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Foreword

This book is very timely. The issues of food security and climate change are both at the top of the political agenda. The agricultural sector is a significant contributor to greenhouse gas emissions and changes in climate are projected to affect agricultural productivity and food security, hence the need to limit greenhouse gases from the agricultural sector, and for the agricultural sector to adapt to a changing climate.

The last couple of years have been a period of increased food prices, increasing the number of people going to bed hungry at night to over one billion. The underlying causes of the increases in food prices are complex and include two factors related to climate change, i.e. poor harvests due to an increasingly variable climate (e.g. the Australian drought, which could be linked to human-induced climate change) and the use of food crops for biofuels (e.g. maize for bioethanol – addressing climate change by replacing fossil fuel energy with bioenergy), as well as increased demand from rapidly growing economies (especially China), higher energy and fertilizer prices, low food stocks per capita, export restrictions on agricultural products from a number of significant exporters to protect domestic consumers (e.g. Argentina, India and Ukraine) and speculation on the commodity futures market. In addition, many developed country agricultural import tariffs and export subsidies distort global markets: depressing world prices in some cases, for example via subsidized 'dumping' (making local production difficult in developing countries); and increasing global prices by inflating OECD (Organisation for Economic Co-operation and Development) prices.

Some factors impacting food prices are shorter term than others. For example the effects of adverse weather conditions tend to be relatively short-lived, but recurrent. High prices stimulate increased production, but rebuilding depleted global stocks to levels that markets are comfortable with will take years. Longer-term issues include the future cost of energy and the impact of global warming, which may give rise to more enduring climate change, more variable weather and more frequent occurrences of extreme weather events leading to potentially greater agricultural price variability in future. Therefore, a key question is: what do we need to know and what do we need to do if we are to provide sustainable, nutritious and affordable food for the world in an environmentally and socially sustainable manner? This book addresses many of these issues.

The goal of affordable nutritious food for all in an environmentally sustainable manner is achievable, but it cannot be achieved through current agricultural 'business as usual'. Instead, if a large part of the world isn't to go hungry in the 21st century, we need nothing short of a new 'agricultural revolution', with a more rational use of scarce land and water resources, an equitable trade regime, as well as widespread recognition and action on climate change. We also need to recognize that in this changing world we need new tools, which means increased investments in agricultural knowledge, science and technology.

It is undeniable that over the past century, agricultural science and new technologies have boosted production, with enormous gains in yields and reductions in the price of food. But these benefits have been unevenly distributed; for example, today (i.e. mid-2009) over one billion people still go to bed undernourished every night, especially in parts of sub-Saharan Africa and South-east Asia – there have been an additional 100–150 million people in the last couple of years associated with the increase in food prices and the global economic downturn. Primarily this is a problem of distribution and local production, but solutions are going to be increasingly difficult. In coming decades we need to double food availability, meet food safety standards, enhance rural livelihoods and stimulate economic growth in an environmentally and socially sustainable manner. All of this at a time when the rate of increase in productivity per hectare for most cereals is decreasing, when there will be less labour in many developing countries as a result of HIV/AIDs and other endemic diseases (e.g. malaria in Africa), when competition from other sectors will make water even more scarce, when there will be less arable land due to soil degradation and competition from biofuels, when biodiversity is being lost at the genetic, species and ecosystem level, and when the climate will be changing, resulting in higher temperatures, changing and more variable rainfall patterns (more intense rainfall events and less light rainfall events) and more frequent floods and droughts.

There is no doubt that the Earth's climate has changed over the past century due to human activities (use of fossil fuels to produce energy, coupled with unsustainable agricultural and land-use practices), and future change is inevitable. The magnitude of changes in the Earth's climate over the next two to three decades is independent of any post-Kyoto agreement and is controlled by historic emissions. However, changes in climate beyond the decade of the 2030s are critically dependent upon agreements to reduce global emissions of greenhouse gases as soon as possible.

This book comprehensively addresses the impact of climate change on crop productivity and approaches to adapt to both biotic and abiotic stresses, as well as approaches to reduce greenhouse gases. Crop productivity will not only be affected by changes in climatically related abiotic stresses (i.e. increasing temperatures, decreasing water availability, increasing salinity and inundation) and biotic stresses (such as increases in pests and diseases), but also changes in the atmospheric concentration of carbon dioxide, acid deposition and ground level ozone. Hence, a key challenge is to assess how crops will respond to simultaneous changes to the full range of biotic and abiotic stresses. Responding to these challenges will require advances in crop research and the adoption of appropriate technologies.

The new agricultural revolution needed to meet this challenge will require a fundamental rethink of the role of agricultural knowledge, science and technology. Agriculture can no longer be thought of as production alone, but the inescapable interconnectedness of agriculture's different economic, social and environmental roles and functions must also be explicitly recognized.

Thankfully, many of the technologies and practices we need to meet the challenge of sustainable agriculture already exist. For instance, we know how to manage soil and water more effectively to increase water retention and decrease erosion; we already have access to microbiological techniques to suppress diseases in soils; and conventional biotechnology (plant breeding) can help us produce improved crop varieties. But climate change and new and emerging animal diseases are throwing up problems that we have not considered before and which will need advances in agricultural knowledge, science and technology to address. In addition, we need to use technologies that already exist to reduce postharvest loss and improve food safety. We need to integrate, as appropriate, local and traditional knowledge with formal knowledge, ensuring that the needs of the small-scale farmer are addressed.

Climate change has the potential to irreversibly damage the natural resource base on which agriculture depends, and in general adversely affects agricultural productivity. While moderate increases in temperature can have small beneficial effects on crop yields in mid- to high latitudes, in low latitudes even moderate temperature increases are likely to have negative effects on yields. Water scarcity and the timing of availability will increasingly constrain production, and it will be critical to take a new look at water storage to cope with more extreme precipitation events, higher intra- and inter-seasonal variations (floods and droughts) and increased evapotranspiration. Climate change is already affecting, and is likely to increase, invasive species, pests and disease vectors, all adversely affecting agricultural productivity. Advances in agricultural knowledge, science and technology will be required to develop improved crop traits, for example temperature, drought, pest and salt tolerance. In addition, it will be critical to reduce greenhouse gas emissions from the agricultural sector – methane from livestock and rice and nitrous oxide from the use of fertilizers.

And while biofuels can offer potential benefits (i.e. energy security, reducing greenhouse gas emissions and improving rural economies) the production of first generation biofuels, which are predominantly produced from agricultural crops (e.g. bioethanol from maize, and biodiesel from palm oil and soya), can raise food prices and reduce our ability to alleviate hunger. There is also considerable debate over the environmental impact of biofuels, including the degree to which greenhouse gas emissions are reduced, and their impact on biodiversity, soils and water. Increased public and private investments are needed to develop future generation biofuels, such as cellulosic ethanol and biomass-to-liquids technologies, so that cheaper and more abundant feedstocks can be converted into biofuels, potentially reducing the demands for agricultural land.

Currently the most contentious issue in agricultural science is the use of recombinant DNA techniques to produce transgenic products because there is not widespread agreement on the environmental, human health and economic risks and benefits of such products. Many believe that less technology and intervention is the answer. But against a backdrop of a changing climate and the threat of even larger parts of the world going hungry, it is clear that integrated advances in biotechnology, nanotechnology, remote-sensing and communication technologies for instance, in combination with agroecological practices, will be important in providing opportunities for more resource-efficient and site-specific agriculture. Advances in genomics will play a critical role in traditional plant breeding as well as in possible options for genetically modified (GM) crops. No technology should be ruled out; however, it will be critical to assess the risks and benefits of any technology on a case-by-case basis. This book explores the full range of techniques that can be used to develop the crop traits needed to adapt to a changing climate.

Today's hunger problems can be addressed with appropriate use of current technologies, emphasizing agroecological practices (e.g. no/low till, integrated pest management (IPM) and integrated natural resource management (INRM)), combined with decreased postharvest losses, and trade reform and rural development more broadly. Small-scale farmers need access to the best seeds, financing and access to markets, and we need to create opportunities for innovation and entrepreneurship and invest in science and technology and extension services to meet their needs. We also need to provide payments to the farmer for maintaining and enhancing ecosystem services, and to recognize the important role of women and empower them through education, access to financing and property rights. But doubling food availability over the coming decades in the context of climate change and other stresses will require advances in crop research and improved agricultural practices, with emphasis on the sustainable management of water and soils.

Meeting the goal of affordable nutritious food for all in an environmentally sustainable manner is achievable, but we will need to decrease the vulnerability of agricultural productivity to projected changes in climate, develop the next generation of biofuels and transform the trade system to benefit the small-scale farmer. The future is not preordained, but is in our collective hands. While we can build upon our successes, we must also recognize that an extrapolation of business-as-usual will not suffice. Instead, we need to be bold enough to rethink agriculture. Most importantly, if we are to help today's and tomorrow's poor and disadvantaged, we need to acknowledge that the time to act is now.

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Preface

In light of population growth and climate change, investment in agriculture is the only way to avert wide-scale food shortages or, in the worst-case scenario, catastrophic human suffering. Assuming investment is forthcoming, maintaining food security will require crop scientists to integrate and apply a broad range of strategies. These include tried and tested technologies such as conventional breeding and agronomy as well as new approaches such as molecular genetics and conservation agriculture. Each topic in this book has been selected for its potential contribution to maintain and increase crop productivity in unpredictable environments, providing readers with an overview of the state of the art in respective fields. Examples of successful applications as well as future prospects of how each discipline can be expected to evolve over the next 30 years are presented. The objectives of the book are two-fold: (i) to lay out some basic concepts for crop scientists who, given changes in crop environments, may find it necessary to explore new disciplines in which they lack practical experience; and (ii) to provide an overview of the essential disciplines required for sustainable crop production for policy makers, academics and students of agriculture.

Dedication

This book is dedicated to Norman E. Borlaug, father of the Green Revolution, for a life dedicated to improving food security for resource-poor people worldwide.

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Adapting Crops to Climate Change: a Summary

Matthew P. Reynolds and Rodomiro Ortiz

The Intergovermental Panel on Climate Change (IPCC, 2009) indicates that rising temperatures, drought, floods, desertification and weather extremes will severely affect agriculture, especially in the developing world. While the convergence of population growth and climate change threatens food security on a worldwide scale, the opportunity also exists to address the pernicious threat of famine. Indeed the prerequisites to develop a globally coordinated effort to ensure long-term food security are available for the first time in human history. Namely: (i) the realization that agricultural problems worldwide have a common scientific basis; (ii) a vast and expanding database encompassing all disciplines that impinge on agricultural productivity; (iii) a de facto network of agricultural scientists working in almost every country in the world; and (iv) unprecedented opportunities for communication, data analysis and investment. These elements, the indisputable fruits of an industrialized global economy, were not available to our predecessors, which is probably why climate change in history spelt death. For example, analysis of high-resolution palaeoclimatic data – AD 1400–1900 – showed that in both Europe and China, long-term weather patterns were strongly linked to the frequency of wars (Zhang *et al.*, 2007), while recent analysis in Africa indicates that global warming increases risk of civil war (Burke *et al.*, 2009).

Agricultural researchers worldwide are, therefore, working to mitigate these and other effects of climate change to increase productivity within a finite natural resource basis. Assuming investment is forthcoming, maintaining food security in the face of population growth and climate change will require a holistic approach that includes stress-tolerant germplasm, coupled with sustainable crop and natural resource management as well as sound policy interventions. There will be duplication of effort as regions struggle with parallel challenges; however, judicious public investment can reduce redundancy of effort permitting local organizations to focus on adaptive research. The Green Revolution was precipitated by a sense of urgency about famine in South Asia, yet has benefited millions of farmers worldwide, especially in resource-constrained countries (Lipton and Longhurst, 1989; Evenson and Gollin, 2003). Although these impacts were achieved with modest investment, the more universal problem of climate change will require backstopping from a larger segment of the scientific and development assistance communities if predicted levels of demand for staple foods are to be met under progressively less favourable conditions (Federoff *et al.*, 2010). The topics in this book have been selected to cover the broad range of disciplines that will need to be implemented as part of a consolidated research effort to maintain and increase crop productivity in unpredictable environments.

Predictions of Climate Change and its Impact on Crop Productivity

In the first section of the book, chapters by Lobell and Burke (Chapter 3) and Jarvis *et al.* (Chapter 2) address predictions of climate change over the next 30+ years and their likely biological and economic consequences in the context of crop productivity. Their main points are summarized as follows.

Developing countries will be affected most for three reasons: (i) climate change will have its most negative effects in tropical and subtropical regions; (ii) most of the predicted population growth to 2030 will occur in the developing world (United Nations Population Division DoEaSA, 2009); and (iii) more than half of the overall work force in the developing world is involved in agriculture (FAO, 2005).

While anthropogenic effects on climate have been apparent for several decades, modelling future climate change is not an exact science due to the complexity and incomplete understanding of atmospheric processes. None the less, there is broad agreement that, in addition to increased temperatures (see Plate 1), climate change will bring about regionally dependent increases or decreases in rainfall (see Plate 2), an increase in cloud cover and increases in sea level. Extreme climate events will also increase in intensity or frequency, such as higher maximum temperatures, more intense precipitation events, increased risk and duration of drought, and increased peak wind intensities of cyclones. Predictions in sea level rise indicate that this will continue for centuries after temperatures stabilize, causing flooding of coastal lands and salinization of soils and subsurface water in coastal regions.

Models of crop response to climate change mainly consider temperature, soil moisture and increased carbon dioxide. However, many other processes not easily incorporated into models could potentially have significant effects including: pests and diseases, brief exposures of crops to very high temperatures, elevated ozone, loss of irrigation water, and increase in inter-annual climate variability associated with monsoons and phenomena like El Niño. The model outputs, while encompassing a wide range of potential outcomes, tend to have the following in common:

- The yield potential of staple foods will decline in most production environments and commodity prices will rise.
- While projections for a few countries with northerly latitudes indicate net positive impacts of climate change, projections for most developing countries are negative.
- Only 'best-case' scenarios predict no net effect of climate change on global cereal yields by 2030 but predictions beyond that time frame are much more pessimistic.

On a more positive note, Lobell and Burke (Chapter 3) also state that an important factor in terms of maintaining productivity in the face of climate change will be the way farmers adapt their cropping systems: for example by diversifying when faced by increased risk, or by adopting new technologies derived from centrally planned efforts, such as cultivars bred to resist biotic and abiotic stresses as well as improved and more sustainable cropping practices that permit the genetic potential of new cultivars to be realized. These issues are addressed in subsequent chapters.

Adapting to Biotic and Abiotic Stresses Through Crop Breeding

One of the most challenging aspects of adapting crops to climate change will be to maintain their genetic resistance to pests and diseases, including weeds, herbivorous insects, arthropods, nematodes, fungi, bacteria and viruses. Rising temperatures and variations in humidity affect the diversity and responsiveness of agricultural pests and diseases and are likely to lead to new and perhaps unpredictable epidemiologies (Gregory *et al.*, 2009). Legrève and Duveiller in Chapter 4 explain that, for a disease to occur, three essential components are required simultaneously: a virulent pathogen, a susceptible host and a favourable environment – often referred to as the 'disease triangle'. Climate change, as well as sometimes fulfilling the last link of that triangle, can also drive evolutionary change in pathogen populations by forcing changes in reproductive behaviour. Changes in cropping systems can lead to the development of new pathogens, for example through interspecific hybridization between introduced and endemic pathogens, and history has shown how devastating such events can be to food security. Legrève and Duveiller point out that strategies to limit the effect of climate change on pests and diseases do not fundamentally differ from existing integrated pest management practices, although there will need to be a much greater emphasis on modelling and forecasting systems, while breeding for host resistance will continue to have a pivotal role. They cite the rapid response of the scientific community to the dispersal of the Ug99 wheat stem rust race as an example of how internationally coordinated monitoring and breeding efforts can mitigate the threat of potential epidemics (Singh *et al*., 2008).

The major abiotic stresses that are expected to increase in response to climate change are heat, drought, salinity, waterlogging and inundation. The former are addressed by Reynolds *et al.* in Chapter 5. The responses of crops to these two abiotic stresses have a number of similarities, although the genetic basis is not necessarily the same. Growth rate is accelerated due to increased plant temperature, which reduces the window of opportunity for photosynthesis since the life cycle is truncated, while both heat and drought stress may also inhibit growth directly at the metabolic level. Furthermore, harvest index may be reduced if reproductive processes are impaired by stress that occurs at critical developmental stages. Genetic improvement under these environments has been achieved by incorporating stress-adaptive traits into good agronomic backgrounds (Richards, 2006). As understanding of the physiological and genetic basis of adaptation is improved, this approach can be expanded in conjunction with molecular approaches to tackle even some of the most challenging aspects of climate change, such as adaptation to higher temperatures without loss of water-use efficiency, and tolerance to sudden extreme climatic events or combinations of stress factors. Given the complexity of the target environments themselves, as well as the constant fluxes in weather and other factors such as biotic stresses, plant selection will for the foreseeable future require empirical approaches such as multi-location testing. A number of crop-specific examples of successful breeding approaches are discussed as well as the potential of biotechnology to improve the efficiency of breeding through marker assisted selection (MAS), and the use of genetic resources to broaden the genetic base of crop species.

In Chapter 6, Mullan and Barrett-Lennard explain that climate change is expected to reduce water availability in general making the use of low-quality water resources more common. Water-stressed hydrological basins already affect approximately 1.5–2.0 billion people (Bates *et al*., 2008), a figure expected to increase substantially leading to problems of soil salinity and sodicity. Climate change will also bring inundation in low-lying landscapes associated with increased runoff from tropical storms while sea level rise will increase levels of salinity, waterlogging and inundation in coastal regions. The authors go on to explain that soil salinity affects plant growth and survival because ions (mainly Na^+ and Cl^-) increase in the soil solution, causing osmotic stress, while their accumulation in plant tissue impairs metabolism. Waterlogging leads to the displacement of air from the soil pores, leading to hypoxia (O_2 deficiency, which is especially detrimental to root growth and eventually impairs all aspects of plant growth). A range of adaptive traits is discussed; however, large areas of land subject to salinity and waterlogging are still to benefit from plant breeding. Climate change is likely to increase these areas, making it imperative to address the genetic challenges of productivity in such environments.

It is important to remember that waterlogging and salinity, which already constrain productivity on hundreds of millions of hectares worldwide, also have potential engineering solutions (Bhutta and Smedema, 2007). Although beyond the scope of this book, given the scale of the problem and the challenges ahead associated with population growth and climate change, engineering interventions will require major investment; failure to do so will lead to desertification and an overall net reduction in potential global productivity.

Development and dissemination of new germplasm can be a slow process without public sector investment that provides new genotypes to seed companies. The most comprehensive germplasm development and deployment exercise ever undertaken was that associated with the Green Revolution rice and wheat cultivars, and its legacy includes some of the largest and most effective breeding programmes in the world for the major cereal crops. Chapter 7 by Braun *et al*. describes how these global breeding programmes function – using examples drawn from maize, rice and wheat – and their unique remit to provide useful new cultivars for a range of environments that already encompasses many of the stress factors that climate change will make more widespread in years to come. The authors explain the benefit of genetic resources as a global public good, implemented through an extensive system of international nursery trials with a breeding hub, free sharing of germplasm, collaboration in information collection, the development of human resources, and an international collaborative network. Broad-based, widely adapted, stress-tolerant cultivars, coupled with sustainable crop and natural resource management, will provide means for farmers to cope with climate change and benefit consumers worldwide. Chapter 7 also provides an overview on climate change impacts on the three main cereals that feed the world as well as ongoing breeding research to adapt the crop to the expected warm and drought-prone environments where they will grow. The authors end their chapter by discussing the future of crop mega-environments (MEs) as a breeder's tool. MEs are broad, often non-contiguous or transcontinental areas with similar biotic or abiotic stresses, cropping systems, consumer preferences and volumes of production. Braun *et al*. conclude that under new climate change scenarios the ME can be refined geographically to address evolving needs of various production systems.

Because agriculture is a potential contributor to climate change, it is pertinent to consider mitigation strategies as well as those of adaptation. This is addressed in the context of crop management in the next section of the book, while Parry and Hawkesford discuss breeding strategies in Chapter 8. Genetic manipulation to enhance the specificity of Rubisco for CO_2 relative to O_2 and to increase the catalytic rate of Rubisco in crop plants would increase yield potential, thereby increasing input-use efficiency of cropping systems as a whole, because efficiencies of scale can be expected in terms of use of nitrogen, diesel fuel, etc. Similarly, introducing C_4 photosynthesis into C_3 crops can be expected to increase yield potential at warmer temperatures and moderate levels of water deficit, though this is recognized to be a long-term research undertaking due to the need for introducing multiple structural and metabolic traits into C_3 plants. Selecting for genetic mechanisms that improve N-use efficiency can also mitigate climate change by reducing greenhouse gas (GHG) emissions. Transgenic approaches that allow plant roots to release inhibitory compounds to suppress nitrification in the rhizosphere could substantially decrease the emission of nitrous oxide (N_2O), one of the most potent GHGs.

Sustainable and Resource-conserving Technologies for Adaptation to and Mitigation of Climate Change

Sustainable and resource-conserving crop management technologies offer several major benefits under climate change. These include:

1. Practices such as reduced tillage in combination with crop residue retention can buffer crops against severe climatic events, for example, by increasing water harvest and thereby offsetting water shortages that will intensify as global temperatures rise.

2. In addition, by improving the overall environment for root growth, such practices permit the genetic potential of improved cultivars to be more optimally expressed helping to close yield gaps that may already exist.

3. Diversification of cropping systems helps to control soilborne diseases.

Longer-term benefits include:

4. Reduced emission of GHGs through greater precision in the application of N and water as well as reduced use of diesel fuel.

5. More robust soils, which are less prone to becoming degraded even as climate change increases the need for more intensive cultivation in still productive regions.

Ortiz-Monasterio *et al*. focus Chapter 9 on the management options that could mitigate methane (CH_4) or N_2O emissions from the intensive cropping systems where they are grown. The chapter describes the main elements of each of the cropping systems that affect the environment and what alternatives are available for reducing their impact on climate change, for example mid-season drainage in rice paddy fields, or best practices to manage N use in maize and wheat fields. The authors also explain how conservation agriculture (CA) and other sustainable farming practices can reduce GHG emissions and their potential for sequestering C. For example, one of the best options for mitigating GHG emissions from rice fields includes management that leads to greater oxidative soils, allows organic decomposition under more aerobic conditions, and uses zero tillage, which seems to be very practical due to cost and labour savings. N rates, timing, source and placement in maize and wheat cropping systems could also assist in mitigating N_2O emissions. In this regard, spectral sensor-based N management can be used to establish the optimum N fertilization rates, thereby minimizing the risk of over fertilizing.

Hobbs and Govaerts in Chapter 10 point out that while resource conserving technologies help mitigate climate change by reducing GHG emissions, agronomic practices must also protect against extreme weather events such as drought, flooding, etc., and prevent further soil degradation. They provide evidence that adoption of practices such as CA can achieve both objectives through reducing the surface tillage to a minimum while introducing residue retention and crop rotations into the system. Their combined effect is to protect the soil from water and wind erosion, reduce water runoff and evaporation, increase infiltration of water thereby reducing inundation and salinity build up, and, in combination with appropriate crop rotation, enhance the physical, chemical and biological properties of the soil (Hobbs *et al.*, 2008). Additional benefits include increased N-use efficiency and less use of fossil fuel – associated with tillage operations – and therefore reduced GHG emissions. Under CA, species diversity in the soil is increased creating more possibilities for integrated pest control. The presence of increased biological activity also improves nutrient cycling, water infiltration and soil physical properties (Verhulst *et al.*, 2010).

As already mentioned, climate change will influence the spectrum of diseases that normally affect a crop species while increasing selection pressure on pre-existing threats. In Chapter 11, Mark Mazzola points out that, compared with diseases affecting aerial plant parts, soilborne diseases are more difficult to detect and to control. That given, it is extremely challenging to select for genetic resistance, making crop management strategies an essential component of the control of soilborne diseases. The most effective control method has been soil fumigation (mostly with methyl bromide), which has highly detrimental environmental consequences. Alternatives such as host resistance or application of microbiological control agents are generally effective towards a more limited and targeted pathogen population but operate on sound ecological principals (Weller *et al.*, 2002). Naturally disease-suppressive soils also exist associated with the presence of resident microorganisms (Cook and Baker, 1983), and such soils can even be used to ‘seed’ other soils to increase their capacity for suppression. In addition, approaches such as introducing organic residues including green manures, as well as growing alternate crops in rotations can increase a soil’s ability to suppress pathogens. In this context, practices associated with CA, including crop rotation and residue retention, offer some strategies that can positively influence disease-suppressive soil characteristics. Likely pressures on disease evolution associated with climate change as well as intensification of cropping systems, in conjunction with restrictions on the use of chemical control methods, make it opportune to further develop this field as a viable strategy to control soilborne diseases that are likely to escalate as agricultural systems are intensified to match growing demand.

New Tools for Enhancing Crop Adaptation to Climate Change

The final section of the book presents tools at the 'cutting edge' of agricultural technology. Increased integration of these approaches into breeding programmes is inevitable, at least for those providing unequivocal benefits. Recent advances in genomics research address the multigenic nature of plant abiotic stress adaptation, including the potential of genetic engineering of new traits which are not amenable to conventional breeding (Ortiz, 2008; Federoff *et al.*, 2010). The marriage of geographic information systems (GIS) with sophisticated statistical and modelling tools is also addressed as a means to better target breeding efforts through enhanced understanding of the interaction of complex and changing environments with genes and genomes.

As pointed out by Whitford *et al.* in Chapter 12, important new tools are becoming available to assist with breeding for climate change. Chapter 12 is also helpful in introducing some of the basic concepts of biotechnology. The authors provide details of induced genetic variation in crops, such as introgression through backcrossing, amphidiploidy, mutagenesis, *in vitro* culture and transgenics. Recent advances in genomics are highlighted as tools to dissect stress adaptive mechanisms both metabolically and genetically. The authors also indicate the use of model plant systems and their ability for predicting, through modelling, traits in other crops. Molecular breeding tools such as marker-aided backcrossing (MABC) or MAS are presented as the promising new additions to the breeder toolkit. Other methods such as early generation MAS, *in silico* breeding and metabolite-assisted breeding are also described. The analysis of diversity and population dynamics are other important uses of DNA markers for designing knowledge-led plant breeding approaches and managing genebank collections for further use in crop improvement. High-throughput genotyping and phenotyping are also important tools for accelerating both population improvement and cultivar development. The authors explain in detail the steps of transgenic approaches as well as the advances in gene discovery technology that can assist plant-breeding endeavours to address climate change. The chapter ends by discussing investments on capacity building by both private and public sectors, and access to technology, whose deployment may be affected by intellectual property issues and regulatory systems.

While GIS and crop modelling are essential tools in predicting climate change, the same tools have a variety of other applications that can assist with many of the research areas discussed in previous chapters. Chapter 13 by Hodson and White demonstrates a central role for these technologies, including: (i) interpolating meteorological data to define climatic zones; (ii) estimating spatial variation in soils to infer agronomic potential; (iii) defining climatic suitability zones of pests and diseases to predict the likelihood of their incidence; and (iv) identification of potential collection sites of crop wild relatives in terms of likely genetic potential based on environmental selection pressures. One of the major benefits of improved characterization of target environments is that resources for crop improvement can be deployed more effectively. Crop simulation models simulate the key physiological processes believed to determine crop performance so as to predict crop development, adaptation and performance. Therefore, in combination with GIS databases, which capture the heterogeneity of environments in both space and time, crop modelling permits a more systematic approach to understanding how genotypes interact with environmental factors and are likely to perform in response to climatic as well as other environmental variables. Given the considerable challenges facing crop scientists to maintain food security, it can be expected that application of these tools will soon become routine in crop research. A recent application has been to monitor shifting abiotic and biotic stress distributions for major cereal crops, indicating likely changes in the size and distribution of target environments in the near future; this has important implications for how breeding resources must be redeployed to meet demands 10–20 years from now as outlined by Braun *et al.* (Chapter 7).

As climate changes and becomes less predictable, the use of statistical tools to achieve a better understanding of how cultivars interact with environment will become invaluable both in deploying genes and germplasm and in defining 'weak links' as targets for research investment. Chapter 14 by Crossa *et al.* provides an overview of several statistical models and their application for explaining the climatic and genetic causes of genotype × environment (GE) interaction. Their advantages and shortcomings are also highlighted by the authors, who claim that multi-environment trials are very important for breeding cultivars with general or specific adaptation and yield stability, studying GE interactions, and predicting the performance of new cultivars in future years and new locations. They indicate that data ensuing from such trials should include not only phenotypic measurements of cultivars across environments but also climatic and soil data as well as molecular markers representing genetic data. Some examples are given to illustrate the use of appropriate statistical models for gaining better insights about the GE interaction in multi-environment trials.

Conclusions

Current trends in population growth suggest that global food production is unlikely to satisfy future demand under predicted climate change scenarios unless rates of crop improvement are accelerated (or radical changes occur in patterns of human food consumption). The situation is generally more serious in less developed countries where agroecosystems are already fragile, investment in agriculture is limited, and climate change is predicted to have its most devastating effects. The following crop-oriented technical solutions can be implemented to increase food security:

- application of crop and land management practices that maximize sustainable productivity from a given natural resource and permit the full genetic potential of cultivars to be realized;
- implementation of both management and breeding strategies to reduce GHG emissions from cropping systems – thereby mitigating negative impacts of agriculture on climate change – such as precision application of inputs and genetic enhancement of input-use efficiency;
- crop breeding with emphasis on rapid deployment of lines adapted to the harsher environments anticipated from climate change models, while improving genetic yield thresholds in general;
- systematic evaluation of genetic resources to better target their use in cultivar improvement;
- investment in characterizing target agroecosystems (taking into account cultivation, climatic, biotic and edaphic factors) to permit different models of genetic adaptation to be systematically evaluated;
- integrated use of research techniques (e.g. remote sensing for precision phenotyping, networks of field operations, state-of-the-art molecular techniques, etc.) that will permit genome analysis to be more precisely linked to the adaptive responses of crops;
- determination of the theoretical limits to resource-use efficiency of cropping systems (including nutrients, water and light) to help establish realistic research goals when estimating potential productivity in future climate scenarios; this should take into account crop response and potential adaptation to extreme climatic events;
- monitoring and modelling the spread of diseases and pests in response to climatic

factors to reduce crop losses and reduce the risk of epidemics; and

- establishment of research consortia whereby interest in solving a common problem brings together complementary skills and research platforms.

In summary, the gap between current and achievable yields must be closed through breeding and natural resource management to reduce the risk of catastrophic food shortages.

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