Climate Change and the need for agricultural adaptation

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Abstract

Agriculture and food security are predicted to be significantly impacted by climate change, though the impact will vary by region and by crop. Combined with the increasing global population, there is an urgent need for agriculture to adapt to ensure future food security for this growing population. Adaptation strategies include changing land and cropping practices, the development of improved crop varieties and changing food consumption and waste. Recent advances in genomics and agronomy can help alleviate some of the impacts of climate change on food production, however, given the timeframe for crop improvement, significant investment is required to realise these changes. Ultimately, there is a limit as to how far agriculture can adapt to the changing climate, and a political will to reduce the impact of burning of fossil fuels on the global climate is essential for long term food security.

Introduction

The burning of fossil fuels and widespread deforestation over the last few centuries have caused elevated atmospheric Greenhouse Gas (GHG) concentrations, and these changes in GHG have resulted in significant climate shifts globally [1]. Climate change has already warmed the planet: from the preindustrial period (1850-1900) to the present (1998-2018), the global average temperature over land has increased by 1.41^{o}C [1]. This increased global temperature has led to a rise in the number of hot days and nights, and a fall in the number of cold days and nights [2–6], as well as changes in the frequency and severity of extreme weather events such as drought [7] and precipitation events [8–11] at a highly regional scale [2–12]. Industrialization and increases in global population have contributed to continued deforestation and increased demands for land, leading to continued elevated GHG emissions [1]. Even with significant and immediate reduction, GHG emissions have already led to major changes to our ecosystems [1].

Agricultural yield is influenced by a range of factors, including climate conditions, crop and land management practices, pathogens and pests, and the occurrence of extreme weather events [5,13–17]. For each degree of global temperature increase, wheat yields are expected to reduce by 4-6% [18,19], increases in temperature are expected to similarly impact maize productivity and by the end of the century the areas producing 56% of the world's maize are predicted to experience a decline in yield [20–22]. Plant pathogens and pests have already demonstrated latitudinal distribution shifts as a product of climate change [23–25], and the changes in regional climate conditions are expected to alter plant pathogen virulence and infection rates [26,27], exacerbating yield losses. With changes in climatic conditions such as the number of unusually hot or cold days, it is also likely that optimal locations for planting different crops will alter [5], and crop management and cultivar production will have to keep pace with these changes. This could include crop changes, for example the expansion of drought tolerant crops such as Sorghum in drought-prone areas, as well as the breeding of new varieties of crops which are better adapted to the changing environment.

The world's population is anticipated to rise to 9.7 billion people by 2050 [28], and global crop production will have to increase substantially to keep up with this demand whilst simultaneously reducing its environmental impact [29]. Mitigation strategies to reduce GHG emissions need to be combined with adaptation strategies that aim to reduce the negative effects and exploit beneficial opportunities under climate change (IPCC 2014). Climate change and a growing global population are significant issues when considering future food security, and to ensure global food security, agricultural practices, crop cultivars and public practices and attitudes will all need to change.

Effects of Climate Change on Agriculture

Carbon Dioxide Concentration

Carbon dioxide, a major GHG, is a plant nutrient, and under elevated CO_2 conditions, several crop species have displayed increased yields [30,31], suggesting that elevated CO_2 levels can increase agricultural output. Experiments in contained air environments have demonstrated increased yield, however Free-Air Carbon dioxide Enrichment (FACE) experiments did not achieve the same yield gains, and it's been suggested that alterations in crop management are required to maximise yield increases under higher CO_2 concentrations [32–34]. Under elevated CO_2, the nutritional quality of some C_3 crop species was reduced in terms of protein, zinc and iron, whilst C_4 crops and legumes were not affected [32,35], suggesting further agronomic adaptation and breeding will be required to maintain nutritional value.

Increased CO_2 concentration is related to drought stress resilience [36], as under higher CO_2 concentrations, plants need fewer open stomata for gas exchange and hence lose less water through transpiration, increasing water use efficiency. IPCC short-term predictions indicate that under several climate change scenarios, yield gains are expected in Europe and North America due to warmer conditions that extend the growing season at high latitudes and elevated CO_2. In lower latitudes increased CO_2 concentrations are less likely to compensate for climatic change and particularly in the tropics, yield is expected to decrease [12,16,22].

Abiotic stress

Long term trends in drought occurrence, heat stress and floods highlight geographical variation on the impact of climate change on agriculture. Extreme heat and droughts have reduced global cereal production by 9-10% between 1964-2007, and droughts from 1985-2007 caused 13.7% higher loss than the estimated 6.7% in the previous years (1964-1984) [37]. In India, warming temperatures have reduced wheat yields by 5.2% between 1981 and 2009 [38], and the Hindu-Kush Himalayan region has experienced an increase in extreme conditions over the last decade, with both droughts and increasing floods negatively affecting agricultural yields [39,40]. The outlook is more varied in Europe, and while trends indicate an overall decline in wheat and barley yields of 2.5% and 3.8% respectively since 1989, the impacts are not evenly distributed, with declines in Southern Europe regions of 5% or greater [41]. In the Czech Republic, warming has increased the yield of fruiting vegetables by 4.9-12%, whilst root vegetable yields have declined [42]. In Russia, wheat yield per hectare and the area dedicated to wheat production have increased since 1980 [43], and warming has led to an extension of the growing season in Scotland, with increased potato yields since 1960 [44].

Shorter periods of temperature and rainfall fluctuation can cause significant changes in productivity. In the 2010-2012 period, the Southern U.S., Western Russia, Western Australia and East Africa experienced higher temperatures and less precipitation than decadal averages and reported 14-80% decline in yield of several crop species including barley, wheat and sorghum, contributing to famine and disease outbreaks in East Africa. In 2015-2016, regional shifts in precipitation resulted in drought and widespread crop failure in Ethiopia, again contributing to famine [14,45,46]. In contrast, in the 2010-2012 period, high rainfall and cooler temperatures in South Eastern Australia resulted in almost doubled cotton harvests and flooding in Southern Queensland [14,47–49]. Flooding and cooler temperatures in the UK in 2007 caused a 6% reduction in the national wheat yield compared to the previous year, and it was estimated that yields were reduced in flooded areas by up to 40% [50].

Climate zones are expected to shift poleward due to climate change and this will change the distribution of highly productive agricultural areas, with lower yields expected in lower latitudes and increased yields in higher latitudes [16,22]. In mid and high latitudes, warmer temperatures will extend the growing season, and open up areas for maize and wheat production in Russia and Canada that were previously unsuitable [22]. In contrast, rice production is expected to deteriorate in the tropics, and areas of low latitude are expected to experience reductions in yields [16,22]. Several modelling studies have predicted that under a variety of climate change scenarios, disparity in production between most developed and developing countries will increase, where developed countries are mostly expected to benefit from climate change whilst developing countries are expected to experience yield reductions [51], further increasing the wealth gap between rich and poor nations.

Biotic stress

Pathogen virulence is influenced by atmospheric CO_2 concentrations, temperature and water availability [26,27]. Rain, high air humidity and high soil moisture favour many plant diseases by increasing virulence and infection rates, though there are exceptions [29]. For each plant-pathogen interaction there are optimum temperature ranges for infection, and temperature response variation has already been observed for geographically distributed *Phytophthora infestans* populations [52]. Elevated CO_2 concentrations increased the virulence of *Fusarium graminearum* on wheat [53], whereas *Peronospora manshurica* virulence against soybean plants decreased by more than 50% under increased CO_2 [54]. A similar pattern of variability is present in plant immunity processes, where species displayed contrasting responses to humidity and temperature [26]. Daily temperature fluctuations of only 5^{o}C have been demonstrated to make potatoes more susceptible to *P. infestans* infection [55], and temperature fluctuations also make bacterial communities more susceptible to invasion of novel taxa [56]. Given the expected increases in temperature variability, precipitation patterns and CO_2 concentrations, it is possible that pathogen distribution changes will expose cultivars to new pathogens or strains that are more virulent [23,26,56].

The comparatively short time scale of pathogen reproduction and evolution allow pathogens to respond rapidly to changes in their environment, therefore crop management procedures and cultivar choice are essential aspects of outbreak control[26]. Natural vegetation and crops which require longer growth periods (such as forestry and orchard crops) may be at a higher risk of plant pathogen infection, as management procedures and cultivars are less flexible [27]. The complexity of pathogen infection and plant susceptibility, together with the ability of pathogen populations to rapidly respond to their environment makes prediction of pests and disease incredibly complicated, and so careful modelling and rapid response to outbreaks will be required to minimise impacts on food security.

Adaptation Strategies

Land Use and Management Systems

Increases in agricultural yield throughout the last century in developed nations have come at the expense of the environment and natural resources, with significant damage to local ecosystems resulting from increased deforestation and changed water use practices [1]. In the face of climate change, land management strategies will need to adapt to changing climate patterns, and prevalent pests and pathogens, with the aim to maximise yield and minimise environmental impact [1,12].

Particular challenges to land management practices include changes in growing season length and timing [20,21,44], alterations in the distribution of suitable production areas [1,16,22], and increased incidences of extreme weather events [1]. Legislative restrictions related to the use of pesticides, fungicides and other chemical treatments may restrict farmer responses to pathogens as their distribution and infection rates change [26,27]. While there is a growing public awareness of the risks of chemical use, this is not balanced by awareness of the benefits they have provided for food security, with resulting legislation potentially limiting the future development of new agrochemicals. Extended growing seasons in northern latitudes will require new crop varieties and in low latitudes, predicted declines in crop yields may require alternative crops to ensure stable food supply.

The adaptation of land, crop and livestock management practices to climate change includes a wide range of activities including soil nutrient management, tillage intensity, crop choice and rotation, water management, livestock choice and breeding outcomes, and agricultural diversification [1]. Water availability is a significant concern in semi-arid and arid areas as rainfall variability increases, and water harvesting, storage and utilisation practices have the opportunity to reduce some of the risks associated with extended periods of little rainfall [1].

Crop Improvement

Crop varieties need to be able to cope with increasing rates of abiotic and biotic stress and still produce high yields to support the growing human population. Genomics and other ‘omics technologies have been integrated into crop breeding strategies, though improvement remains slow. Acceleration of the breeding cycle will require significant investment in plant genomic and phenotypic resources to determine the genetic basis of agricultural traits. New technologies such as genome editing may assist in the targeted production of improved varieties, but issues in public perception and policy remain as limitations to the effective use of these tools [57]. To produce adapted varieties, both gene editing technologies and accelerated breeding procedures will require expansion in genomic and phenotypic resources for a wide variety of crops.

Drought and heat stress often occur in combination for many crops, such as maize and wheat [58,59], and the combination of these types of stress cause more significant yield reductions than each individual stress [58,60]. Drought and heat stress reduce nutrient uptake and photosynthetic efficiency in crops, and stress responses include a wide variety of physiological and biochemical responses [62]. The difficulty in producing stress tolerant crops is the large number of genes involved in stress responses [63]. Transcription Factors are an important component in signalling, and overexpression of the transcription factor CDF3 in Arabidopsis increased drought, cold and salt tolerance [64,65] , and overexpression of the transcription factor OsWRKY11 increased drought and heat stress resilience in rice [66]. The modulation of transcription factors may be an effective way to increase the environmental stress tolerance of many crops and targeting these within traditional and new breeding technologies could be an effective strategy to produce better crops.

Waterlogging and flooding of the soil reduces yield due to anoxia and increased incidences of root diseases [14,50,67]. Morphological changes such as adventitious roots and root aerenchyma assist in maintaining gas exchange, allowing plants to survive brief or extended incidences of waterlogging [68]. In rice breeding populations, gene discovery has been performed for flooding tolerance for short periods (submergence) [69], long periods (stagnant flooding) and submergence at the germination stage (anaerobic germination) [70,71]. From this work, commercially available lines have been produced for short term flooding tolerance [72–74], and for anaerobic germination, with subsequent combinations of these genes maintaining both types of flooding tolerance [75].

Food Use and Demand

Food security can be improved by increasing global agricultural production, altering food demand patterns and reducing food waste and loss. Diets vary in their nutritional capacity, local availability and resource requirements, and diets that contain substantial amounts of animal products (particularly red meat) require the highest agricultural input per person [1]. Not only do these diets require significantly higher rates of water, land and other resources, but enteric fermentation also produces GHG, further driving climate change

[76–78]. Diets that produce a lower amount of greenhouse gases (vegan, vegetarian and flexitarian as defined by the IPCC) would reduce the demand for more agricultural land and allow land to be restored or revegetated to act as a carbon sink [1].

Food waste and loss have increased by 44% between 1961 and 2011, and currently between 25 and 30% of food produced globally is lost or wasted [79,80]. Developing countries mainly experience food loss due to issues with infrastructure [81], whereas in the developed world food waste occurs at the household level [82]. Food waste and loss will be impossible to eradicate, however improving the efficiency of food use is a significant opportunity for improving food security.

Outlook

Climate change has already caused significant changes to agricultural production and yield, and even with immediate and significant reductions in GHG emissions worldwide, changes will continue [1]. The degree to which climate change will influence the food security of individual nations is dependent on their geographical location, adaptability and their GDP [1,51]. Developing nations are predicted to suffer the greatest impact of temperature variability and increased extreme weather events, and have restricted resources to adapt to these agricultural changes [1,51,83,84]. The 2014 IPCC report identified that marginalised groups in developing nations such as women and children were most at risk of climate change, and already experience higher rates of food insecurity and malnutrition [85,86]. Food security has been linked with conflict due to higher food prices reducing social stability, and conflict can further reduce food accessibility and agricultural reform through the disruption of stable economic and governmental processes [87], and climate change will further restrict the economic prosperity of developing nations, exacerbating security issues and poverty [1,12,83,84].

Reductions in GHG emissions to reduce further climate change is essential and requires urgent and significant action from populations, governments and with international cooperation. Changes at government, industry and public levels are important for climate change adaptation, and should be encouraged through policy, regulation and education. Major changes in agricultural practices, technology and public attitudes need to be enacted effectively and quickly to ensure food security under the threat of climate change.

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