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Innovations in plant genetics adapting agriculture to climate change

Robert J Henry

Developing new genotypes of plants is one of the key options for adaptation of agriculture to climate change. Plants may be required to provide resilience in changed climates or support the migration of agriculture to new regions. Very different genotypes may be required to perform in the modified environments of protected agriculture. Consumers will continue to demand taste, convenience, healthy and safe food and sustainably and ethically produced food, despite the greater challenges of climate in the future. Improving the nutritional value of foods in response to climate change is a significant challenge. Genomic sequences of relevant germplasm and an understanding of the functional role of alleles controlling key traits will be an enabling platform for this innovation.

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Introduction

The adaptation of agriculture to climate change requires the implementation of one or more of a range of complementary strategies. These include developing technology (genotypes and productions systems) to make agriculture resilient to climate change within the current footprint, moving agriculture to new locations to follow environmental change, or adopting protected agriculture by partial or completely controlling the environment. All three of these options (Figure 1) have an important role to play in delivering food security in response to climate change. A focus on design breeding will help to address these challenges. The data to support this are beginning to emerge for some major species and traits. Direct selection of all desirable alleles and or gene editing will be required to deliver genotypes with the targeted alleles to provide the required yield and to deliver food with the necessary nutritional and functional traits for the new environments.

More resilient genetics and agronomy

The development of agricultural productions systems with greater climate resilience is an important strategy in dealing with climate change. Conventional plant breeding usually relies upon selection in the target production environment. In this way breeding adapts varieties to the test environment and climate change as it impacts on the testing environment. Selection for performance under optimal growth conditions and nutrition has been shown to also improve yield in less favorable situations [1]. However, more rapid climate change may require a more proactive approach to climate adaptation especially for species for which genotypes with long production life or plants with a long life (such as trees). Genomics is providing a key platform for the understanding of the response of plants to the environment and the breeding of better adapted crop varieties that might anticipate future climate changes [2]. Advances in tools for analysis of plant performance are also supporting the development of optimal agronomic practices. This needs to be targeted at the crops that are likely to be grown in environments of the future. Current research may not be prioritizing the crops that will be important in the future [3]. However, the potential for existing crops to be adapted to new regions is a key consideration.

Relocation

Movement of agricultural production to new areas to keep within the current environmental ranges of the current production system is an option. The movement of premium wine production to new regions is one of the most notable changes predicted [4]. Research on matching crops to production environments has the potential to make an important contribution by allowing better planning of geographic shifts in production. The mix of crops grown within any region may need to change rapidly to respond to climate change. Production of crops in new areas may require genetics to adapt to specific aspects of the new environment. For example, crops might easily move to areas with climates that have become suitable due to climate change but the soils encountered may be very different and this may require genetic adaptation.

Relocation of rice production in Australia in response to climate change is a good example of the need for genetic changes to adapt to climate change. Rice has traditionally

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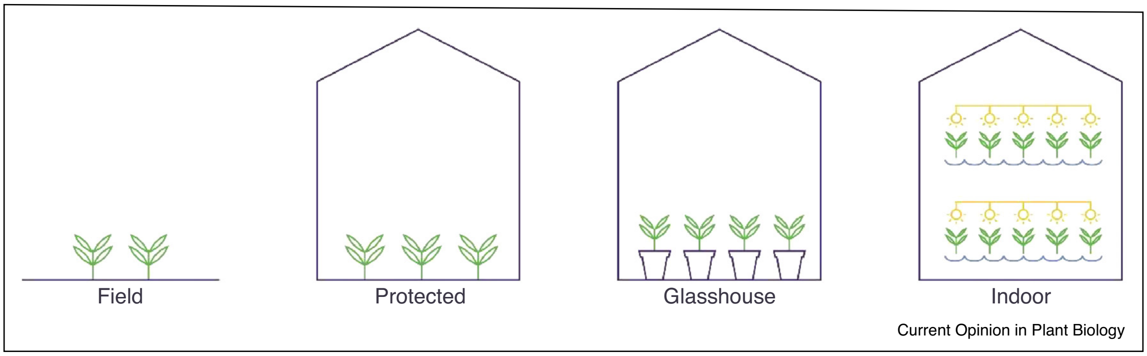
Figure 1



Moving genetic targets for plant breeders in response to climate change driving the adoption of protected cropping.
Increasing protection of crops to reduce the impact of climate change will change the genetic targets from those designed to cope with the environment and its variation towards optimal performance in a selected controlled environment. Crop protect comes in many forms with differing degrees of control and cost. Field grown crops can be protected with a simple structure (this option often relies on passive heating or cooling but may moderate the environment significantly, plants may remain growing in the ground), grown in pots in a glasshouse (this option may allow significant control of temperatures, supplemental lighting and growth medium) or grown indoors with complete environmental control (including all light) and all nutrition by hydroponics. Field crops are likely to remain in open fields while horticultural crops are more protected. Indoor production is currently mostly focused on products such as leafy vegetables. Expansion to a wider range of plants will see more adoption of this technology, changing dramatically the genetic requirements.

been produced with irrigation in southern areas but reductions in the amount of available water have directed attention to establishing rice in rain fed northern tropical environments. In contrast to the situation in southern Australia, rice is a native plant in northern Australia with the presence of native pests and diseases so genotypes with resistance to these local diseases will be essential for rice production in these new environments. Understanding of the genetic basis of reproductive barriers will facilitate the transfer of disease resistance from local populations to domesticated rice [5].

Protected agriculture

The treat of a changing and more variable climate can be avoided by moving agricultural production into protected environments. This involves moving to production in a greenhouse or to a completely controlled intensified production environment in vertical farming [6]. This may be considered the last resort but is likely to be an option that becomes more important as food demand increases and climate change advances.

This is great challenge for plant breeders as the requirements for protected agriculture will be very different from those of conventional outdoor agriculture. Lack of suitable varieties may be a major barrier to the development of vertical farming. It is vital that the timing of this technological change be judged especially for species with long breeding cycles. For some high value crops a complete transfer to protected cropping can be expected while some may never justify the investment. For others, part of the market may be served by protected cropping, while in other regions, or for other market segments, conventional production persists. The rate of climate change may determine how quickly this becomes a central issue for plant breeders. The upper range of predictions of global warming for this century would drive rapid change.

Breeding plants for protected agriculture is a process that may have a progressive series of objectives as crops are selected for optimal performance in the environments that can be created by cost effective manipulation. Technology to deliver increasingly controlled environments will allow the breeding of plants with increasingly exact performance optima. Maximal food production per unit area or volume of controlled environment per unit time will be the yield objective. The genetic requirements for pest and disease control may change dramatically. A transition to continuous light would allow the maximum growth rate and shorten the time required for crop production and increase the number of crops that can be produced per year. This may require the development of plants with genetics that can take advantage of this opportunity. The limited breeding for protected cropping to date has focused on traits of importance in these systems including, adaptation to hydroponics, specific diseases in protected systems, and optimal exploitation of the light conditions [7].

Consumer drivers

The challenge of crop production to climate change will not lessen the growing consumer focus on traits such as taste, convenience, nutritional and health benefits, food safety and sustainability and ethics of production systems. Many of the traits that have been selected by humans as

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part of domestication may be controlled by relatively few genes compared with traits such as yield in wild plants that has been the product of natural selection over the much longer evolution of the species. However, yield in an agricultural environment may be controlled by genes that adapt the plant to the unique features of the domesticated environment. Plant breeding has probably strongly selected for the genes encoding these post-domestication traits and this may make discovery of the molecular basis of these traits easier to discover. Application of genomics techniques has yielded significant advances in understanding of food quality traits [8]. These advances should allow accelerated production of crop varieties adapted to climate change by removing the barriers imposed by the complex phenotypic selection for these quality traits. Small holder farmers who are producing substance crops may not be impacted directly by the need for these consumer traits in their varieties. Their breeding requirements will remain those related to yield in the changing environments they face. However, incorporation of desirable consumer traits will probably become more important in enabling them to trade their produce.

Implications of demand for protein and type of protein

Consumer preference for plant-based proteins is growing either because of concerns about the environmental footprint of animal production or animal welfare issues. This demand must be met in a changing environment in which the protein content of grain crops may decline due to the impact of carbon fertilization due to higher atmospheric CO_2 concentrations [9]. Protein from plants may be consumed directly or via animals. Insects are an emerging protein source for human food directly or via use as feed for animals [10]. Plants that support insect growth may need to be specifically bred.

Nutritional implications

Climate has been shown to have the potential to significantly alter the nutritional value of major crops. Climate has been shown to have a potential to impact on the protein content as discussed above but also on other food constituents such as lipids and secondary metabolite levels. Wheat grown at higher temperatures had higher levels of saturated fatty acids [11] and changing the composition of stable foods like wheat has potential to impact on population health. This study also found high levels of phenolics that could act as antioxidants but might also contribute to cancer risk. The quality and nutritional value of traditionally produced food may be adversely impacted by changing production environments but protected cropping may allow management of the environment to optimize quality and nutritional value [12].

Design-based crop improvement

Advances in genetics and molecular understanding of the functionality of the genes controlling many key traits in crop plants is making designer plant breeding [13] the likely approach to plant improvement in the future. This approach involves determining the best allele of each gene in the genotype being developed with regard to target production environment, desired pest and disease resistance and product functional and nutritional quality. Rapid production of the desired genotype will be facilitated by starting with the genotype with the closest sequence to the desired end product and then making the desired changes by backcrossing, transgenic approaches or gene editing to build the genotype with the target genome. Progress and quality assurance of the completed variety will be facilitated by whole genome sequencing.

The availability of genome sequences and the ability to readily sequence the genome of a genotype constitute the key capability now facilitating the identification of targets for genetic manipulation in genetic improvement. Knowledge of the whole genome sequence is necessary to identify unique sequences to target for genetic change and avoid impact on other loci with similar sequences. Crop breeding can be accelerated by using techniques such as speed breeding [14] to bring products of carefully targeted genetic innovation to production.

Key role of advancing genomics tools

The continuing advances in DNA sequencing technologies are delivering an ongoing collapse in the cost of sequencing. Plant genome sequencing is becoming much more efficient and routine [15]. DNA sequencing advances have included; reduced sequencing costs for short read sequencing [16], increased output and reduced costs for long read sequencing, longer reads, assembly of longer contigs [17,18], improved scaffolding [19,20], chromosome level assembly tools [21,22] and optical mapping [23,24]. This provides an ever more cost effective option for characterization of available genetic diversity, increased understanding of the mechanisms of climate adaptation and application in crop breeding. The latest developments include a dramatic reduction in the cost of long read sequencing [25–27]. This has in some cases been effectively combined with short read sequencing [28]. This will support more rapid and efficient generation of *de novo* genome sequences for plants and greatly accelerate the application of genomics to minor crops. Most major crops now have a high quality references genome available and increasing proportions of the germplasm pools of these species are being sequenced [29]. Recent genomes reported include: wild rices [29], sugarcane [30] and tea [31]. The few remaining challenges include very large [32], complex and polyploid [33] genomes such as sugarcane [34] but some progress is being made even with these species [30]. This will

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Table 1

Genetic technologies that have been applied in plant improvement

Technology	Dates from (approximate date of first use)	Length of use (approximate number of years of use)	Contribution to crop improvement
Phenotypic selection	Crop domestication	10 000	Eco geographical adaptation
Cross breeding	1900	100	Strong yield increases, adaptation to agronomic improvement and climatic fluctuations
Genetic manipulation	1970s	40	Reduction of dependency on agrochemicals
Molecular markers	1980s	30	Resistance breeding
Genomic Selection	2010s	10	Increased rate of genetic gain
Gene editing	2015	5	Novel products

ultimately provide the sequences of a complete set of the available alleles for these crop species. The pan genome concept [35] will support wider utilization of the gene pool for the species. The sequence of more than 3000 genotypes of rice [36] has been used to support a wide range of genetic analysis. Plant biodiversity in general is being surveyed by genome sequencing on a larger scale [37–39]. Transcriptome analysis is a key resource for discovery of the key genes for selection [40] in breeding with recent great advances in efficient analysis of complex transcriptomes using long read technology to capture reliably all the full length transcripts including splice variants [41]. Analysis of the coffee transcriptome [41] suggests that the loss of desirable high altitude production environments due to climate change may require the production of coffee in environments that are designed to allow the slow development of the coffee bean. Genetic selection for a longer maturation phase might also deliver high quality coffee in more widely available production environments.

The genes for traits that will support the breeding of genotypes better adapted to new environments is being supported by the discovery of the genetic basis of these traits. The molecular basis of resistance to heat [42], cold [43], drought [44], salt [45] and biotic stress [46] is being advanced by genomic analysis but efforts need to be increased in response to the recent improvements in genomic technologies.

Genetic improvement technology

Changes in the regulation and consumer acceptance of genetic technologies will be crucial in shaping the extent to which genetics can contribute to adaptation of agriculture to climate change. The regulation of genetic change by these methods and limits on access to genetic resources will restrict the extent to which the benefits of this technology can be applied to production of more environmentally sustainable, nutritionally enhanced foods for the support of healthy human populations.

Plant genetic improvement for agriculture has been supported by new technologies that have arisen at an ever increasing rate. Plant breeding has progressed through major developments such as the application of molecular markers in selection, the use of genetic transformation, genomic selection to the recent development of gene editing (Table1). The ultimate extension of the use of molecular markers has been the use of genomic selection. The availability of technology to easily obtain complete genome sequences may make the technologies based upon genetic linkage redundant or much less powerful in relation to the current options. We can now focus on association of traits with the causal variations in DNA sequence and understanding the functional basis of traits. It is increasingly possible to select for the sequences that determine the trait without relying on linkage or position in the genome or to edit in the favorable allele and eliminate the need to cross to generate useful recombination events. The exception may be very complex traits such as yield for which genomic selection may remain the best option until many more of the genes involved are characterized.

Gene editing is currently being widely applied and can be used to directly generate new crop varieties However, gene editing [47] can also provide a very useful tool for testing the phenotype conferred by alleles discovered in germplasm, wild populations of environmentally adapted germplasm or determining the functional role of synthetic alleles. Application of gene editing to breed crops adapted to tropical climates is progressing [48]. The combination of advances in genomic analysis and gene editing should allow a new phase of plant improvement based upon design and building of genotypes to target specific objectives such as adaptation of crops to new field or protected environments.

Capturing more biodiversity and knowledge of natural systems

Plant biodiversity remains a relatively poorly exploited source of variation that is available to support the breeding of crops adapted to new climates. More diverse germplasm from the domesticated gene pool may need to be utilized. In wheat, genotypes have been found with much greater heat tolerance than those in widespread production [49]. Genomics is providing access to diversity

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in crop wild relatives by facilitating genome sequencing [50] and novel allele identification. Crop wild relatives contain a reservoir of genetic diversity to support adaptation of crops to climate change. This is probably also a great place to search for novel variation that might suit the completely new optimized environments possible in indoor farming.

Studies of wild plant populations growing in diverse environments can reveal how plants adapt to climate difference under natural selection [51]. This knowledge can guide efforts to breed crop plants with climate resilience [52]. Studies of this type are supported by increasing amounts of data with technology advances.

Conclusions

Future food production will rely on the continued development of new crop varieties including novel crops and new types of plant-based foods. Crop species that are currently underutilized will need research attention to be able to contribute to climate adaptation [53]. This may require the domestication of new species and the more extensive use of crop wild relatives capturing much more of the available plant biodiversity. Strategies for the capture of novel variation may include the use of techniques such as gene editing to directly introduce novel alleles found in wild plants into domesticated crop varieties. This would allow the rapid and definitive evaluation of the genetic contribution of the introduced allele relative to the earlier much less effective and efficient approaches of extensive backcrossing. More consideration will need to be given to the options of breeding for protected systems [54] relative to breeding for continued field production. The emphasis on breeding for more protected environments will increase as climate change progresses especially for higher value horticultural products. Extension to major field crops such as cereals is only likely in the near future for very high value speciality crops.

Ultimately, plant breeders may be able to design and then construct the required genotype by selecting the best allele for each locus to deliver performance in the target environment. Functional genomics is rapidly defining the path to this approach.

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Conflict of interest statement

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