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Enhancing food security amid climate change through rewilding and *de novo* domestication

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An Editorial on the Frontiers in Science Lead Article

Adapting crops for climate change: regaining lost abiotic stress tolerance in crops

Key points

- Abiotic stress restricts crop production and will increase with climate change, impacting negatively on future food security.
- Optimized agronomy, genetic improvement of current germplasm, and diversification of crops under cultivation will contribute to enhanced crop production under future adverse environments.
- Development of resistant and high-yielding new crops and varieties may be achieved by *de novo* domestication of under-utilized crops, wild relatives of crops, and ancestral germplasm.

Demands for food production

Global food production is dominated by a few major crops such as maize, wheat, and rice. Historically, the breeding of these crops has focused primarily on increasing yield potential and, secondarily, on enhancing biotic and abiotic resistance to help achieve and protect that potential. Although agricultural outputs have increased in modern times due to both genetic gain and improvements in agronomy, the current rates of yield improvement for most crops will almost certainly be insufficient to meet projected future food demands. Climate change is already having a negative impact on agriculture by creating local conditions that are suboptimal for current agricultural practice and germplasm. This will be exacerbated given future projections of global climate change. One study projected that maize yields could decline by 24% under a high greenhouse gas emission scenario due to increases in temperature and shifts in rainfall patterns, among other factors (1). Step changes in increases in local and global production, either from germplasm improvement or modified agronomic practice, are required, but such major improvements have been implemented infrequently. A notable example of a step change toward increasing crop yields is the pioneering work of Norman Borlaug, credited with being the father of the first green revolution. As part of a whole systems approach, Borlaug introduced dwarfing genes into modern crops, preventing lodging tendencies and increasing the harvest index, and thereby allowing much greater yields driven by higher inputs of nitrogen (2). However, boosting crop yields by adding large amounts of nitrogen and water, for example, is not a sustainable approach. In fact, inefficient use of nitrogen can have serious environmental consequences. While it is an essential element to enhance plant development and growth, nitrogen fertilizer that is not taken up by crops but instead leaks into the ecosystem can lead to negative consequences such as water pollution, the release of greenhouse gases, and soil acidification (3).

Furthermore, high-yielding cropping systems may be particularly susceptible to abiotic and biotic stresses as driven by changing climatic conditions, leading to variable harvests and, hence, compromised yield stability. Present and future food security will depend on improving current crops and cropping systems toward increased intrinsic yield potential and higher resistance to environmental stressors. This is particularly relevant when we need to raise production in naturally low-yielding environments across the globe or to extend cropping areas where conditions are currently suboptimal. It requires embracing a wide variety of novel approaches to crop improvement, including but not limited to exploiting genetic diversity in breeding programs, exploitation of under-utilized crops, *de novo* domestication of resistant but low-yielding germplasm, and potentially, precision breeding technologies of gene transformation and genome editing.

Environmental stressors limiting crop production

In recent years, many abiotic stresses associated with non-optimal temperature and precipitation patterns during the growing season have become more widespread and extreme due to climate change. Suggestions of a future positive "fertilizer" effect of increasing atmospheric carbon dioxide levels on yield (4) will most likely be offset by changing influences of temperature and rain patterns, as shown, for example, for wheat (5), with both ambient and extreme events having negative impacts on crop metabolism, development, fertility, and productivity. Furthermore, such abiotic stressors influence biotic interactions, often enhancing pathogen abundance, spread, and efficacy. In addition, changing climatic conditions can have numerous impacts on soil health, including waterlogging, drying, and affecting soil biodiversity. In many regions, extreme climate events, such as more frequent and intense droughts, severely limit productivity, often due to restricted water availability. Lack of water can be overcome by irrigation systems; however, in many cases this process raises soil salt content, leading to a new, anthropogenically created, soil salinity stress. Soil salinity has a major negative impact on crop production and regions affected by salinity stress, specifically due to irrigation activities, are increasing worldwide (6). While most major crops have minimal tolerance to saline environments, there are many salt-tolerant plants, but these are generally not cultivated as crops due to their limited economic value or lack of desirable agricultural traits.

Consequently, the yield potentials of most crops are seldom achieved in most areas of the globe, due to one or more biotic or abiotic environmental stresses, often made worse by climate change. This failure to achieve yield potential results in a "yield gap", that is, the difference between theoretical achievable yield with a defined germplasm compared to what is practically achieved by a farmer. This difference is often substantial, impacting on farmer income and food security. Furthermore, these yield gaps appear to be steadily increasing for many crops (7).

Rewilding domesticated crops

Yield and productivity are extremely complex multigenic traits involving multiple physiological and developmental processes and are inevitably underpinned by a large number of genes. Interactions with abiotic stressors are likely to be just as complex. Furthermore, tolerance and resistance to most stressors are conferred by multiple mechanisms. Direct engineering of such traits via targeted gene manipulation is possible in exceptional circumstances, namely where only a limited number of genes are required to confer enhanced resistance. In such cases, it is feasible to introduce genes or alleles from ancestral resistant germplasm in a so-called "rewilding" approach using targeted or precision breeding. In their lead article published in *Frontiers in Science*, Palmgren and Shabala (8) discuss the rewilding approach by bringing lost genes from wild ancestors back to domesticated crops in order to increase salt tolerance or resistance.

More commonly, an approach of selection of improved varieties by conventional breeding is taken. However, conventional breeding, which can be slow and complex, will always be limited by the genetic variation and gene pool size that exists for a crop, although recent work in wheat suggests that only a fraction of available diversity in landraces is utilized in the modern breeding pool (9). Wider crossing with ancestral relatives may provide even further diversity, including greater tolerance to many unfavorable conditions (10, 11). Nonetheless, even with increased diversity, resilience to environmental stressors within the gene pools of common crop species may still be rather limited.

De novo domestication of crops

A radical alternative approach to adapting crop production to adverse cultivation conditions would be to diversify our present food sources and increase the use of some of the many under-utilized crops, whose current wide adoption is mainly limited by low yields. Such species should be chosen based on their natural resistance to extreme temperatures, limited water availability, and increased salinity—environmental phenomena that are already affecting current agricultural output and are anticipated to become an even greater threat for future production. The main challenge would be to improve the yield potential of these plants. While domestication of most major crops has taken many thousands of years, this process may be replicated in a targeted and accelerated approach utilizing our modern knowledge of the minimal genes required to produce cultivatable crops in a process termed *de novo* domestication (8, 12). For this to be successful, identification of the key traits that enable acceptable yield to be obtained under cultivation is required. Such traits include harvest index, size of the harvested component (e.g. grain, fruit, and fiber), characteristics of seeds to facilitate collection, for example seed harvestability through lack of shattering, and adaptation to local environments in terms of photoperiod and thermal temperature requirements throughout the growing season. Many of the genes or loci required for domestication are already well known in cultivated species and artificially engineering these domestication traits in the stress-resistant wild species, using genome editing or genetic manipulation, is within the reach of current technology. Farming will need to adapt to the cultivation of novel crops, requiring substantial financial investment, and therefore ensuring consumer acceptance will be paramount to economic viability.

Conclusion

Food security is currently the most pressing challenge for society and will be solved primarily by agriculture. Historically, both plant breeding and optimized agronomic practice have resulted in steady incremental improvements in agricultural outputs, including greater resistance to abiotic and biotic stressors. However, meeting the ever-increasing demands for production while resisting the increasingly extreme impacts of various stressors—often enhanced by climate change and driven by the needs to farm in less optimal environments—will require new and novel technologies, including advanced plant breeding. Key among such technologies, as outlined by Palmgren and Shabala (8), are rewilding by reintroducing lost traits and *de novo* domestication of wild species with inherent resistance.

Statements

Author contributions

MH: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author declares that the research was conducted in the absence of financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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