I am indebted to the many friends and colleagues who have, wittingly or not, inspired and assisted me in various ways during the writing of this book. This includes those colleagues at the John Innes Centre and University of Glamorgan with whom I have had numerous fruitful discussions over the past 15 years. Special thanks are due to Eddie Arthur and Ray Matthias with whom I tried (and failed) to interest funding agencies in the domestication of new crops – rest assured, our time will come. As an initially somewhat reductionist molecular biologist, I was challenged in the early 1990s by Colin Law who remained a true believer in traditional plant breeding, and a sceptic of the many chiliastic claims of agbiotech. I guess some of his sentiments must have eventually rubbed off on me, as this book shows. Other colleagues, including Ian Bartle, Gerry Roberts and Colette Murphy provided valuable feedback on various drafts of the manuscript, as did various anonymous referees. Finally, many thanks to Katrina Halliday and the staff at Cambridge University Press for their patience and encouragement during the gestation of this project.

***Denis J. Murphy***
Glamorgan, Wales, April 2006

# Using this book

This book is aimed at several audiences, from botanists to economists, and from business people to agronomists. Each group of readers will have different technical backgrounds and different types of expertise. The book is therefore written on three levels, namely the main text, a series of more than 900 endnotes, and a bibliography. For the general reader or specialist in other areas, the main text of each chapter should suffice to convey its key message. However, for those wishing to follow up points in more detail, the endnotes provide additional information that is in turn linked to a comprehensive bibliography of over 750 citations, mostly from the peer-reviewed primary literature. Wherever possible, I have also provided web links to the many articles that are now available online. Many of the better scientific journals now make their articles freely available on the Internet within a year of publication, and such web links tend to be relatively stable. These primary research articles can often be surprisingly accessible, even to the interested layperson, and I recommend interested readers to consult at least one or two examples.

Secondary literature sources, e.g. scholarly reviews, government reports, conference papers etc., are also often available on the Internet and can frequently be useful resources, especially for the technical specialist from a different field. Such articles generally give a broader perspective than primary research papers, but may not necessarily be peer reviewed. 'Tertiary' sources, including newspaper and magazine articles, are rarely peer reviewed. Such articles tend to be more 'fresh' and accessible in their content, but can also be less factually reliable, and rarely provide a broad overview of the topic in question. Tertiary sources also tend to be more ephemeral in their Internet locations (hence, *caveat lector* and my apologies in advance if some of the web links no longer work). Nevertheless, newspaper and magazine articles often add a welcome degree of colour and immediacy to a discussion that contrasts favourably with the more sober and restrained tone of most mainstream scientific literature.

# Nomenclature and terminology

*Measurements and dates*

The metric system is used throughout for all physical measurements. All prices are given in US dollars ($) and, unless stated otherwise, they relate to the period in question, i.e. prices are not corrected to present-day values. Some historical dates are expressed as BCE (before common era) or CE (common era). All unqualified dates refer to CE.

*Initials and acronyms*

I have tried to forebear, as much as possible, from using unfamiliar initials and acronyms in the main text. Where this is impractical, I give the full version of each term in the text when it is first used. A full list of such terms, plus some additional explanation of their significance, is also given in the Abbreviations and glossary section (see below).

*Industrial and developing countries*

In describing the major global economic blocs, the term 'industrial' is used to describe those countries that have already completed a thorough industrialising process. In many cases such countries are now at a post-industrial stage of development. Included here are the major globalised economies of North America, Europe, Australasia and Japan. I use the term 'developing' to describe those countries in which industrialisation is still proceeding, albeit often at an advanced stage. This group includes the Asian giants India and China, as well as most of the remainder of Asia, Africa and Latin America. This terminology is by no means perfect and there will always be exceptions. Neither is it meant as a value judgement since all countries are always in the process of some sort of development. But it remains, withal, a useful shorthand.

# Abbreviations and glossary

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| ADAS | Agricultural Development and Advisory Service (UK) – The former public sector agricultural advisory service for England and Wales. ADAS was gradually privatised during the 1990s until it became a private company in 1997. |
| AEBC | Agriculture and Environment Biotechnology Commission (UK) – the UK government strategic advisory body on biotechnology issues affecting agriculture and the environment. Established in 2000, the AEBC was wound up in 2005, following criticisms of its narrow remit and dissension among members. |
| BBSRC | Biotechnology and Biological Sciences Research Council (UK) – the major UK public sector funding agency for research in biological sciences, with an annual budget of about $550 million. |
| BIOS | Biological Innovation for Open Society – an initiative of **CAMBIA** to 'foster democratic innovation in applications of biological technologies to sustainable development'. |
| Bt | *Bacillus thuringiensis* – a bacterium that produces a variety of insecticidal protein toxins. Bt sprays (containing bacterial spores and toxin crystals) are regularly used as insecticides by organic farmers, while the Bt toxin gene has been added to some crops to provide inbuilt insect protection. |
| CAMBIA | Center for the Application of Molecular Biology to International Agriculture – non-profit, Australian-based scientific organisation working for the development of new **open access technologies** for crop improvement across the world. |

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| CGIAR | Consultative Group on International Agricultural Research – an alliance of countries, international and regional organisations, and private foundations that supports 15 Research Centres. The Centres work with national agricultural research systems and civil society organisations including the private sector and generate global public goods that are freely available to all. CGIAR research centres include **CIAT**, **CIFOR**, **CIMMYT**, **CIP**, **ICARDA**, **ICRAF**, **ICRISAT**, **IFPRI**, **IITA**, **ILRI**, **IPGRI**, **IRRI**, **IWMU**, **WARDA** and **WFC**. |
| CIAT | Centro Internacional de Agricultura Tropical (Columbia) – one of the **CGIAR** crop improvement centres. |
| CIFOR | Center for International Forestry Research (Indonesia) – one of the **CGIAR** crop improvement centres. |
| CIMMYT | Centro Internacional de Mejoramiento de Maiz y Trigo (International Maize and Wheat Improvement Center Mexico) – one of the **CGIAR** crop improvement centres. |
| CIP | Centro Internacional de la Papa (Peru) – one of the **CGIAR** crop improvement centres. |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation – the principal public sector research organisation in Australia that covers agribusiness; information, manufacturing and minerals; and sustainable energy and environment. CSIRO manages several research centres that work on crop-related topics. One of the best known of these is CSIRO Plant Industry in Canberra, which is especially noted for its research on plant molecular and developmental biology. The annual budget is about $700 million. |
| Cultivar | a cultivated variety of a crop – such varieties have normally been selected by breeding and are adapted for a particular agricultural use or climatic region. |
| DEFRA | Department for Environment, Food and Rural Affairs (UK) – formerly known as **MAFF**, DEFRA was created in 2001 in the wake of the BSE scandal but lost its role in food safety to the new Food Standards Agency (**FSA**). |
| EMBRAPA | Empresa Brasileira de Pesquisa Agropecuária–Brazilian Agricultural Research Corporation. |

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| EST | expressed sequence tag – a small portion of a gene that can be used to help identify unknown genes and to map their positions within a genome. |
| *Ex situ* conservation | the maintenance of biological specimens away from their normal habitat, normally under closely controlled conditions, such as in arboretums (trees), and botanical (plants) or zoological (animals) gardens. The term also refers to the keeping of stocks, such as seeds, cuttings, or other propagules in germplasm repositories. |
| FAO | Food and Agriculture Organisation – United Nations agency, set up in 1945, whose mandate is: 'to raise levels of nutrition, improve agricultural productivity, better the lives of rural populations and contribute to the growth of the world economy.' Its annual $750 million budget covers both ongoing programmes and emergency relief work. |
| Farm-scale evaluations | a $9 million research exercise in the UK to determine the on-farm effects to fauna and flora of growing and managing herbicide tolerant crops compared to non-tolerant varieties of the same crops. |
| FMD | foot and mouth disease – also known as hoof and mouth disease in the USA, this virulent viral disease spread across the UK in 2001. Following scientific advice that has since been questioned, the UK government implemented a drastic cull that resulted in the slaughter of 6 million animals, at an estimated cost to the economy of $15 billion. |
| FSA | Food Standards Agency (UK) – established in 2000 'to protect the public's health and consumer interests in relation to food.' |
| Germplasm | the genetic material, i.e. the DNA, of an organism. The term is often used in connection with the collection or conservation of seeds, cuttings, cell cultures, or other germplasm resources, in repositories such as gene banks. |
| GM | genetically modified or genetically manipulated – a term normally used to describe an organism into which DNA, containing one or more genes, has been transferred from elsewhere. The transferred DNA is never itself actually from another organism, but may be an exogenous copy of DNA (i.e. from a different species). |

Alternatively the transferred DNA may be an extra copy of an endogenous gene (i.e. from the same species). Finally, the transferred DNA may be completely synthetic and hence of non-biological origin. An organism containing any of these categories of introduced gene is called **transgenic**.

Heterosis — also called hybrid vigour, the phenomenon whereby a hybrid of genetically distinct (but often inbred) parents is sometimes much more vigorous than either parent. In crop terms, hybrids exhibiting heterosis can out-yield their parents by as much as 30–40%.

HRI — Horticulture Research Institute (UK) – also called Horticulture Research International, HRI is a former public sector plant science research centre that was transferred to ownership of the University of Warwick in 2005.

Hybrid — an organism resulting from a cross between parents of differing genotypes. Hybrids may be fertile or sterile, depending on qualitative and/or quantitative differences in the genomes of the two parents. Hybrids are most commonly formed by sexual cross-fertilisation between compatible organisms, but cell fusion and tissue culture techniques now allow their production from less related organisms.

ICARDA — International Center for Agricultural Research in the Dry Areas – this CGIAR-affiliated centre, established in 1977 with its head-quarters in Aleppo, Syria, has a mission 'to improve the welfare of poor people and alleviate poverty through research and training in dry areas of the developing world, by increasing the production, productivity and nutritional quality of food, while preserving and enhancing the natural resource base.'

ICRAF — World Agroforestry Centre (Kenya) – one of the **CGIAR** crop improvement centres.

ICRISAT — International Crops Research Institute for the Semi-Arid Tropics (India) – one of the **CGIAR** crop improvement centres.

IFPRI — International Food Policy Research Institute (USA) – one of the **CGIAR** agricultural improvement centres.

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| IGER | Institute for Grassland and Environmental Research (UK – formed by a merger between the Welsh Plant Breeding Station and the Grassland Research Institute at Hurley. |
| IITA | International Institute of Tropical Agriculture (Nigeria) – one of the **CGIAR** crop improvement centres. |
| ILRI | International Livestock Research Institute (Kenya) – one of the **CGIAR** crop improvement centres. |
| Input trait | a genetic character that affects how the crop is grown without changing the nature of the harvested product. For example, herbicide tolerance and insect resistance are agronomically useful input traits in the context of crop management, but they do not normally alter seed quality or other so-called **output traits** that are related to the useful product of the crop. |
| *In situ* conservation | the maintenance of a species or population in its normal biological habitat. In the case of plants, this applies particularly to natural populations of crop species and/or their wild relatives that may be future sources of genetic variation, as well as to endangered species in general. *In situ* conservation is especially useful in the preservation of traditional crop **landraces**, many of which are under threat from the increasing use of higher yielding but more genetically uniform modern varieties in agriculture. |
| IPGRI | International Plant Genetic Resources Institute (Italy) – an international **CGIAR**-affiliated research institute with a mandate to advance the conservation and use of genetic diversity for the well being of present and future generations. |
| IPR | Intellectual Property Rights – as defined by the World Trade Organization: 'Intellectual property rights are the rights given to persons over the creations of their minds. They usually give the creator an exclusive right over the use of his/her creation for a certain period of time.' IPR covers literary and artistic works (via copyright) in addition to industrial inventions (via patents and trademarks) and typically lasts for about 20 years. IPR protection of living organisms, such as plant varieties, is a more recent and controversial development. |

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| IRRI | International Rice Research Institute (Philippines) – an independent, non-profit agricultural research and training organisation and **CGIAR** centre that is focused on rice improvement. IRRI was established in 1960 by the Ford and Rockefeller foundations in cooperation with the Philippines government with its main site at Los Baños, near Manila |
| ISNAR | International Service for National Agricultural Research (USA) – assists developing countries in improving the performance of their national agricultural research systems and organisations by promoting appropriate agricultural research policies, sustainable research institutions, and improved research management. |
| IWMU | International Water Management Institute (Sri Lanka) – one of the **CGIAR** crop improvement centres. |
| JIC | John Innes Centre (UK) – a **BBSRC**-funded plant and microbial science research centre near Norwich. |
| Land Grant Universities | US network of agriculturally focused universities established by the Morill Act in 1862. |
| Landrace | a genetically diverse and dynamic population of a given crop produced by traditional breeding. Landraces largely fell out of favour in commercial farming during the twentieth century and many have died out. Landraces are often seen as potentially useful sources of novel genetic variation and efforts are under way to conserve the survivors. |
| MAFF | Ministry of Agriculture, Fisheries and Food (UK) – the government department responsible for oversight of UK agriculture, including the commissioning of some research areas. MAFF was reorganised as **DEFRA** in 2001. |
| NSDO | National Seed Development Organisation – commercial arm of **PBI** in the UK. |
| Nutraceutical | a neologism combining nutritional with pharmaceutical and meaning a food product that has been determined to have a specific physiological benefit for human health. The term has no regulatory definition and is primarily used in promotion and marketing. |

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| Open access technology (OAT) | technology that may be protected but which is made available in the public domain. Some OATs might be freely available for unrestricted use, while others might only be available to members of a consortium who agree to use the technologies in a particular manner, e.g. solely as non-profit public goods. The best known OAT is the Linux computer operating system, but analogous OATs have recently been developed in the field of agbiotech, most notably by **CAMBIA**. |
| Output trait | a genetic character that alters the quality of the crop product itself, e.g. by altering its starch, protein, vitamin or oil composition. |
| PBI | Plant Breeding Institute – widely regarded as the premier centre of plant breeding research in the UK, based in Cambridge, PBI was privatised in 1989 and subsequently sold on to a series of multinational companies. |
| PBR | Plant breeders' rights – a form of intellectual property protection in the European Union (via **UPOV**) designed specifically for new varieties of plants. |
| PCR | Polymerase chain reaction – a technique for rapidly copying a particular piece of DNA in the test tube (rather than in living cells). PCR has made possible the detection of tiny amounts of specific DNA sequences in complex mixtures. It is now used for DNA fingerprinting in police work, in genetic testing and in plant and animal breeding. |
| PSIPRA | Public Sector Intellectual Property Resource for Agriculture (USA) – initiative of the Rockefeller and McKnight Foundations, in collaboration with ten of the major US **Land Grant Universities**. As with **CAMBIA**, this US initiative is designed to support plant biotechnology research in developing countries. |
| PVPA | Plant Variety Protection Act – legislation enacted in 1970 by the US Congress that extended **UPOV**-like legal protection to plant germplasm. |
| Quantitative genetics | the study of continuous traits (such as height or weight) and its underlying mechanisms. |

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| Quantitative trait locus (QTL) | DNA region associated with a particular trait, such as plant height. While QTLs are not necessarily genes themselves, they are closely linked to the genes that regulate the trait in question. QTLs normally regulate so called complex or quantitative traits that vary continuously over a wide range. While a complex trait may be regulated by many QTLs, the majority of the variation in the trait can sometimes be traced to a few key genes. |
| RAE | Research Assessment Exercise – method used in the UK to rank university research on the basis of the perceived quality of a 'unit of assessment' that normally corresponds to a department. This ranking is then used to apportion funding selectively in favour of higher ranked departments. |
| SAES | State Agricultural Experiment Station (USA) – established by the Hatch Act of 1887, the nationwide network of SAESs works with **Land Grant Universities** to carry out a joint research/teaching/extension mission. |
| Species | a group of organisms capable of interbreeding freely with each other but not with members of other species (this is a much simplified definition, the species concept is much more complex). A species can also be defined as a taxonomic rank below a genus, consisting of similar individuals capable of exchanging genes or interbreeding. |
| Teosinte | the original wild grass, native to Mexico, from which cultivated maize is derived; it is now classified as part of the same species as maize, *Zea mays*. |
| TILLING | Targeting Induced Local Lesions IN Genomes – the directed identification of random mutations controlling a wide range of plant characters. A more sophisticated DNA-based version of mutagenesis breeding, TILLING does not involve **transgenesis**. |
| Transgenesis | the process of creating a **transgenic** organism. |
| Transgenic | an organism into which DNA, normally containing one or more genes, has been transferred from elsewhere (see **GM**). |
| UPOV | Union for the Protection of New Varieties – established in 1960 by six European nations to extend legal ownership rights to plant germplasm. |

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| USDA | United States Department of Agriculture (USA) – established by President Lincoln in 1862, USDA is the government department responsible for all matters pertaining to agriculture, including aspects of trade policy, food safety and the environment. |
| WARDA | Africa Rice Center (formerly called West Africa Rice Development Association) – one of the **CGIAR** crop improvement centres. |
| WFC | World Fish Center (Malaysia) – one of the **CGIAR** agricultural improvement centres. |
| Wide crossing | in plant breeding this refers to a genetic cross where one parent is from outside the immediate gene pool of the other, e.g. a wild relative from one species crossed with a modern crop cultivar of another species. |
| Wild relative | plant or animal species that is taxonomically related to crop or livestock species and serves as a potential source of genes for breeding new crops or livestock varieties. |