Trends in
Plant Science

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Opinion

Gaining Acceptance of Novel Plant Breeding Technologies

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Ensuring the sustainability of agriculture under climate change has led to a surge in alternative strategies for crop improvement. Advances in integrated crop breeding, social acceptance, and farm-level adoption are crucial to address future challenges to food security. Societal acceptance can be slow when consumers do not see the need for innovation or immediate benefits. We consider how best to address the issue of social licence and harmonised governance for novel gene technologies in plant breeding. In addition, we highlight optimised breeding strategies that will enable long-term genetic gains to be achieved. Promoted by harmonised global policy change, innovative plant breeding can realise high and sustainable productivity together with enhanced nutritional traits.

Highlights

Current agricultural practices are unsustainable. Moreover, an enhanced ability to adapt to changing climates, enabling expansion of cultivation and yield resilience, is required to maintain and increase crop productivity.

Significant advances in genome editing can lead to improved crop resilience, but such technologies have been met with resistance from society and governments.

Similarly, advances in plant breeding have been relatively slow, lacking the novel and transformative innovations that have been achieved in basic plant science. The gap between advances in basic plant science and acceptance of genome editing innovations by society is large and unyielding. We highlight the problems and offer potential solutions.

The Gap between Plant Science Advances and Society

The evidence presented by the *Intergovernmental Panel on Climate Change* (IPCC) puts into question the sustainability of current agriculture, leaving society and many experts with never-before levels of uncertainty over future food security. Agricultural emissions of CO_2, methane, and nitrous oxides account for roughly 23% of global greenhouse gas emissions [1]. While this figure also does not factor in the compensating CO_2 fixation by agricultural crop production, the stark profile of the IPCC's *Climate Change and Land* report highlights the complexity of interdependent climatic, environmental, and economic factors that have experts calling for imminent and wide-ranging changes to land and water use, food production, and diets [2]. Investment in innovative breeding of plants [3] and animals [4] has the potential to greatly reduce agricultural emissions and improve agricultural sustainability while improving productivity and nutritional biofortification of crops (Box 1). Yet, the gap between advances in plant science and acceptance of novel genetic technologies by societies around the world remains large and unyielding.

Links between climatic and agronomic parameters are well documented [5]. However, field experts and policymakers currently face a lack of an integrated understanding of how terrestrial ecosystems determine the yields of globally important food crops such as rice (*Oryza sativum*), maize (*Zea mays*), wheat (*Triticum aestivum*), and potato (*Solanum tuberosum*) (Box 1, Figure 1). Production of these crops is unlikely to keep pace with predicted future demand under climate change (Box 2) [6–8]. Hence, the future of food security relies critically on plant science and breeding to rapidly develop crop varieties that are adapted to climatic stresses, have improved production traits, and at the same time address the global nutrition challenge. However, an 'orchestrated and coordinated' approach from science, society, and policy perspectives is required to achieve this goal.

Next-generation sequencing technologies and genome-editing technologies (Box 3) allow the targeted modification of genes necessary to engineer entirely new traits and preferred trait combinations, thus overcoming the incompatibility barriers between species [9]. While these

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technologies offer a clear pathway to more climate-resilient crops, the underlying science and technology have not always been accepted by society [10]. The real contribution of emerging crop breeding technologies thus has to be measured by their ability to overcome societal opposition. Such adoption barriers are the root cause of hesitant policymaking that perpetuates regulatory uncertainty and stifles investment [11,12].

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Current Yields Under Existing Breeding Regimes and Future Demands

Average global wheat yields increased by 1% per year during the 20th century, and maize yield in the USA continued to grow at 200 kg/ha/yr or 1.8% per year until drought devastated the crop in 2012 [13,14]. However, global rates of yield improvement in major food crops must increase beyond 1% per year to meet future global demand [14] (Box 2). To complicate matters, yield improvement and adoption of new varieties are low across much of Africa and South Asia [15], and wheat yields in developed economies such as Australia have declined in the 21st century as a result of climate change [16]. The IPCC recommendations [7,8] to prevent potential climate havoc in the global food system are (i) an immediate and significant shift in dietary trends away from meat and towards sustainable plant-based diets and (ii) an equally immediate and significant boost to public and private investment in agricultural research and supportive policy frameworks that translate scientific advances into adoptable, resilient agricultural practices and systems. For these interventions to be successful, significant disruption and sacrifices are required on the part of citizens, consumers, and stakeholders in global agrifood systems and supply chains. However, the scale of such impacts, their geographical distribution, and potential mitigating solutions are largely unknown.

Future dietary trends and global demand are set by a population that is projected to grow to 9.7 billion by 2050 [17]. Without intervention, increasing caloric needs, income growth, and resulting shifts in dietary demands will increase agricultural emissions by up to 40% and also put unprecedented pressures on natural resources. Recent growth in middle-class households across Asia (led by China) has increased the demand for higher-quality foods and especially meat, and this sector now consumes over 17% of global caloric intake. Overall, the gross increase in meat and milk demand alone by 2050 is in the order of 70–80% of current consumption levels [18].

Box 1. Animal-Based Foods Are More Resource Intensive Than Plant-Based Foods

The food security of a growing global population rests on the efficient use of available land and water resources in agricultural production. The current global production of animal-based foods supplies about 37% of global protein supply but accounts for more than three-quarters of agricultural land use and two-thirds of agricultural greenhouse gas (GHG) emissions [1]. This makes the sustainability of protein supply a major limiting factor in assuring future food security. A similar conclusion to shift diets away from animal-based protein was reached by the EAT–*Lancet* Commission on healthy diets from sustainable food systems [19]. The reliance of most livestock and aquaculture systems on the production of land-based feedstock to supply protein contributes to their relative inefficiency. Consequently, when compared on a metric tonne of protein consumed, all plant-based sources of protein outrank animal-based sources of protein in terms of their land-use and water resource intensity (Figure I). Beef is among the least efficient sources of protein from a resource conversion efficiency perspective. Given the rising levels of meat and especially beef demand globally, a shift in diets away from animal-based to plant-based proteins not only would result in a reduction of agricultural GHG emissions but also would enable a more efficient expansion of global protein supply. A greater reliance of plant-based protein supply thus has the ability to bolster future food security while helping to preserve critical environmental resources in agriculture. The EAT–*Lancet* Commission proposed a ‘Great Food Transformation’ [19], and gene technology is a key component of this transformation. Gene technology can help to improve both the yield and nutritional value of crops, as proposed by the Consultative Group for International Agricultural Research (CGIAR) HarvestPlus initiative (www.harvestplus.org). The CGIAR’s HarvestPlus initiative oversees complex interdisciplinary research activities with the goal of reducing mineral and vitamin deficiencies among the global poor through biofortification. While diversification of crop agriculture and biofortification within the HarvestPlus food basket approach directly addresses two of the food security goals of the United Nations Sustainable Development Goals (SDGs), development of alternative food commodities that can rival the likes of wheat, rice, and maize are underway but remain insignificant (www.oecd-ilibrary.org/sites/57d27093-en/index.html?itemId=/content/component/57d27093-en).

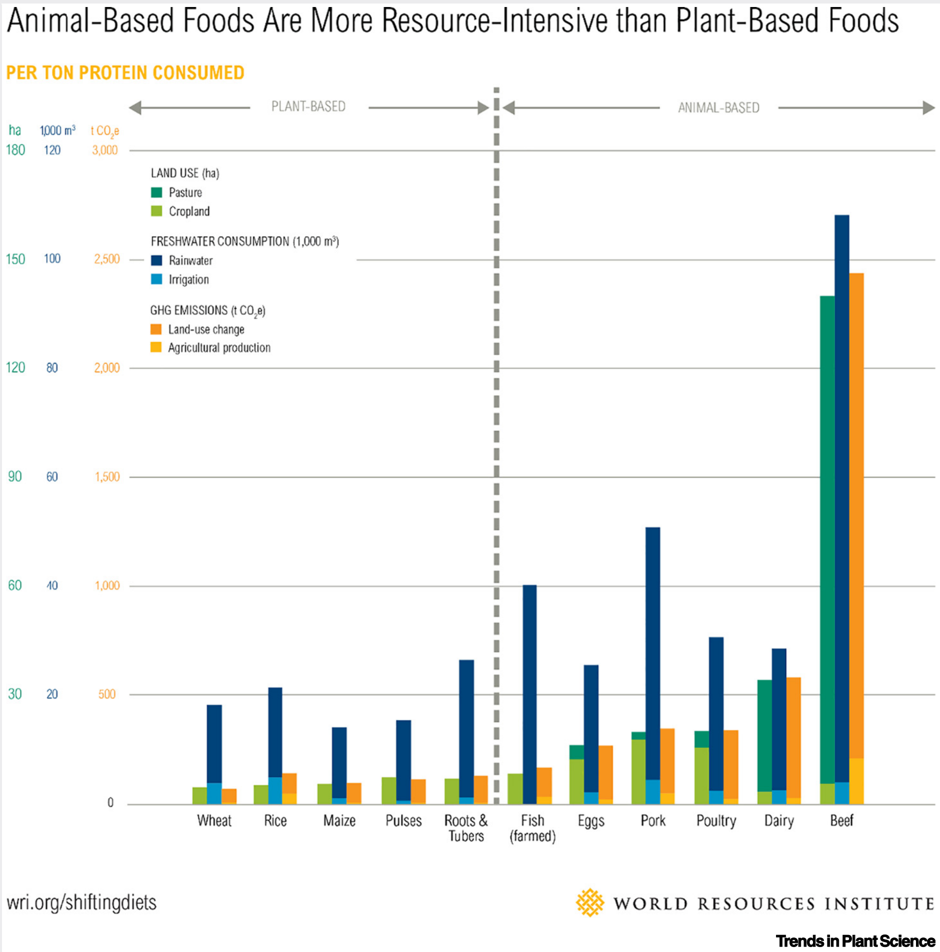

Figure I. Resource Use of Different Agricultural Practices in Protein Production. Abbreviation: GHG, greenhouse gas. Reproduced with permission from www.wri.org/resources/charts-graphs/animal-based-foods-are-more-resource-intensive-plant-based-foods.

Moreover, climate change–associated stresses threaten food security for over 820 million already undernourished and vulnerable people [13].

Engle's law predicts the highest income elasticities of demand for food quality, food safety, and animal-based proteins for households in the lower-income range (less than US $20 000 per year). Mainly located across Asia and sub-Saharan Africa, lower-income consumers are predicted to drive the global rise in demand for caloric needs and especially animal-based proteins of between 176 and 233%. On the other end of the income spectrum, affluent Western societies have started to consider a behavioural change in diet 'beyond meat' and towards climate-smart lifestyles [19]. However, all consumers (independent of income or social status) are united in their propensity to view any new technology, particularly regarding food, with suspicion, risk aversion, and often fear [20].

Economic arguments in the debate about food security and climate change emphasise the wider societal and policy implications of changes in agricultural productivity and resultant shocks to the

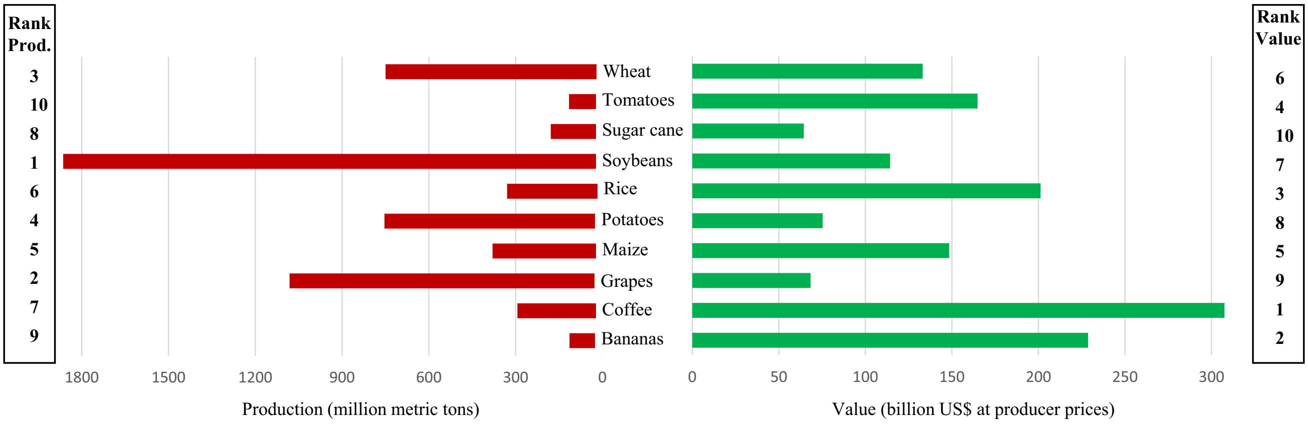

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Figure 1. Global Top Ten Crops, by Production Volume and Value. Food and Agriculture Organization of the United Nations (FAOSTAT), Statistical Database, published online. http://www.fao.org/faostat/en/#data.

food supply [21]. Innovations in plant agricultural systems via advances in breeding and seed technologies are of great economic significance, especially to the livelihoods of large rural populations in developing countries [22]. The rate of innovation in agriculture has long been a function of public and growing private research and development (R&D) investments. However, despite the importance of investment in maintaining agricultural yields, its share has fallen consistently over the course of decades [22]. As consumers and wealthier 'donor' countries place greater emphasis on food safety, processing, and credence attributes, both regulators and food industry investors have diverted increasing shares of agricultural R&D towards such demands and away from immediate primary production traits concerning yields and resilience factors important to crop breeders and farmers around the world [22]. The anticipated benefits of new breeding technologies therefore critically hinge on direct farmer consultation via participatory innovation in crop improvement and breeding to assure widespread adoption in order to improve future food security under climate change [21].

A few major food crops, such as wheat, maize, rice, potato, and soybean (*Glycine max*), account for a major share of caloric intakes and agricultural incomes worldwide (Box 1, Figure I). The price-inelastic nature of markets for food and land, increased yield uncertainty, food supply shortages, and ill-advised policy responses to plant improvement technologies may contribute to the IPCC's projection of a median increase in cereal prices of 7.6% and up to 23% by 2050. This prediction highlights the dire socioeconomic consequences of relying on only a few major crop species for human nutrition (Box 1, Figure I) in a period of climate change–induced uncertainty for both consumers and farmers [7,8]. While a cost burden on poor households, rising food prices are often associated with direct benefits to farmers and declining rural poverty. Whether such benefits are enough to offset the adverse economic effects of more expensive food is ambiguous. Integrated research evidence that considers the outcomes of scientific advances, economic outcomes for farmers and consumers, and supportive policy strategies is essential. Current evidence points to the need for a broader assessment of the economic effects of climate change impacts on agriculture within and across countries. Such studies need to consider key questions of farm-level adoption and policies that facilitate technology diffusion among millions of resource-poor farmers with distinct needs and challenges [23]. However, access to genome-based

Box 2. FAO Scenario Predictions for Major Crops to 2050

The challenge of food insecurity features prominently in the SDGs. Agricultural production projections for the top ten global food crops to 2050 by the Food and Agriculture Organization of the United Nations (FAO) suggest that further growth is possible. Measured against 2015–2018 average global production levels, output for seven of ten commodity crops is predicted to increase under a ‘business as usual’ scenario that perpetuates currently prevailing high-input, resource-intensive farming systems (Figure I).

Under ‘business as usual,’ vegetable, sugar cane, and soybean production are predicted to decline as the growth in yield necessary to offset growing land and water resource constraints becomes unattainable. Under a ‘towards sustainability’ scenario, the FAO predicts a smooth transition to sustainable agricultural practices, including the creation of the necessary policy framework conditions and investment to support climate-mitigative and responsible resource use in agriculture. The ‘towards sustainability’ approach is associated with a reduction in the growth of crop production by between 1 and 18%, mainly due to lower crop production intensities. As ‘business as usual’ is increasingly viewed as unacceptable, the FAO emphasises the critical importance of targeted investment in breeding technology as a necessary condition to move towards food security under climate change.

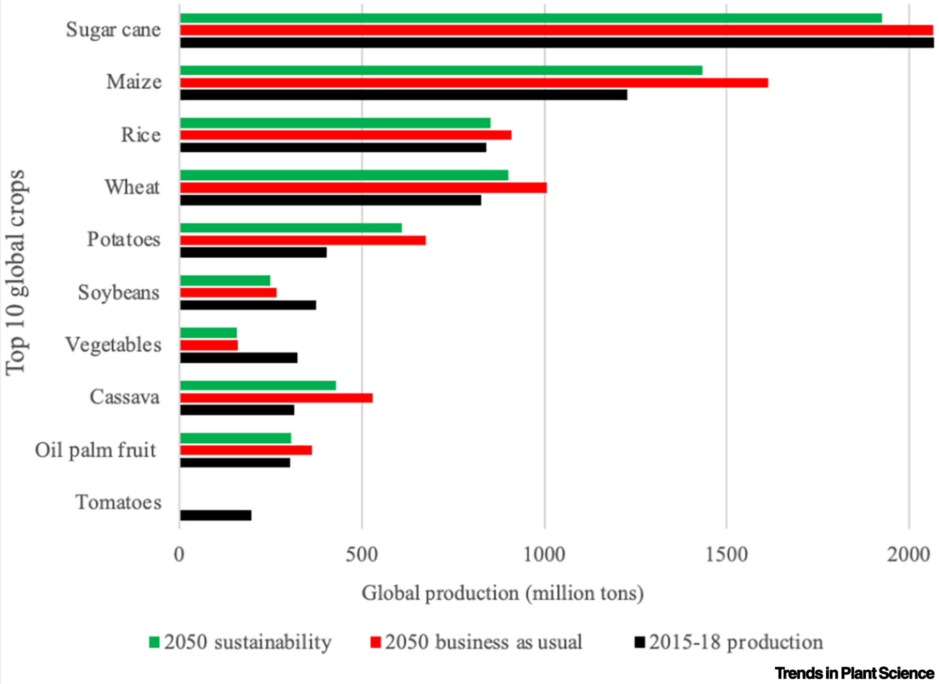

Figure I. FAO Scenario Predictions for Major Crops to 2050. Abbreviation: FAO, Food and Agriculture Organization of the United Nations

technologies (Box 3) is increasingly restricted by regulatory environments, consumer demands, and farmer acceptance. Genetic innovations that offer promising solutions are often overshadowed by the ‘technology controversy’ that has reduced the adoption of genetic modification and gene-editing technologies globally [24].

Barriers to Adoption of New Technologies

Society cares about food, including how crops and animals are bred. New technology in crop breeding is subject to a high level of public and policy scrutiny. This is particularly true for gene editing via CRISPR (clustered regularly interspaced short palindromic repeats). Although the EU is committed to safeguarding new technologies in plants [25], current EU regulations that treat gene-editing CRISPR-produced crops the same as other forms of genetic engineering present a major hurdle to realising future benefits of gene editing in crop breeding [26]. The EU’s

Box 3. Integration of the Appropriate Technologies

Recent literature highlights the power of genome-sequencing and gene-editing technologies [35,46]. Rapid and cost-effective sequencing platforms have revolutionised genome sequencing. However, relatively few laboratory-tested technologies have been validated in the field in a way that would be meaningful to the farmer [47]. Results obtained from controlled environment experiments are often very different from those observed under field conditions. The possibility of *de novo* domestication of wild plants has also been proposed as a route to food security and sustainable low-input agriculture [48]. Similarly, climate change adaptation may be delivered by rapid-cycle breeding programmes that generate improved varieties (Figure I). In this strategy, rapid varietal turnover requires active dissemination of new varieties together with withdrawal of obsolete ones. In addition to influences on genetic controls governing plant responses to the stresses associated with climate change, the epigenome is also strongly regulated by environmental triggers [49]. Most plant genomes are composed primarily of retrotransposons (RLXs), which are a highly dynamic part of the genome [50]. Moreover, RLXs are major drivers of genome evolution and mutation as well as plant responses to climate change–associated stresses, such as heat and drought [51], and other interactive factors, such as UV light. The read-through from RLX promoters exerts a strong influence on the expression of adjacent genes. Moreover, RLX expression triggers epigenetic targeting by the RNAi pathway for both post-transcriptional silencing and CHG DNA methylation, which acts downstream of the siRNA pathway to label DNA for silencing. Heterochromatin formation may be a consequence of nearby RLX insertions [52]. RLX methylation can spread outwards to neighbouring genes, with concomitant silencing. Crucially, many important cereal genes are neighbours of RLXs. The induction of RLXs may therefore play a key role in the coordination of epigenetic status in response to climate change–associated stresses. A much more in-depth understanding of how climate change–associated stresses influence RLX replication and, consequently, genome size growth is required to incorporate these factors into current plant-breeding strategies. Nevertheless, the use of RLX technologies in crop breeding is predicted to help further breeders to achieve high and sustainable productivity.

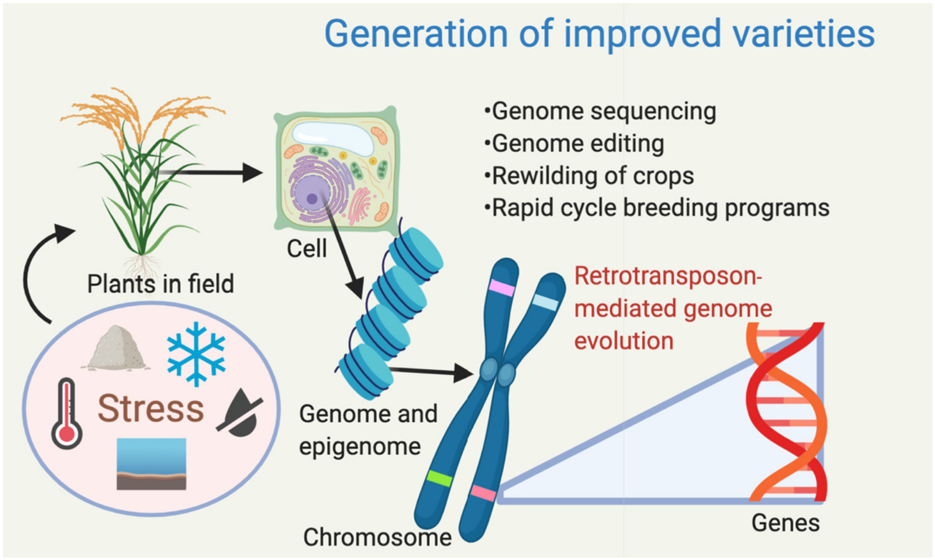

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Figure I. Generation of Improved Varieties.

conservative antigenetic engineering policies in crops have had major impacts beyond its borders, and, likewise, EU regulation of gene editing will extend far beyond its borders [10]. Beyond regulatory and political framework conditions, societal norms and beliefs in both developed and developing countries stand in the way of widespread acceptance and regulation of new crop-breeding technologies. Two of the world’s most populous countries, China and India, have a poor record of considering the needs and demands of their farming communities in policy decisions. The recent uprising of Indian farmers over price support policies stands as exemplary for how far removed policy decisions can be from what farmers find acceptable. Hence, crop-breeding solutions to current food security challenges cannot be viewed in isolation from their scientifically proven and otherwise perceived risks and benefits by consumers or from their impact on agronomic and cultural practices of farmers.

For example, high beta-carotene (golden) rice is the first genetically engineered crop to alleviate a public health issue (vitamin A deficiency) in a lower-income country following its approval for consumption and processing in the Philippines in January 2020. This approval came 20 years after golden rice was first developed by committed researchers who worked together with partners over many years to achieve 'freedom to operate' for public research institutions in developing countries to transfer the high–beta-carotene genes into the best locally adapted varieties [27]. The lack of acceptance by farmers in the Philippines (and other Asian countries) was traced back to several issues: first, a lack of social trust in institutional actors; second, the foremost concerns of rice farmers were around agronomic factors, production, yield stability, and cost rather than the nutritional properties that benefit consumers, who are able to pay for golden rice; and third, a perceived lack of marketing know-how and support of farmers wanting to grow golden rice [28]. Undoubtedly, gene editing via CRISPR holds immense potential for advancing global challenges ranging from abiotic stressors to micronutrient biofortification. Combating any of these challenges requires the unreserved cooperation of millions of farmers and consumers with diverse agronomic and cultural backgrounds.

Since the inception of genetically modified (GM) plant production, numerous studies have emphasised that these technologies pose no greater risks to society than conventional agriculture [29,30]. Nevertheless, the general perception of GM and other disruptive technologies remains negative. The emergence of genome-editing technologies has generated huge expectations amongst plant scientists, breeding companies, and the food industry, with the consensus view being that science can change consumer perception. Even though acceptance of CRISPR/Cas technologies is greater than that for GM plant production, food technology neophobia still influences consumer acceptance globally [31,32]. This perspective has been driven in part by the legislature that equates genome-edited crops with the first-generation GM plants [30]. Currently, seven countries accept genome-edited crops that do not incorporate foreign DNA with no restrictions, because these are considered to be conventional plants. Knowledge of how farmers, many in developing countries, view CRISPR/Cas technologies from their unique adopters' perspective is unclear because research into adoption preferences and barriers is lacking.

Optimising Crop Breeding to Secure the Value of New Technology

Recent advances in plant-breeding technologies show great promise to contribute to sustainable future food security. The 'breeder's equation' describes the response to selection in the next generation and suggests how best to integrate new technologies into crop breeding [15,33]: response to selection (R) is the product of additive genetic variation in the breeding population (σ_A), selection intensity (i), and accuracy of selection (r) and is divided by cycle time (L) to determine R per year [34]. Gene editing may contribute genetic value (increase σ_A) for abiotic stresses [35]. Rapid single-seed descent or 'speed breeding' [36,37] decreases L (and increases R) compared with traditional crop breeding methods. A new method of selection in self-pollinating crops, optimal contribution selection (OCS), is important for increasing genetic gain in multiple traits in the long run [33,38].

Animal breeders pioneered the use of genomic selection to accelerate genetic gain and adapted their breeding methods to the increasingly complex array of technology, including gene editing, epigenomics, and transcriptomics [39]. Crop breeders have been urged to adopt 'multi-objective optimised genomic breeding strategies' to secure future food security [40]. For example, new alleles from gene editing could contribute to heat tolerance in crops, which will be vital for improving grain yield over the next 60 years of global warming [41]. OCS was developed by animal breeders to limit inbreeding depression and minimise genetic drift and loss of potentially valuable alleles [42]. Genetic drift is potentially large in traditional crop-breeding programmes due to small effective population size. Drift also increases the risk of loss of valuable gene edits, but this risk is reduced by OCS (Box 4). OCS increased long-term genetic gain for grain yield, disease resistance, and other traits in a model wheat-breeding programme while improving heat stress tolerance during the next 60 years of global warming (Box 4). Besides OCS, new approaches to optimise genomic selection have been suggested, such as a look-ahead selection algorithm in crops to optimise selection decisions and mating designs for long-term genetic gain [43].

Resolving Key Issues

The application of plant science advances has the potential to improve the sustainability of crop yields while addressing the challenges of climate change. Farmers are first in line when it comes to

Box 4. Optimising Crop-Breeding Strategies Secures the Value of New Gene Technology

Summary

Crop genetic diversity from all sources, including from novel technologies, may be lost in the future from traditional crop-breeding programmes due to inefficient selection strategies. Optimal contribution selection (OCS) of an index of traits minimises genetic drift and increases the potential for long-term genetic gain [41]. OCS secures long-term genetic gain in all economic traits, such as disease resistance, grain yield (GY), and heat stress tolerance (HST). Without genetic improvement in HST, future GY may fall due to heat stress caused by global warming.

Introduction

The predicted response to selection (line) ± standard error (shading) is shown (Figure I) for the outcomes of a stochastic quantitative genetics model for selection during 60 years of global warming in two hypothetical wheat-breeding programmes [41]. The breeding programme (Figure I, left) represents a ‘traditional’ wheat breeding programme with a moderate effective population size ($n_e = 40$) and sequential selection for traits by truncation and independent culling. The breeding programme (Figure I, right) is based on a selection index subject to OCS, with higher effective population size ($n_e = 100$) and priority selection for HST during 60 years of global warming. The model assumes an increase in temperature on arable land of +4°C from 2017 to 2077. The goal is to increase HST ($h^2 = 0.3$) from 30 to 34 units to match +4°C global warming from 2017 to 2077 while selecting for GY ($h^2 = 0.3$), disease resistance ($h^2 = 0.3$), stem strength ($h^2 = 0.3$), and flowering time ($h^2 = 0.5$).

The traditional (Figure I, left) and OCS breeding programmes (Figure I, right) undergo 2-year cycles of rapid recurrent selection for these traits during 60 years. The target of rate of improvement in HST score is 0.133 units per cycle to match global warming of +4°C from 2017 to 2077; if this fails, adjusted GY is reduced by heat stress [41].

Results

In the traditional breeding programme (Figure I, left), beyond 2055, HST stopped improving due to high rates of population inbreeding and loss of genetic diversity. Selection was no longer effective for HST, and, consequently, adjusted GY declined rapidly beyond 2055 due to global warming and inadequate HST. Disease resistance and stem strength also stopped improving in the traditional breeding programme [41].

In the OCS breeding programme (Figure I, right), HST improved by almost four units during 60 years of global warming, and adjusted GY doubled by 2077.

Conclusions

The GY of future varieties was protected from heat stress by gradual genetic improvements in HST during 60 years. However, this was successful only in the OCS breeding programme. OCS improves genetic long-term gain for all traits in the selection index, including HST, by conserving genetic diversity and protecting new genes from loss due to genetic drift [41]. Also, OCS promotes effective recombination while reducing linkage drag caused by inferior alleles [53].

The traditional breeding programme was limited by high rates of population inbreeding, loss of genetic diversity by drift, and inability to improve HST beyond 2055. Without HST, adjusted GY was reduced by global warming, and future food security was threatened. The future value of novel gene technology is at risk in the traditional breeding programme due to failure to improve HST to match predicted rates of global warming. All data are from Table S3 in [41] and are reproduced with the permission of the authors.

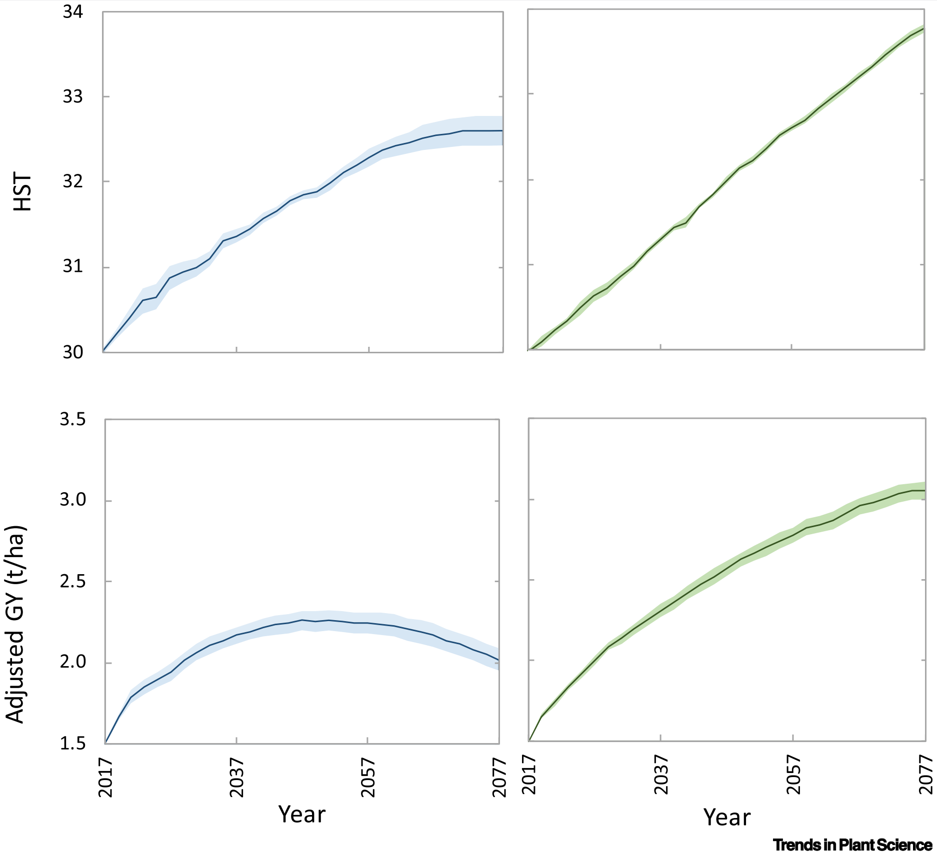

Figure I. Optimising Crop Breeding Secures the Value of New Gene Technology.

the acceptance of new breeding technologies. A major barrier to realising the benefits of new breeding technologies is therefore to bridge the gap between the capacity and needs of small-scale producers, national food security strategies, and multinational breeding efforts (and companies). Without targeted investment that strengthens the innovative capacity of agriculture in developing countries, the widespread adoption of new crop innovations will continue to be limited. Innovative plant breeding can disrupt the current bottlenecks to achieve high-value crop varieties incorporating new gene technology and should lead to widespread acceptance of plant-breeding innovations (Box 5).

The development of functioning supply chains that effectively integrate and coordinate activities, especially amongst small-scale farmers, is essential. Better connected and market-oriented farmers are more likely to produce quality food products to meet market demands. A critical step in bridging the current gap is the integration of scientific and economic research, along with the development of new varieties. Such a collaborative approach also needs to consider the cost-effectiveness of new lines and the balance of supply and demand in the global food system. Farmer participatory research in rice and corn has shown that consideration of farmers' needs and preferences speeds up selection. This is particularly true for economic evaluations of new lines for their cost-effectiveness and agronomic risks. These are important to farmer adoption decisions and hence should become part of routine breeding assessments [44]. Overall, it is crucial to

Box 5. Challenges and Solutions

The challenge

- (i) Climate change brings significant risks for food production and global food security. Extremes of weather, which have already caused a substantial impact on agricultural production, are likely to become more frequent, providing additional challenges to farmers to increase productivity for an increasing population with less available agricultural land [5–8].
- (ii) The ability to adapt to alternative climates, enabling expansion of cultivation and yield resilience, is key to maintain and increase crop productivity. Crop resilience needs to be multifaceted and ideally will provide resilience to a range of abiotic stresses that a crop may encounter over different years.
- (iii) Significant advances in genome editing lead to improved crop resilience, but such technologies have been met with resistance from society and governments.
- (iv) Advances in plant breeding have been relatively slow, lacking the novel and transformative innovations that have been achieved in basic plant science.
- (v) The gap between advances in basic plant science and acceptance of genome editing innovations by society is large and unyielding.

The solution: delivering global food system transformation

Novel, transformative, and disruptive mechanisms are required to meet the challenge of transforming the global food system.

- (i) The application of plant science has the potential to improve the sustainability of crop yields and address the problem of climate change, particularly if we simultaneously diversify our cropping systems for greater resilience and environmental benefits.
- (ii) The lack of societal acceptance of current gene-editing technologies means that these approaches alone cannot ensure continued productivity of staple crops under climate change. Thus, there is an urgent need for innovative plant breeding to accelerate the production and introduction of new crop varieties. The widespread if not universal acceptance of innovative plant-breeding methods based on an evolutionary or 'look-ahead' algorithm is therefore imperative to disrupt the current bottlenecks to progress [40–43].
- (iii) Sustainable agriculture must be protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe, and healthy while optimising natural and human resources.
- (iv) Future food production and supply, economics, and culture are components of a complex adaptive system driven by human behaviour and climate change. Delivering healthy and accessible diets and sustainable food production therefore requires cross-disciplinary action for personal, public, and planetary health. An integration of cutting-edge fundamental and social sciences is required to address supply and demand in the global food system (i.e., here defined as the product of socioeconomic and environmental processes involved in integrated production, sale, and consumption of food).
- (v) There is an urgent need to transform current diets for better population health and to achieve social, economic, and environmental benefits. A more plant-based diet has been proposed to support better planetary health [7,8]. Being more sustainable, such a diet would have lower environmental impacts and improve food and nutrition security and health for present and future generations.

build and maintain trust between producers, companies, organisations, and national governments involved in the breeding and dissemination of new varieties. Facilitating horizontal coordination between smallholders will help to build more competitive and resilient supply chain structures. Recent evidence suggests that entering into contract farming may be a viable avenue for disseminating new varieties with market-relevant quality attributes in some countries [45].

Concluding Remarks and Future Perspectives

Plant-breeding systems must be strengthened and modernised to better serve the needs of farmers and consumers. While powerful new genome-editing and next-generation sequencing technologies provide unprecedented possibilities, their potential contribution is currently constrained by widespread societal opposition, including rejection among farmers in developing regions of the world. Heightened public and policy scrutiny of agricultural innovation is deeply rooted in consumers' natural interest in their food supply. Society's rejection of 'incomprehensible' scientific innovations has become a major barrier to regulating gene-editing technology.

There is no future in fighting climate havoc in the global food system by promoting widespread dietary change alone. Instead, breeding innovations that emphasise all-important yield together

Outstanding Questions

The concept that novel, transformative, and disruptive mechanisms are required to meet the challenge of transforming the global food system is widely accepted, but many questions still remain concerning how this can be achieved:

- How can sustainable agriculture that is protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe, and healthy be achieved while optimising natural and human resources?
- How can societal acceptance of current gene-editing technologies be achieved? Will these approaches alone be sufficient to ensure continued productivity of staple crops under climate change?
- There is an urgent need for innovative plant breeding to accelerate the production and introduction of new crop varieties. Can universal acceptance of innovative plant-breeding methods based on an evolutionary or 'look-ahead' algorithm be achieved to disrupt the current bottlenecks to progress?
- How can cutting-edge fundamental and social sciences be integrated to address supply and demand in the global food system?
- What cross-disciplinary actions are required on a personal, public, and planetary level to ensure successful outcomes?

with environmental and climate resilience factors that benefit farmers' bottom lines are gaining momentum as crucial response strategies. This message has started to resonate with policymakers and investors after decades of declining investment in agriculture and food security research. The literature has long argued that the efficient use of agricultural and natural resources (towards sustainability) is the best food security policy. This makes innovative plant-breeding technologies (Boxes 2 and 3) and their integration into sustainable breeding systems (Box 5) the key to success and strengthens the message that science itself must be more receptive to solving the global challenges that society prioritises. Appropriate policies and regulations are required to harness this, together with the essential social acceptance that facilitates regulatory and policy actions towards sustainable future food security. As we argue in this opinion article, it is the responsibility of the scientific community (crop researchers and breeders) to actively promote the safety and ethics of gene-editing technology.

Many plant scientists are already engaged in integrated and collaborative approaches to effectively counteract the adverse impacts of climate change on crop resilience and productivity. However, the ultimate success of such strategies is dependent on the recognition of the interdependence of basic science, current breeding developments, governance processes, and crucially the jurisdiction in the form of stakeholder and broader societal acceptance. If history is any example, achieving acceptance of gene editing via a 'wait and see' approach may take decades. Unfortunately, efforts to understand and manage the complexity of independence between science, agriculture, environment, and society is currently hampered by a lack of organisation and coordination and misunderstanding of the risks and benefits of applications of cutting-edge scientific methods in assuring sustainable food security. An encouraging example is a collaborative effort by Re-Imagine Europa, All European Academies, the EU Strategic Advisory Group of Experts and the Bill and Melinda Gates Foundation, and the European Commission motivated by EU Council Decision 2019/1904 on the status of novel genomic techniques and particularly genome editing. The initiative's goal is to stimulate interdisciplinary and intersectoral debates to support the positive regulation of gene editing. At the same time, the consortium emphasises public engagement and education as a key to the process of weighing the opportunities and challenges of new technological innovations in agriculture.

Innovative plant-breeding technologies are an essential component of strategies to achieve sustainable food security. Recent attempts to adopt optimised breeding strategies in crop breeding have been successful [40–43], and OCS was shown to be superior to traditional approaches to plant breeding for improving crop yields during climate change (Box 5). We consider that plant breeders who optimise their breeding programmes for long-term genetic gain will be in pole position to serve the needs of farmers and society and to integrate new technologies (particularly gene editing) as they are developed or approved. This approach ensures that all valuable alleles are retained for future genetic gain (including gene edits as they become available). We fear that if such innovate crop-breeding approaches are not embraced by the wider plant science community, we may not succeed in improving and sustaining grain yields under climate change, and we will fail to meet the needs and expectations of society (see Outstanding Questions).

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Declaration of Interests

The authors have no interests to declare.

Author Contributions

S.A., W.C., and C.H.F. designed and wrote the manuscript and produced figures. K.J.G., S.L.S.-P., and A.P. contributed figures and assisted in the production of the manuscript.

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