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Opinion

Resilient plants, sustainable future

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The accelerated pace of climate change over the past several years should serve as a wake-up call for all scientists, farmers, and decision makers, as it severely threatens our food supply and could result in famine, migration, war, and an overall destabilization of our society. Rapid and significant changes are therefore needed in the way we conduct research on plant resilience, develop new crop varieties, and cultivate those crops in our agricultural systems. Here, we describe the main bottlenecks for these processes and outline a set of key recommendations on how to accelerate research in this critical area for our society.

Highlights

The urgency of climate change impacts on agriculture requires rapid and innovative solutions for plant resilience to ensure food security.

Plant breeding and genome editing are key tools for the development of climate-resilient crops, but faster alternatives should be explored.

A major bottleneck in plant resilience research is translating laboratory findings to field conditions, especially for crops grown under diverse environmental stresses, and a field-to-lab-to-field research paradigm should be explored.

Collaboration between scientists, farmers, consumers, and policymakers is essential to address real-world agricultural challenges and advance resilient crop solutions.

Public acceptance and a streamlined positive regulatory framework are critical in implementing new genetic technologies in agriculture.

Urgency of climate solutions for food security

Climate change is rapidly emerging as the defining crisis of our time. Its impacts are far-reaching, affecting not only the environment, but also human health, agriculture, energy, and food security. Increasing global temperatures severely threaten the performance and yield of crops. Stress from higher baseline temperatures is exacerbated by an unprecedented increase in the frequency and intensity of heat waves, drought, flooding, and pest and pathogen outbreaks, resulting in massive yield losses to staple crops [1]. While increased CO_2 concentrations that enhance crop yields might offset some of these effects, they also diminish the nutritional quality of edible food products [2], presenting a significant challenge in ensuring that our food supply remains both abundant and nutritious. This triple threat of degradation of nutritional quality, rising temperatures, and increased frequency of biotic and abiotic stresses necessitates urgent and innovative strategies to safeguard our food systems. Current yields of domesticated crops are no longer increasing as they did during the green revolution and now are threatened by climate change, despite significant efforts to develop crops with abiotic and biotic stress tolerance traits [3]. At the same time, agriculture directly contributes to climate change, producing ~26% of worldwide greenhouse gas emissions, including carbon dioxide, nitrous oxide, and methane, as well as driving land-use change and erosion [4]. The effects of climate change are exacerbated under low-input agricultural systems common in some parts of the world, particularly Africa, Asia, and Latin America, calling for urgent interventions.

To address these challenges, it is essential to improve both current crops and cropping systems. Developing new and adaptable cropping systems can diversify agricultural production, benefiting biodiversity, crop resilience, and carbon sequestration. Identifying the genes and biological processes that enable plants to withstand and possibly thrive in challenging and novel climatic conditions is crucial to sustain crop yields in the face of climate change. Without enhanced plant resilience, future climates will lead to lower yields per unit land area, demanding more arable land and threatening biodiversity. Therefore, resilience traits – such as reduced water and fertilizer requirements – are critical to mitigate the climate's impact on agriculture. Plant breeding can

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provide climate change-adapted crops by leveraging the genetic diversity of landraces, rare breeds, and closely related wild relatives of domesticated species. Although conventional plant breeding is often slow and costly, together with emerging technologies using genome sequencing and editing as well as soil- and plant–microbial communities, offer faster, more affordable approaches to boost crop resilience [5]. Given the rapid pace of climate change, these innovations are crucial to ensure food security for the world's growing population.

Current bottlenecks and opportunities

While great gains have been made in understanding how plants respond at the molecular and physiological levels to environmental change, translating this knowledge from the laboratory to the field has been a major challenge [6]. In part, this is because mechanistic insights come from tightly controlled greenhouse experiments on limited germplasm, whereas agricultural systems are characterized by a broad range of plant cultivars and varieties grown under highly variable field conditions. Due to cost and experimental complexity, what is often missing is an integration of these two approaches that enables mechanistic studies under field conditions or deconvolution of field observations in the laboratory through the identification of underlying mechanisms. Additionally, embracing the complexity of multistress environments, by exposing plants to combined abiotic and/or biotic stresses [7], is an area that requires greater emphasis to develop strategies to enhance resilience in the real world.

Plant breeding remains the gold standard for developing crop resilience, although plant genome engineering is a promising and viable alternative. However, for woody perennials, breeding benefits may not materialize quickly enough to address climate change or emerging diseases. Bacterial pathogens spread by insects pose significant threats to these crops, with some diseases like citrus greening or Pierce's disease in grapevine remaining untreatable [8]. Developing crop protection products requires both a therapeutic molecule and a delivery strategy, but early economic yield measurement during product development is challenging, and high commercialization and regulatory costs limit options for woody perennials as well as multiple minor crops. Disparate regulations among states and countries further hinder rapid adoption of new solutions. Innovative approaches to accelerate the discovery and delivery of therapeutic molecules for plant protection are urgently needed [9].

Despite the substantial contribution of agriculture to greenhouse gas emissions, only 4% of global climate finance (~US$850 billion) goes towards agriculture and agrifood systems annually [10]. Further, only a small portion of the ~US$35 billion spent on agriculture and agrifood systems each year globally is funneled to the research and development of climate-resilient crops [11,12]. Research and development investment is primarily focused on commodity crops grown using practices and high-intensity conditions common in developed nations. Additionally, private investment has a goal of obtaining a return on investment, measured in terms of revenues and profits, which is targeted to large-scale agriculture. While this system has been effective in raising the yield of key crops in the Global North, it has left behind many innovative ideas and failed to address challenges faced by the Global South. By embracing the full complexity of stress resilience research, as well as approaches not necessarily attractive to private investment, we can discover strategies that not only help the Global South but can bring paradigm-shifting insights to high-intensity systems as well.

To secure crop production in the face of climate change, holistic solutions are needed, which involve a combination of breeding, transgenesis, and gene editing, as well as emerging synthetic biology tools that increase the precision and rate of crop improvement. A current impediment to the commercial application of this holistic crop improvement strategy is the regulatory burden for new crop germplasm developed by modern genetic approaches. The high costs and time

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involved in addressing regulatory requirements stifles innovation and reduces the participation of startup companies and academic and government researchers in transitioning new technologies to the development of high-yielding resilient crops. Moreover, there is a critical need to strengthen research capacity in the Global South, which is crucial to ensure that we can develop and implement context-specific, resilient agricultural solutions and practices that can withstand climate-related stresses. Additionally, lack of acceptance of genetically modified (GM) crops has driven individual country policies that limit trade. For many challenges, the regulatory and technological hurdles may be too high to justify investment in the use of GM technology. In those cases, the best strategy will likely involve investment in targeted breeding programs that are enabled by genomic and phenomic prediction. Most crops still have large levels of standing genetic variation, which has yet to be exploited for breeding where it is not economically advantageous or socially acceptable to use transgenics.

Recommendations

Based on the current state of research and future prospects for innovations in the field of plant resilience, we propose a set of five recommendations to leverage plants to mitigate and adapt our society to the changing climate (Figure 1).

(i) Establish global research initiatives

Addressing climate change transcends national boundaries and requires a holistic global strategy that leverages the collective expertise and resources of diverse communities [13]. Solutions will need to be shaped and targeted differently to respond to different problems and requirements at the global scale. Coordinated, international efforts will be pivotal in enabling research that might otherwise lack financial support, particularly in developing regions where the impact of climate change is felt most acutely. Merging efforts from researchers who focus on advanced biotechnologies with those who bring unique environments and natural resources as well as knowledge of local agricultural practices can lead to the development of innovative farming techniques that are both technologically advanced and culturally relevant. For instance, the success of CGIAR centers in some regions of the Global South could be extended via partnerships with the National Agricultural Research and Extension Systems and research institutes in the Global North. Also, public–private sector partnerships, especially with large companies, will be important in accelerating climate-resilient crop development. Finally, Freedom to Operate analysis, a legal assessment that determines whether a product or service can be used without infringing on another party's intellectual property (IP) rights, should be an inherent part of the development and dissemination of resilient crops. By emphasizing inclusivity and collaboration across foundational and applied research sectors, we can foster not only scientific advancement but also social equity, ensuring that all communities have the tools and knowledge they need for sustainable agricultural practices that can adapt to the changing climate. In this way, addressing climate change can become an opportunity for scientific synergies, global unity, and innovation, driving communities and countries to work together for a healthier planet and combat the enormous challenges that could rapidly lead to famine, migration, and global destabilization of our society.

(ii) Embrace complexity of stress resilience research

Plant resilience is complex and polygenic in nature and must be understood and engineered in the context of the plant as a holobiont embedded in its soil, air, water, and biotic environment. This field needs to strike a balance between studies of complex systems (e.g., ecology, systems biology) with reductionist approaches (e.g., biochemistry, biophysics) to reveal the principles underlying plant resilience against environmental hardship. Advances in generative artificial

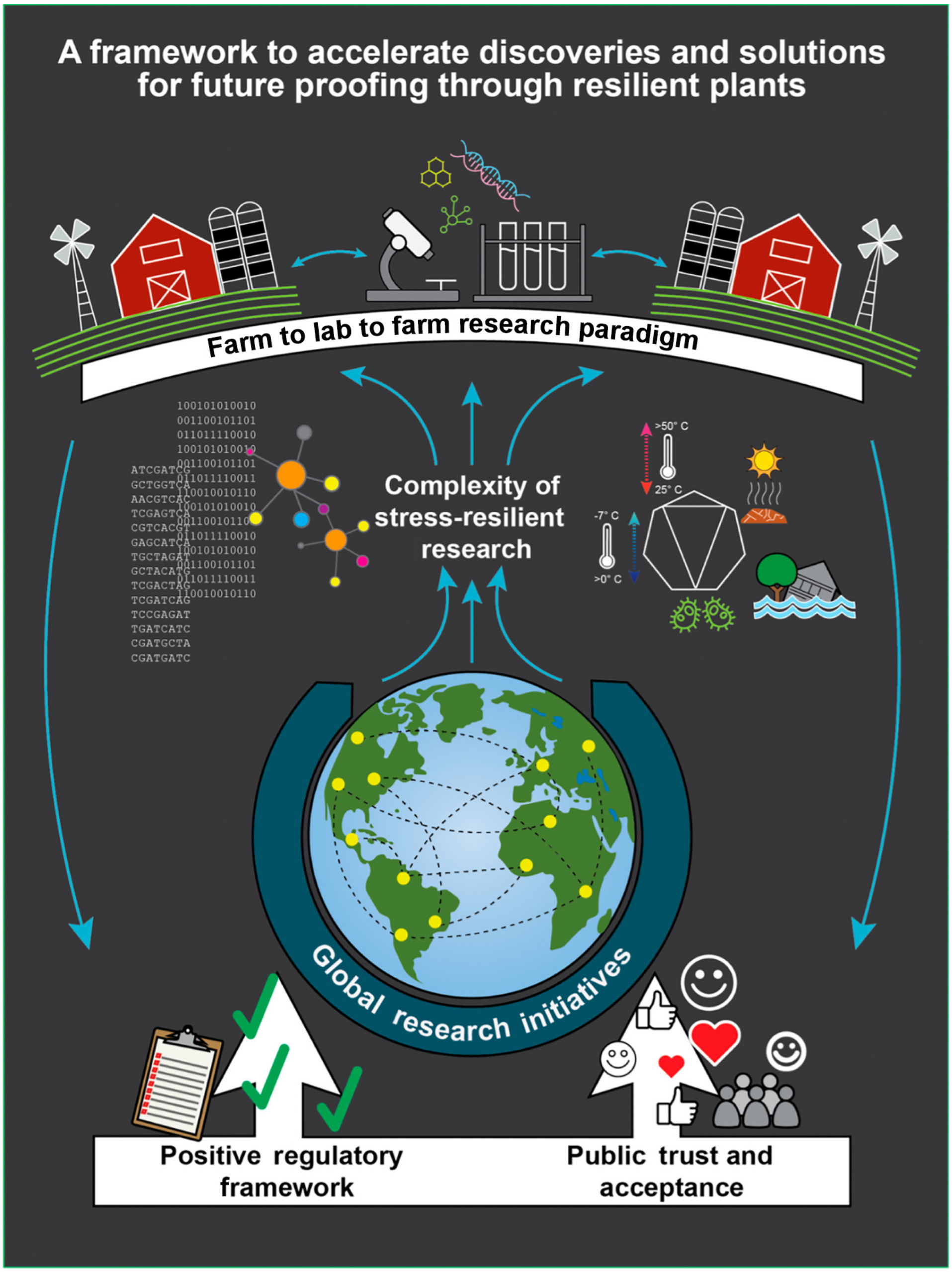

Figure 1. A set of recommendations to achieve a sustainable future through resilient plants.

intelligence (AI) tools, single-cell approaches, genome editing, and the emergence of large-scale, cost-effective phenotyping systems are exciting examples of how this approach can be fruitful. One major current limitation is the lack of global, extensive, and connected experimental field stations where researchers can test traits and genotypes directly in the field or natural ecosystems without having to first rely on laboratory testing. We advocate for a concerted effort to leverage the extent of genetic variation and modern molecular approaches in a field-based experimental pipeline. We need multiple locations around the world with cutting-edge outdoor phenotyping and monitoring capabilities that are ideal for large-scale, field-based stress experiments [14]. We propose appropriate levels of funding of such locations to develop richer comparative omics resources to identify conserved and species-specific resilience. These data could be integrated into multimodal models to: (i) identify conserved regulators of resilience, in the vein of recent efforts to increase water and nutrient use efficiency [15,16]; and (ii) predict how plants with multiple genetic improvements will perform in tomorrow's climate. This type of infrastructure is not unlike the Giant Magellan Telescope, the Large Hadron Collider, or the International Thermonuclear Experimental Reactor (ITER) in the astronomy and physics world and could transform the way plant scientists study plant resilience strategies and mechanisms. The National Science Foundation (NSF) and US Department of Agriculture (USDA)'s Long-Term Ecological Research and Long-Term Agricultural Research networks are great examples from the ecology and agricultural angles, but more programs that focus on linking ecological or applied research with molecular mechanistic research could enhance these efforts at a global scale.

(iii) Adopt a 'farm-to-lab-to-farm' paradigm to accelerate solutions and discoveries

One of the greatest opportunities to develop more resilient crops is through the partnership of fundamental plant researchers, applied scientists and farmers working on crops in the field, and consumers of the plants and their products. Often these partnerships are driven by discoveries that occur first in the laboratory and then are translated to the field [17]. However, far more progress is likely to be made when fundamental laboratory research is driven by an understanding of the real-world challenges faced by farmers that then inspires laboratory and field researchers to address these needs. Thus, it is imperative that future plant resilience research programs involve teams of scientists that span the divide between laboratory, field, and farm. These types of partnerships can be difficult because they necessarily involve good communication, listening, and a willingness of scientists to alter their existing research programs to complement the challenges faced by crops in the field. While challenging, these partnerships will lead to a research ecosystem where the field and farm inform the laboratory, which in turn will provide new resources and approaches for the field and farm and result in a more climate-secure world.

(iv) Build public trust and acceptance of new technologies: engage with the public

Public acceptance of crop engineering using genetic modification is important in transforming our understanding of plant resilience to solutions that mitigate climate change. It is well known that science communication strategies focused only on increasing the understanding of a technology tend to fail in changing public opinion [18]. To increase acceptance, it is important to improve the experience of the general public with plants developed with the new genetic technology. For example, the developers of gamma-aminobutyric acid (GABA)-accumulating tomatoes distributed the tomato seedlings to home gardeners who were encouraged to grow, harvest, cook, and eat the new tomato to enhance their experience with it [19]. GABA is an amino acid neurotransmitter thought to be associated with relaxation and calming. As a result of the strategy to involve the consumers in producing the tomatoes, these genome-edited tomatoes are now being sold in grocery stores in Japan. In addition, implementation of new strategies for the development of resilient crops and production systems must also be done in conjunction with farmers and commodity boards. The profitability of agricultural products, the well-being of farmers and consumers, and assurance of food sovereignty for the people are keys to the ultimate adoption of new technologies.

(v) Establish a positive regulatory framework

The current system stifles innovation and limits the participation of startups and public-sector researchers in translating new technologies to develop resilient crops. Regulation needs to be more science based, rapid, and streamlined to make it feasible and less cost prohibitive for publicly funded innovations to find their way to market. A positive regulatory framework for agricultural innovations should ensure that decisions are rooted in robust scientific evidence to effectively assess risks and benefits. Proportionality is key, with regulatory requirements matched to the level of risk, allowing low-risk technologies, such as minor gene edits, to face fewer hurdles. Transparency and stakeholder inclusion are essential to build public trust, address societal concerns, and ensure diverse voices, including farmers, consumers, scientists, and policymakers, are heard. The framework must also be flexible and adaptable to accommodate rapidly evolving technologies like CRISPR and synthetic biology, with periodic reviews to stay relevant. Global harmonization is vital to align with international standards, reducing trade barriers and facilitating market access. Sustainability should be a core focus, encouraging innovations that improve resource efficiency, reduce environmental impact, and align with global goals like the United Nation's Sustainability Development Goals.[i] Additionally, the framework should promote equity, ensuring innovations benefit smallholder farmers and marginalized communities. Approaches to achieve this framework include streamlined approval processes for low-risk innovations, public-private partnerships, and investments in regulatory capacity building. Incentivizing innovation through tax credits, grants, or subsidies, alongside pilot projects for real-world testing, can accelerate the adoption of sustainable technologies. Public engagement and education are also critical to address misinformation and increase acceptance. By integrating agricultural innovation policies with broader economic, environmental, and trade strategies, governments can foster a regulatory environment that balances safety, sustainability, and societal benefits while supporting local and global innovation.

Concluding remarks

The accelerated pace of climate change necessitates a significant change in the current processes and concepts used to develop resilient crops and to introduce these improved crops into our agricultural settings. Critical bottlenecks that must be removed to allow this change include insufficient resources and research centers that focus on this problem, the limited research conducted on plants embedded within their native soil, air, water, and biotic environment, the limited public trust of new technologies, and the slow pace and extensive cost of regulatory processes used to approve new varieties/treatments/practices before they can be introduced into our agricultural systems. Education and training of next-generation scientists, extension scientists, and farmers are essential to sustain the recommended strategies and foster a long-term, globally equipped research community. Moreover, these solutions cannot be fully realized without a strong foundation of scientific and research capacity in the Global South. By alleviating these bottlenecks and fostering collaboration across these diverse fields, we can develop resilient agricultural systems that not only withstand the impacts of climate change but also enhance food security and nutritional outcomes. This integrated effort is vital to devise effective solutions to the complex problems posed by climate change, ensuring a sustainable and healthy future for generations to come (see Outstanding questions).

Outstanding questions

How can we effectively accelerate the translation of plant resilience research from controlled laboratory environments to variable field conditions?

What new strategies can enhance plant resilience to multistress environments, including both abiotic and biotic factors?

How can emerging bioengineering technologies be optimized and scaled for wide adoption in enhancing crop stress tolerance?

What regulatory reforms are needed to expedite the commercialization of engineered and edited crops, especially in developing regions?

How can international collaborations be structured to address climate-related agricultural challenges more inclusively and equitably?

What methods can be developed to foster greater public trust and acceptance of crops developed through modern genetic technologies?

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Declaration of interests

R.M. is on the Advisory Board of *Trends in Plant Science*.

Resources

[i]https://sdgs.un.org/goals.

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