David Edwards · Jacqueline Batley
Editors

Plant Genomics and Climate Change

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Preface

The sustainability of agriculture is being challenged by climate change and rising food demand from a larger and wealthier human population. Humanity faces a global food deficit unless the efficiency and resilience of crop production is improved.

Within the coming decades challenges to international food production will occur like no other time in human history, and a substantial increase in the production of food is essential if we are to continue to feed the growing human population. There is an urgent need to increase crop yield, quality and stability of production, enhancing the resilience of crops to climate variability and increasing the productivity of minor crops to diversify food production.

Improvements in agricultural practice and the increased use of fertilisers and pesticides have increased food production over the last few decades; however it is now considered that further such improvements are limited. The science of genomics offers the greatest potential for crop improvement.

This book explores the impact of climate change on agriculture and our future ability to produce the crops which are the foundation of the human diet. Further chapters address the specific climate change issues and explore the potential for genomics-assisted breeding of improved crops with greater yield and tolerance to the stresses associated with predicted climate change scenarios.

Through the application of genomics technology, it is possible to accelerate the breeding of major crops, bring current orphan crops into accelerated agricultural breeding programs and convert diverse non-crop species into future crops adapted to the changing climate. Through this process we can help secure the food supply for the coming generations.

David Edwards
Jacqueline Batley

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Authors Bios

Prof David Edwards gained an Honours degree in Agricultural Science from the University of Nottingham and a PhD from the Department of Plant Sciences, University of Cambridge. He has held positions within academia (University of Adelaide and University of Queensland, Australia; University of Cambridge, UK; and McGill University, Canada), government (Long Ashton Research Centre, UK, Department of Primary Industries, Victoria, Australia) and industry (ICI seeds, UK). David was appointed as a Centenary Professor at The University of Western Australia in 2015. His research interests include the structure and expression of plant genomes, the discovery and application of genome variation and applied bioinformatics, with a focus on crop plants and accelerating crop improvement in the face of climate change.

Prof Jacqueline Batley is an ARC Future Fellow at the University of Western Australia. She was awarded her PhD from the University of Bristol in 2001 and moved to Australia in 2002. Jacqueline has expertise in the fields of plant and animal molecular biology, genetics and genomics, gained from working in both industry and academia. Her areas of interest include genetic and genomic analysis for applications including genetic diversity, linkage disequilibrium and comparative genomic studies, working across environmental and agricultural areas. Her current research projects include the molecular characterisation of agronomic traits, with a focus on disease resistance in Brassicas, with studies in both the fungal pathogen and the host plant.

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The Impact of Climate Change on Agricultural Crops

Timothy Fitzgerald

Introduction

Human civilization is dependent on agricultural plant production. The vast majority of human calories are derived from agricultural crops either directly, or indirectly as animal feed (Cassidy et al. 2013). A relatively small number of crop species are cultivated on a large scale globally (Prescott-Allen and Prescott-Allen 1990) with the three cereals rice, wheat, and maize accounting for over 60 % of human energy intake alone (Cassman et al. 2003). Our major crops are grown across regions with diverse climates. However, to achieve this, decades of effort have been invested in the development of locally adapted varieties and in optimizing agricultural practices (e.g. timing of sowing and harvest; irrigation), and it is nevertheless true that for a given crop there exists a relatively small climatic window that is optimal for production (Lobell and Gourdji 2012).

Over the last few decades, increases in mean global surface temperature and the atmospheric concentration of greenhouse gases including carbon dioxide (CO_2) and ozone (O_3) have been observed. The Intergovernmental Panel on Climate Change (IPCC) reports that it is almost certain that these trends will continue throughout the twenty-first century (Stocker et al. 2013). There is substantial evidence that this will affect crop productivity (Lobell and Gourdji 2012), and with accelerating gains in crop yields essential to meet demands of an expanding population, food security is becoming one of the most important issues facing humanity.

Here I provide a summary of historic observations of climate change, and predictions for continued changes during the twenty-first century. I then outline current understanding of the effects of climate change (and the associated accumulation of CO_2 and O_3) on plant growth and development, highlighting projected impacts on

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crop productivity. The effect of these factors on plant pathogens and insects (both pests and pollinators) and their interaction with crops, is also discussed. An overview of the potential for adaptation of crop production to a changing climate is provided, with both 'on-farm' and larger-scale options described. Finally, the contribution of crop production itself to climate change is summarised, and proposed strategies to mitigate this are outlined.

Observed and Predicted Climate Change as a Result of Human Activity

As presented in the latest Intergovernmental Panel on Climate Change (IPCC) report (Stocker et al. 2013), it has been demonstrated through multiple lines of evidence that the global climate is changing, and that human activities are a major driving force for this change. Climate change occurring as a result of human activity can be specifically referred to as 'anthropogenic climate change'. The terms 'climate change' and 'anthropogenic climate change' are frequently used interchangeably; however trends and fluctuations in climate independent of human activity are also well-known to occur. In addition to seasonal variations, several natural phenomena contribute to substantial short-term fluctuations in the climate (occurring over periods of years to decades), including the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) (Rosenzweig and Neofotis 2013) and short term solar cycles (Keckhut et al. 2005). Furthermore, longer term climate fluctuations (occurring over centuries to millennia) are driven by factors that include variations in Earth's orbit (Spiegel et al. 2010) and long-term solar cycles (Wilson 2003). The presence of non-anthropogenic phenomena influencing climate change (and their potential interactions with anthropogenic factors) complicates predictions of future climate scenarios; however considerable international effort has been expended to develop models to account for these factors as accurately as possible.

The average surface temperature of Earth has increased by approximately 0.8 °C since the early twentieth century, and the majority of this warming has occurred since 1980 (Carnesale and Chameides 2011). Importantly, changes in surface temperature represent only a small proportion of global warming; 90 % of the Earth's warming since 1971 has occurred in the oceans (Stocker et al. 2013). The scientific consensus, incorporating analysis of both anthropogenic and non-anthropogenic factors influencing climate, is that the majority of this temperature increase is the result of greenhouse gas emissions from human activity (Stocker et al. 2013). Extensive international effort has been invested in the development of models to predict mean temperature increases during the twenty-first century, based on a range of emission scenarios. The most recent IPCC report states that it is 'likely' (>66 % probability) under most future greenhouse gas emission scenarios that the average global surface temperature will increase by more than 1.5 °C by 2100. In a scenario where emissions continue to increase, following historic trends, an average temperature increase of 3.7 °C is predicted (Stocker et al. 2013). Climate modelling and historical data suggest that surface temperature increase as a result of greenhouse gas emissions is more dramatic on land than at sea (Sutton et al. 2007), thus the increase in temperature to which humans and crops are exposed is likely to be greater than these projected averages.

In addition to the observed increase in mean global surface temperature, the early part of the twenty-first century has seen a very high frequency of extreme weather events (Coumou and Rahmstorf 2012) and several recent studies have suggested that these phenomena may be related (Trenberth 2012). The 2013 IPCC report has concluded that, in addition to a rise in mean global surface temperature, it is very likely (>90 % certainty) that by the end of the twenty-first century there will be an increase in the length and intensity of heatwaves, and the frequency and/or duration of heavy rainfall events.

Effects of Climate Change on Crop Productivity

Elevated Mean Surface Temperature

The C3, C4 and CAM photosynthetic pathways are differentially affected by temperature, and thus the effect of elevated temperature on the performance of a given crop is expected to be influenced by the type of photosynthesis it employs. Generally, the optimum temperature for photosynthesis is highest in C4 plants and lowest in CAM plants (Yamori et al. 2014). Broadly however, increased temperature exerts two main direct effects on plant growth and development. Firstly, higher temperatures accelerate development (Yin et al. 1995) resulting in a shorter duration of the cropping cycle in annual crops, which generally translates to lower yield (Wheeler et al. 2000; Porter and Semenov 2005). Secondly, elevated temperature affects photosynthetic rate; this may lead to a loss or gain in efficiency depending on whether the temperature moves closer to or further away from the optimum (Lobell and Gourdji 2012). In addition, changes in temperature exert an indirect effect on growth and development via changes in vapour pressure deficit (VPD) between air and leaf. For a set relative humidity, increases in temperature lead to an increase in vapour pressure deficit (Lobell and Gourdji 2012) resulting in reduced water use efficiency. Plants attempt to offset this by reducing stomatal aperture (Polley 2002), however this in turn leads to decreased rates of photosynthesis and an increase in crop canopy temperature (Leinonen and Jones 2004).

Increases in mean temperature may also have important effects on growing seasons throughout the world. In regions including Russia, Northern China, and Canada, there is expected to be a substantial increase in the frost-free period suitable for crop cultivation during the twenty-first century (Ramankutty et al. 2002). In contrast, in many temperate (including North America and Northern Asia) and tropical regions (including parts of South America, Australia and Asia) crops are more likely to be exposed to heat stress during growing seasons, which can lead to substantial decreases in productivity (Teixeira et al. 2013).

Previous reports have indicated that increases in temperature of up to 2 °C could exert an overall positive effect on global production of the staple cereal crops rice, wheat and maize, with additional temperature increases leading to productivity decreases (Parry 2007). However, a recent large-scale meta-analysis suggests that, with the exception of wheat grown in tropical regions (for which yield increases are predicted for increases in temperature of up to 1 °C) any increase in mean global surface temperature is likely to result in decreased productivity for these crops (Challinor et al. 2014).

Increased Frequency of Extreme Weather Events

An increase in the frequency of heatwaves and extreme rainfall events is predicted, with high confidence, for the twenty-first century (Stocker et al. 2013). Previous IPCC projections have indicated a likely increase in drought and cyclone activity, both of which could have major detrimental effects on global crop productivity (Schmidhuber and Tubiello 2007). However the most recent report incorporating the latest data and models, states a high degree of uncertainty with regard to these phenomena (Stocker et al. 2013).

Both heatwaves and extreme precipitation jeopardise crop yield. Extreme temperatures can damage plant cells, exerting a negative effect on growth and development. The reproductive phase of plant development is highly sensitive to temperature stress (Barnabás et al. 2008); extreme heat during this period can lead to sterility and dramatic decreases in yield. A recent study (Deryng et al. 2014) suggests a strong negative influence of extreme heat events on the productivity of maize, wheat, and soybean by the middle of the twenty-first century, under all likely emission scenarios. Extreme precipitation events can also cause major crop losses, via physical damage from flooding and excess soil moisture. The latter can cause anoxic conditions, leading to above and below ground damage (Kozdrój and van Elsas 2000), and increases the risk of certain plant diseases (Ashraf 1999). Furthermore, excessive rainfall can result in delays in planting and harvest as a result of an inability to effectively operate farming machinery, which can be strongly detrimental for crop production (Rosenzweig et al. 2002).

Rising Sea Level

Increases in sea level have been observed throughout the twentieth and early twenty-first centuries (Nicholls and Cazenave 2010). The major causes of this increase are thermal expansion of the oceans, and increases in the quantity of water in the oceans due to melting of major land ice structures (e.g. glaciers and ice caps/sheets), both of which are related to increases in global temperature (Nicholls and Cazenave 2010). Continued sea level rise is regarded as an inevitable consequence of climate change; a rise in sea level of up to 0.55 m under a low emissions scenario, and up to 0.98 m under a high emissions scenario, is predicted by 2100 (Stocker et al. 2013).

Sea-level rise will impact directly upon agriculture in low-lying regions globally due to flooding and salinization of groundwater (Gornall et al. 2010). However, the percentage of agricultural land that will be affected by sea-level rise during this century is likely to be relatively small (Dasgupta et al. 2009). Nevertheless, dramatic impacts are set to occur in some regions, e.g. the Vietnamese Mekong delta (Wassmann et al. 2004) and the Chinese Yangtze delta (Chen and Zong 1999).

Direct Effects of Carbon Dioxide and Ozone

As well as being the main drivers of anthropogenic climate change, greenhouse gases (GHGs) produced as a result of human activity can directly affect plant growth and development; carbon dioxide (CO_2) and ozone (O_3) are the most important factors in this regard. While there is variation amongst studies and debate in the literature about the extent of the effects of these gases, it is generally accepted that increases in CO_2 concentration likely to occur during the twenty-first century will exert a positive effect on crop productivity, while increases in O_3 concentration will exert a negative effect (Chen and Zong 1999).

The effect of elevated CO_2 concentration on crop performance has been the subject of considerable study; CO_2 is known to stimulate carbon assimilation in C_3 plant species, and to decrease stomatal conductance in both C_3 and C_4 species (Ainsworth and Rogers 2007). Both of these mechanisms can lead to increased crop productivity, however the effect of the latter is generally only detectable under water-limited conditions (Wang et al. 2008). Extensive studies conducted on plants grown in enclosures (e.g. controlled environment chambers, transparent field enclosures, or open-top chambers), have demonstrated large and highly significant gains in productivity associated with increased CO_2 concentration (Long et al. 2006). However, free-air concentration enrichment (FACE; Hendrey and Kimball 1994) experiments, which are designed to more accurately replicate growth conditions in future scenarios of elevated atmospheric CO_2 than enclosure studies, suggest substantially smaller effects than predicted by such enclosure studies (Long et al. 2006).

Air pollutants produced by human activity such as nitrogen oxides, carbon monoxide, and methane are ‘ozone precursors’, which react with hydroxyl radicals in the presence of UV to produce ground level (‘tropospheric’) O_3. Concentrations of tropospheric ozone vary substantially and are related to the local output of ozone precursors. In regions of high air pollution output, peak tropospheric O_3 concentration is much greater now than during pre-industrial times; furthermore there have been observable increases across most global regions, even far away from areas of high pollution output (Stevenson et al. 2013). As outlined by Wilkinson et al. (2012), O_3 can have detrimental effects on crops via several mechanisms, and current tropospheric levels of O_3 have been predicted to reduce global yields of some crops by up to 15 %. Effects of O_3 on crops include early induction of leaf senescence, visible injury to foliage and fruit, reduced carbon uptake and/or fixation, reduced carbon transportation, modulation of flowering, pollen sterility and ovule abortion, and (at least in some cases) reduced tolerance to abiotic stresses via effects on the control of stomatal regulation.

Crop Diseases and Pests

It has been estimated that diseases and pests cost global agriculture ~29 % of production (Oerke 2006). Changes in climate and atmospheric CO_2 concentration have the potential to influence the distribution, abundance, and aggressiveness of these diseases and pests (Luck et al. 2011). However, predicting the overall impact of climate change on crop losses associated with diseases and pests is challenging, in part because of the wide variety of pests and pathogens that may be differentially influenced. Additionally, the effects of climate and greenhouse gases on crops may affect the interaction of these crops with pests and pathogens. For example, several effects of elevated CO_2 concentration on plant growth and development may have indirect effects on crop disease, e.g. increases in leaf wax and epidermal thickness may provide enhanced defence against certain foliar pathogens, changes in canopy humidity may affect proliferation of some pathogens, and increased biomass accumulation may result in an increased reservoir for pathogen colonization (Luck et al. 2011). Recently, West et al. (2012) and Luck et al. (2011) have presented assessments of the effect of changes in climate and CO_2 concentration on diseases of major crops during the twenty-first century. They conclude that both increases and decreases of the incidence of specific diseases will occur, and that this is influenced by the lifestyle of the pathogen, the crop species being infected, and the geographic location of cultivation.

In addition to the ~12 % of crop production lost to disease, weeds and animal pests (primarily insects) are each responsible for losses of ~8 % (Oerke 2006). Currently there is limited data available regarding the potential impact of climate change on crop losses from these pests, nevertheless, there is potential for changes in climate and greenhouse gases to exert a substantial effect via several mechanisms. For example, changes in temperature may alter the distribution of weeds and animal pests (Ziska et al. 2011). Additionally, elevated temperatures will lead to increased reproduction of some weeds and animal pests, which may result in greater crop damage (DeLucia et al. 2012). Changes in nutrient profiles within plant tissues as a result of elevated CO_2 concentration may alter their attractiveness and/or nutritional value to animal pests (DeLucia et al. 2012). Furthermore, altered temperature and CO_2 and/or O_3 concentration may affect the competitiveness of weeds with crops; this is particularly likely where the crop and weed species use contrasting forms of photosynthesis that respond differently to these changes (Mahajan et al. 2012).

Due to the lack of certainty surrounding the impact of climate change on crop losses from pest and diseases, most models of climate change on crop productivity cannot incorporate these factors. This can be considered a major limitation for our ability to accurately predict future crop productivity scenarios (Gregory et al. 2009).

Pollinating Insects

The majority of total crop production globally comes from a small number of species that do not require animal pollinators, instead primarily relying on self-fertilization (e.g. wheat) or outcrossing via wind-pollination (e.g. maize and hybrid rice). Nevertheless, pollinator fertilization contributes substantially to agriculture; as outlined by (Aizen et al. 2009), 70 % of tropical crops, and 85 % of crops cultivated in Europe, benefit to some degree (from minor gains in yield, to complete dependence for reproduction) from biotic pollinators. Aizen et al. (2009) estimated that pollinating insects contribute 5 and 8 % of total crop production in the developed and developing world, respectively. Importantly, several nutrients that are critical for human well-being (e.g. vitamin C, lycopene, and folic acid) are obtained primarily from crops that rely on biotic pollinators (Eilers et al. 2011).

Changes in climate can directly affect the geographic distribution and lifecycle of both plants and pollinators. This has the potential to create spatial or temporal 'mismatches' between crops and their pollinators (Hegland et al. 2009), which could lead to decreased crop productivity (Memmott et al. 2007). There appears to be overlap in the response to temperature of phenology in many plants and pollinating insects, suggesting that these interactions might generally be tolerant of climate change; however, detailed understanding of this phenomenon is currently lacking (Hegland et al. 2009). With increasing demands on crop productivity, and given the importance of these interactions for the supply of certain essential nutrients, even relatively small negative impacts as a result of crop-pollinator mismatches could be problematic.

Strategies for Adaptation of Crop Production in Response to Climate Change

Adaptation has the potential to mitigate negative impacts of climate change on crop productivity. The use of adaptation for this purpose appears promising given that it has been of central importance to agriculture historically, allowing for the successful cultivation of the same or similar crops across a range of relatively diverse environments. Nevertheless, adaptation strategies will need to be tailored according to details of the location, climate change scenario, and the crop or crops being cultivated within each agricultural system that is being addressed (Rosenzweig and Tubiello 2007).

Traditional farm-level methods of crop adaptation include adjusting timing of planting, irrigation, fertilizer and pesticide applications, and the use of varieties that are more suited to the target cropping conditions. In some circumstances, these methods may be effective to offset potential yield decreases from changes in climate. For example, Tubiello et al. (2002) presented results of modelling for three US locations suggesting that for spring wheat, moving planting date forward would fully offset negative effects of temperature increases projected for this century. Their models also suggested that the selection of winter wheat cultivars with increased length of the grain filling period could partially compensate for yield losses associated with acceleration of development by increased temperature. However, traditional on-farm options that allow rapid adaptation with limited disruption will not be effective in all cases. Examples of potential limitations include the degree of phenological variation in available varieties, and the extent to which the cultivation period can be shifted without negative impacts due to other environmental factors (e.g. precipitation; soil moisture content) (Tubiello et al. 2002; Reilly et al. 2003).

Where farm-level adaptation strategies are not effective, more extreme, co-ordinated approaches might be. Breeding of elite cultivars for future climate scenarios is a possible option; however this can take more than a decade via traditional approaches. Genetic modification (GM) has the potential to facilitate the efficient production of highly adapted varieties (Varshney et al. 2012), however GM crops currently have low consumer acceptance and are subject to strong regulatory restrictions in most parts of the world. Perhaps the most extreme adaptation measure would be a shift in the area/s dedicated to crop cultivation within a given broad geographic region (Fischer et al. 2002). Clearly, implementation of such a strategy would be highly disruptive and require vast investment in planning and development of infrastructure.

The Impact of Crop Production on Climate Change, and Strategies to Mitigate This Impact

While crop production is at risk from anthropogenic climate change, it is itself a major contributor to climate change (Rosenzweig and Tubiello 2007). For example, Smith et al. (2007) reported that during 2005 agricultural production directly accounted for up to 12 % of total anthropogenic GHG emissions. Furthermore, a comparable scale of emission is indirectly driven by agriculture, via land clearing, production of fertilizers, and production and operation of farming machinery (Canadell et al. 2007). There is substantial potential for mitigation of GHG emissions from crop production (Smith and Olesen 2010). The development and/or adoption of strategies to reduce emissions from agricultural cultivation can clearly contribute to mitigation efforts. Additionally, practices that lead to increased sequestration of carbon in soil can mitigate atmospheric CO_2 accumulation (Lal 2004).