WORLD RESOURCES INSTITUTE

WORKING PAPER

OPPORTUNITIES FOR CROP RESEARCH, DEVELOPMENT AND ADOPTION TO DRIVE TRANSFORMATIVE ADAPTATION IN AGRICULTURE

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EXECUTIVE SUMMARY

Highlights

- Climate change is already affecting food security, agriculture, and particularly crop production, at regional and global scales. In marginal agricultural areas with high poverty and food insecurity levels, current crops may lose viability as climate impacts intensify and agroecological zones shift.
- While incremental adaptation measures intended to build the resilience of existing crop production systems may be adequate in many places, other locations will require transformative adaptation measures that fundamentally change crop production systems to improve local, regional, and national food security.
- Investments in crop research and development (R&D) have yielded important technological advancements to support incremental adaptation, such as faster breeding times for more stress-resistant, productive, and nutritious crops. These investments should be expanded to enable transformative adaptation by improving farmers' access to new and more diverse crops, creating more robust and agile seed production and distribution systems, and establishing creative market and financial mechanisms for the adoption of new crops suitable for the future climate.
- Alongside investments for crop breeding, research on changing crop suitability patterns are needed to guide local and national adaptation planning, identify opportunities to increase investments, and avoid maladaptation in a socially equitable and gender-responsive way.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working papers may eventually be published in another form and their content may be revised.

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Background

Increasing frequency of extreme events, shifting temperature and rainfall patterns, and higher incidence of pests and diseases have negatively affected crop yields in many locations. Intensifying climate impacts are projected to exacerbate these issues, threatening the agronomic and commercial viability of various crops in different parts of the world. Where the viability of current cropping systems is threatened by climate change, transformative adaptation approaches will be needed. Carter et al. (2018) define transformative adaptation in agriculture as intentional alterations to an agricultural system in response to or in anticipation of climate impacts that are so significant that they change fundamental aspects of the system. Such alterations often include one or more of the following attributes:

- shifting the geographical locations where specific types of crops and livestock are produced
- applying new methodologies and technologies that change the types of agricultural products, or the way existing ones are produced, within a particular region or production system
- fundamentally altering a region's predominant type of agricultural landscape—for example, from cropping to aquaculture—as the result of changes to multiple aspects of food production systems and/or supply chains

Crop R&D systems play a critical role in developing the seeds farmers need to maximize productivity and manage the increasing risks they face. Great strides have been made in crop research and development over the last 75 years, contributing to development of the next generation of seeds that are more resilient against droughts, floods, pests, and diseases, as well as producing crops that are more nutritious and productive (Evenson and Golin 2003).

Despite these advances, this paper identifies a range of challenges that must be addressed if the global crop research and development system is going to successfully support the adaptation of crop production systems in contexts where transformative adaptation will be needed. The capacities to conduct modern and rapid crop research and development are lacking in many low-income countries and focused on major staple and cash crops, rather than on more localized traditional crops that may provide viable alternatives where major crops lose viability. Even with improved crop research and development capacities, the seed systems of low-income countries lack the capacity to quickly reproduce and distribute new seed varieties to farmers, highlighting that investment in adoption and extension pipelines is also critical. At the same time, the speed with which climate change is occurring means that crop research and development cycles must be shortened to stay ahead of climate change impacts. This is especially true in the areas most vulnerable to climate risk, such as the rainfed crop production systems that dominate agricultural systems in the developing world.

This paper examines these issues and identifies ways to promote long-term sustainability for food security and nutrition, economic livelihoods, and climate-resilient cropping systems by making strategic investments in crop research and development systems so that the public and private sectors in countries around the world have greater capacity to anticipate the needs of farmers, develop the seeds they need, and get those seeds into their hands.

Key Findings

Climate change is already affecting crop production, and in some cases is undermining the viability of current crop systems. Recent estimates suggest that this trend will continue: global yields of rice, wheat, and maize are projected to decrease by 10 to 25 percent per degree of global mean surface warming (Deutsch et al. 2018). In low-latitude tropical countries, expected crop yield and nutritional losses may not be overcome through incremental adaptation measures intended to preserve existing cropping systems. The Intergovernmental Panel on Climate Change's *Fifth Assessment Report* has shown that practices such as shifting planting dates or optimizing irrigation or fertilizer use may be beneficial but not enough to mitigate increasingly negative climate impacts (Porter et al. 2014). Addressing the risks of failing cropping systems is becoming more urgent, as the rate of climate impacts will likely surpass incremental adaptation thresholds (Vermeulen et al. 2018).

Greater investment in crop viability and options research is urgently needed, especially in low-income countries, to inform policy, investments, and climate action. While there is a growing body of scientific research on the impacts of climate change on crop production, much more localized and specific analysis of crop viability and options for new crops is needed to inform adaptation planning. Research needs to go beyond crop viability and assess the cost and benefits of new crops, the socioeconomic impact on different communities, on women and men, and on marginalized groups, as well as on the markets and policies needed for new crops to translate into viable livelihoods and sustainable climate-resilient economic development.

Governments, climate adaptation funders, and the private sector need to continue to scale up investments in crop research and development, ensuring that these investments support the development and dissemination of new crops needed for transformative adaptation. Greater basic capacities in crop R&D are prerequisites for transformative adaptation. Governments and adaptation funders should continue to invest in these capacities. These investments should explicitly support efforts to decrease breeding times, expand gene banks and related data systems, expand the range of crops researched (e.g., traditional and orphan crops), expand the diversity of available genetic breeding material, and scale up participatory breeding approaches.

A suite of technological strategies is important. There is no single best strategy for breeding climate-resilient crops, and different breeding strategies may confer a range of agronomic, economic, environmental, and social benefits and challenges. Specifically, greater investment is needed in precision-phenotyping, trials under a range of environmental conditions, and incorporation of traditional, wild, and climate-resilient crops and traits into breeding cycles. By developing more diverse sets of crops with wider ranges of genetic traits, crop researchers will be better able to develop the crops needed under transformative adaptation scenarios.

Investments in crop R&D must be matched by investments in helping farmers adopt new crops. Crop breeding alone will not change the fundamental characteristics of production systems and resource availability. Access to and participation in improved seed systems and agricultural input markets must be strengthened so that farmers are able to effectively grow, consume, and sell new climate-resilient crop varieties and species. This requires investment in extension and adoption pipelines to ensure that new technologies and crops are both appropriate for and accepted by farmers, especially those that are at high risk and have limited access to financial resources, land, and information. Our research illustrates the importance of strengthening seed systems in the most vulnerable countries. For example, in Ethiopia, using participatory plant breeding to improve community seed systems has had immediate benefits and provided a channel for the dissemination of new crops as they are developed.

Governments and their international partners need to make significant policy changes to accelerate the development and adoption of the new crops that transformative adaptation in agriculture will require. To date, few governments have included transformative adaptation in agriculture in their national climate change adaptation or broader economic development plans. Better use of recent investments in improved, more localized analysis of crop viability under climate change, and on the effectiveness of adaptation options, will enable governments and their partners to expand their national climate plans to include transformative adaptation of cropping systems. In addition, national and subnational policymakers must proactively consider redesigning market incentives for the climate-resilient crops required in transformative adaptation scenarios, reducing barriers to adoption. For example, international and national regulation bodies can streamline regulatory processes, intellectual property rights, and crop certification processes so that new technologies and new crops can more quickly be deployed.

Researchers and policymakers must explicitly consider gender and social equity as shifts in crop production systems may exclude the most vulnerable who have the least capacity to adapt and are most at risk from further consolidation of wealth and power. The poor and most vulnerable often face financial, social, or cultural barriers that may prevent them from effectively engaging in transformative adaptation. Researchers and policymakers must carefully consider marginalized communities in the development, selection, and use of new climate-resilient crops. They must integrate marginalized communities and groups into decisions to define new crops and crop traits to develop, where new crops will be grown, how these crops will be distributed and accessed by these groups, and how they will be marketed and transformed after they leave the farmgate.

About This Working Paper

The Transforming Agriculture for Climate Resilience project aims to increase finance for agricultural adaptation and strengthen understanding of, and action and support for, transformative approaches to agricultural adaptation. It seeks to assist adaptation planners, funding entities, and policymakers in integrating transformative approaches into planning processes, projects, and funding. This paper was developed by applying the framework outlined in "Transforming Agriculture for Climate Resilience: A Framework for Systemic Change" (Carter et al. 2018).

This paper was developed through an extensive review of the published academic literature and an analysis of terms related to crop R&D in national adaptation documents and submissions to the Koronivia Joint Work on Agriculture process of the UN Framework Convention on Climate Change. A series of consultations with the working paper's key audiences (adaptation funding entities, planners, policymakers, and researchers) at international climate meetings and with government officials and technical experts in Ethiopia and India also contributed to the technical and conceptual content presented here. This paper is one of four technical papers on key aspects of agriculture; the others are on livestock production, irrigation and water management, and farmer information services. In its next stage, the project will synthesize the key findings and recommendations from the five previous papers into a final report.

As with the framework paper and the other three technical papers, this paper deliberately focuses on "top-down" processes and does not cover "ground-up" efforts, even though many transformations within crop R&D result from the actions taken autonomously by farmers. Given the critical roles that farmers and other rural people play, however, it is essential that top-down processes keep their perspectives, needs, and constraints squarely at their center (Carter et al. 2018).

WHY IS TRANSFORMATIVE ADAPTATION NEEDED IN CROPPING SYSTEMS?

Farmers are on the front lines of climate change, especially in low-income countries where natural resource degradation, poverty, food insecurity, urbanization, and other development challenges amplify the impacts of climate change. Climate change has already affected food security and crop production at regional and global scales (De Pinto et al. 2019; Porter et al. 2014). The most recent *State of Food Security and Nutrition*, released by the Food and Agriculture Organization of the United Nations (FAO), indicates that hunger and malnutrition are on the rise for a fourth year in a row (FAO 2019a). In its 2018 report, FAO indicated that climate variability and extremes are a key force behind the recent rise in global hunger (FAO 2018). Globally, year-to-year variations in yields in maize, soybean, rice, and wheat increased between 9 and 22 percent between 1981 and 2010, with more than 20 percent of this change a result of variability in climate (Iizumi and Ramankutty 2016).

While short-term projections for climate change impacts on cropping systems vary from region to region, there is growing consensus that climate change will adversely affect crop yields by 2030, with significant impacts emerging by 2050, absent any adaptation strategies (Challinor et al. 2016). Recent estimates suggest that global yields of rice, wheat, and maize are projected to decrease by 10 to 25 percent per degree of global mean surface warming (Deutsch et al. 2018). These impacts are expected to be most severe near the equator and tropics, where yields are already significantly below their potential, largely due to a lack of fertilizer use (Mueller et al. 2012; van Ittersum et al. 2016) and where the impact of climate change on food insecurity is growing, particularly among female-headed households (Niles and Brown 2017; Niles and Salerno 2018). In vegetables, exposure to temperatures in the range of 1.8°F to 7.2°F above optimal moderately reduces yield, and exposure to temperatures more than 9°F to 12.6°F above optimal often leads to severe if not total production losses (Melillo et al. 2014).

Evidence also suggests that the nutritional content of crops will be adversely affected by climate change (Porter et al. 2014). The broad scale impacts of such micronutrient decreases, which cannot be visually detected like yield changes, could be profound: one recent study estimates an additional 148.4 million people worldwide may be at risk of protein deficiency by 2050 (Medek et al. 2017).

Especially in low-latitude tropical countries, expected crop yield and nutritional losses may not be overcome through improvements in agricultural practices bolstered by incremental climate change adaptation measures—particularly if warming reaches 3°C or higher, according to the Intergovernmental Panel on Climate Change's *Fifth Assessment Report*. This analysis has shown that practices such as shifting planting dates or optimizing irrigation or fertilizer use may be beneficial but not enough to mitigate increasingly negative climate impacts (Porter et al. 2014). Before the end of the century, this may be especially true for crops such as bananas, maize, and beans (Rippke et al. 2016). The rate of climate change impacts will likely surpass incremental adaptation thresholds, meaning that incremental interventions adaptation (e.g., mulching, improved fertilizer use, shade trees, etc.) will not be able to maintain the viability of crops threatened by climate change (Vermeulen et al. 2018). Considering these impacts, it is concerning that very few nationally determined contributions (NDCs) highlight the need for adaptation measures that go beyond incremental adjustments (see Appendix A for a full analysis).

By 2055, twenty-three crops are projected to experience net losses in suitable area under the A2 ("business as usual") scenario, with the largest reduction in sub-Saharan Africa and the Caribbean. Cold-weather crops expected to experience the most significant decrease in suitable areas for their cultivation include strawberries (32 percent), wheat (18 percent), rye (16 percent), apples (12 percent), and oats (12 percent) (Lane and Jarvis 2007). In the United States by midcentury, 12 percent of the area where maize is currently grown may no longer be viable for cultivation, leading to a potential decline in the U.S. area suitable for maize production of 20 percent for the 2040–69 time period under the Representative Concentration Pathway 8.5 scenario (Elias et al. 2018).

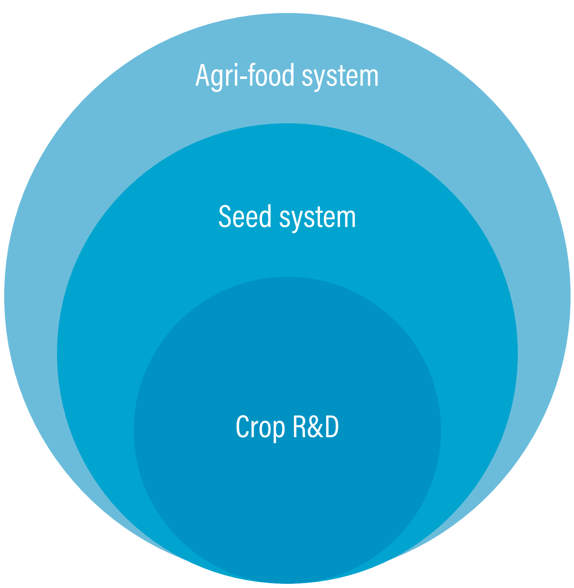
Where and when incremental adaptation measures are inadequate, transformative approaches as described in "Transforming Agriculture for Climate Resilience: A Framework for Systemic Change" (Carter et al. 2018) will be necessary to ensure that crop production remains viable under future climate conditions. This is particularly the case in crop-producing regions that are arid, low-lying coastal, groundwater stressed, or fragile mountain ecosystems. When and where climate impacts are—or are projected to be—so severe that they undermine the continued agronomic and commercial viability of crop production and the livelihoods of the communities, transformative measures such as shifting which crops are grown, where they are grown, and how they are produced will be better than the crisis or collapse that could otherwise occur in these crop production systems.

This paper shows the critical role that crop research and development (R&D) plays in enabling transformative adaptation to occur in crop production systems by developing new, climate-resilient crop production methodologies and technologies. Not only must crop research and development institutions assess where and when the viability thresholds of current crops will reach their limits, they must also identify alternative crops and production methods that will work under changing climate conditions. Armed with such forward-looking analyses, crop breeders and researchers need to support the process from breeding to development to adoption (BDA) of the new crops and crop varieties needed in the communities, countries, and regions most affected by climate change around the world. The paper also provides actionable recommendations to address the serious lack of research on these challenges and solutions to them, in order to inform funders' and governments' long-term planning to ensure climate-resilient, socially equitable outcomes. Appendix B provides a series of critical planning questions for transformative adaptation considering the different stages of crop research and development.

HOW CAN RESEARCH ON SEED SYSTEMS CONTRIBUTE TO TRANSFORMATIVE ADAPTATION?

Seed systems are critical parts of the global agri-food system, which produces, processes, transports, and distributes food to the growing global population. Crop research and development is a critical function of this process and refers to the portion of the process that occurs under controlled conditions, before new crops are introduced to farmers for further refinement. It is carried out by a global network of public and private sector institutions. These institutions include major multinational agribusinesses and research institutions such as the Consultative Group on International Agricultural Research (CGIAR), as well as local universities and extension services in developing and developed countries. We acknowledge that seed systems and crop research and development also exist within farming communities and involve seed saving and sharing outside of an institutional context. While these are critical for the agri-food systems of many locations and have a clear role to play in advancing climate change adaptation, this report focuses on improving the bulk of investments in BDA, which are likely to be made by higher-level institutions.

Figure 1 | **Relationship between Crop R&D Systems, Seed Systems, and Broader Agri-food Systems**



Source: Authors.

In some circumstances, climate change impacts on crop production will be manageable through broader dissemination of climate-resilient crop varieties of already existing species (De Pinto et al. 2019). For example, field trials of salt-tolerant rice grown under moderate coastal saline conditions in India have been shown to increase yields by 58 percent compared to a popular non-salt-tolerant variety (Valarmathi et al. 2019).

Nevertheless, in some contexts, climate change is already or is projected to be so severe that current crops, even climate-resilient varieties, may not be suitable. Instead, communities may need to switch to completely new crops, and as the climate changes they may need to keep shifting.

These kinds of transformations are already happening as a result of changing climate and other conditions. For example, our research found that in the Srinagar Valley in Kashmir, India, decreasing water availability has caused communities to switch from water-intensive rice paddies to less water-intensive fruit trees. Often, switches like this are *autonomous*, meaning that farmers adapt without external intervention. However, our research suggests that the farmers who can make these changes without external support tend to be those with higher risk tolerance, better access to land and information, and greater financial resources. They tend to also have better access to crop research institutions, alternative crops, and the scientific expertise to support divisions on transformative adaptation options. More vulnerable communities and populations generally lack the resources needed to make these kinds of autonomous adaptations.

Crop research and development actors need to focus more on identifying crops that will be suitable in different locations under different climate, soil, and other conditions;

breed and develop crops that farmers and agribusinesses need and want; and help farmers to adopt those seeds that are relevant and appropriate for their systems and needs. The impacts of climate change mean that global and local crop research and development systems need to develop and disseminate crops that are (1) suitable for new climates, (2) developed considering long-term sustainability, (3) designed considering co-benefits such as greenhouse gas mitigation, (4) of benefit to marginalized individuals and communities to support the creation of sustainable, equitable, climate-resilient agricultural and livelihood systems, and (5) developed in concert with farmers to address their needs and suitability. More specifically, seed systems and the BDA and R&D processes that take place within them have the following important roles to play in supporting transformative adaptation where it is needed:

- Identifying where and when current and newly introduced crops may no longer be viable due to climate and other factors.
- Identifying and developing alternative crops that will be viable in these areas.
- Supporting the adoption of new crops by farmers adapting to climate change with research involving farmers, extension, early warnings, and so on.
- Promoting faster adoption and distribution of new crops and crop varieties.
- Researching how agricultural switches may affect greenhouse gas (GHG) emissions and soil carbon sequestration, as well as how they may mitigate climate change. For example, in coastal agricultural systems facing sea level rise, switching from rice paddies to aquaculture is accompanied by a substantial decrease in the amount of methane and nitrous oxide produced from that landscape (Wu et al. 2018). Likewise, a switch from open apple orchards to high-value horticultural greenhouses may affect ecosystem services (Demestihas et al. 2017). There is currently little research considering these trade-offs, and their importance may be underestimated.
- Researching the agri-food systems changes needed to support the adoption of new crops, such as processing infrastructure and market linkage.
- Researching the gender and social dimensions of crop production in order to support inclusive adaptation planning and investments. For example, a study in Uttarakhand, India, revealed that men tended to prioritize the adoption of subsidized seeds during a food crisis, while women preferred to safeguard traditional knowledge and methods of food preparation (Ravera et al. 2016). Intersectional approaches (i.e., approaches that identify diverse dimensions of identity and power relations) are beneficial for understanding climate-resilient crop selection, beyond the field and extending along the entire supply chain to the consumer.

This paper focuses on the status of crop R&D systems and their links to the larger seed and agri-food systems in which they operate. We examine how these systems are working today and how they can be leveraged to fulfill the functions outlined above to enable transformative adaptation. We recognize that global capacities for crop research and development are limited and, in many ways, inadequate for dealing with today's challenges. Even modest improvements to global and local capacities (improving lab infrastructure, building seed banks, expanding and refining extension services, etc.) can have significant impacts on local seed systems and farmers' productivity (e.g., the development of a new crop species suitable for areas facing chronic drought). Yet much of the capacity for developing the adaptation solutions required to shift the fundamentals of agricultural systems still needs to be built. The crop R&D systems in many countries, especially those in sub-Saharan Africa and Southeast Asia, do not yet have the in-country capacity to develop yield-improving crop varieties in a timely manner, let alone to consider long-term climate impacts, shifting agroecological zones, or innovative agricultural system design.

BUILDING ON THE CURRENT STATE OF CROP R&D TO ENABLE TRANSFORMATIVE ADAPTATION

Crop research and development, specifically crop breeding, has historically focused on increasing the yields of major crops. Maize, wheat, rice, and soybean yields more than doubled per harvested hectare between 1961 to 2007, in large part due to improvements in R&D (Alston et al. 2009). The late twentieth and early twenty-first centuries saw a shift toward breeding using genetic modification, corresponding to both technological advances and regulatory acceptance in many countries, particularly the United States (though the lack of regulatory and consumer acceptance in the European Union is notable). However, the majority (80 percent) of commercialized genetically modified crops today are herbicide- and insecticide-tolerant, compared with only 2 percent currently commercialized for abiotic stresses such as drought, which might confer climate adaptation benefits (ISAAA 2020).

Estimates suggest that, at least in maize, yield gains during this time frame resulted in equal measure from breeding and management shifts (Duvick 2005). However, these gains were not universal, especially in Africa (Evenson and Gollin 2003) and small island developing states (Figure 2).

Despite decades of breeding for increased yields, herbicide and insecticide tolerance, and, to a lesser extent, nutritional or climate traits, the current strategies for BDA are falling short (Atlin et al. 2017), particularly in light of climate change.

Current BDA cycles can take up to 30 years, especially in Africa; yet over this period, the climate may have changed significantly since the beginning of the cycle, reducing or eliminating the benefits of the efforts (Challinor et al. 2016). Thirty-year BDA cycles will not produce adapted crop varieties on a continual basis that matches the speed of the changing climate (University of Leeds 2016).

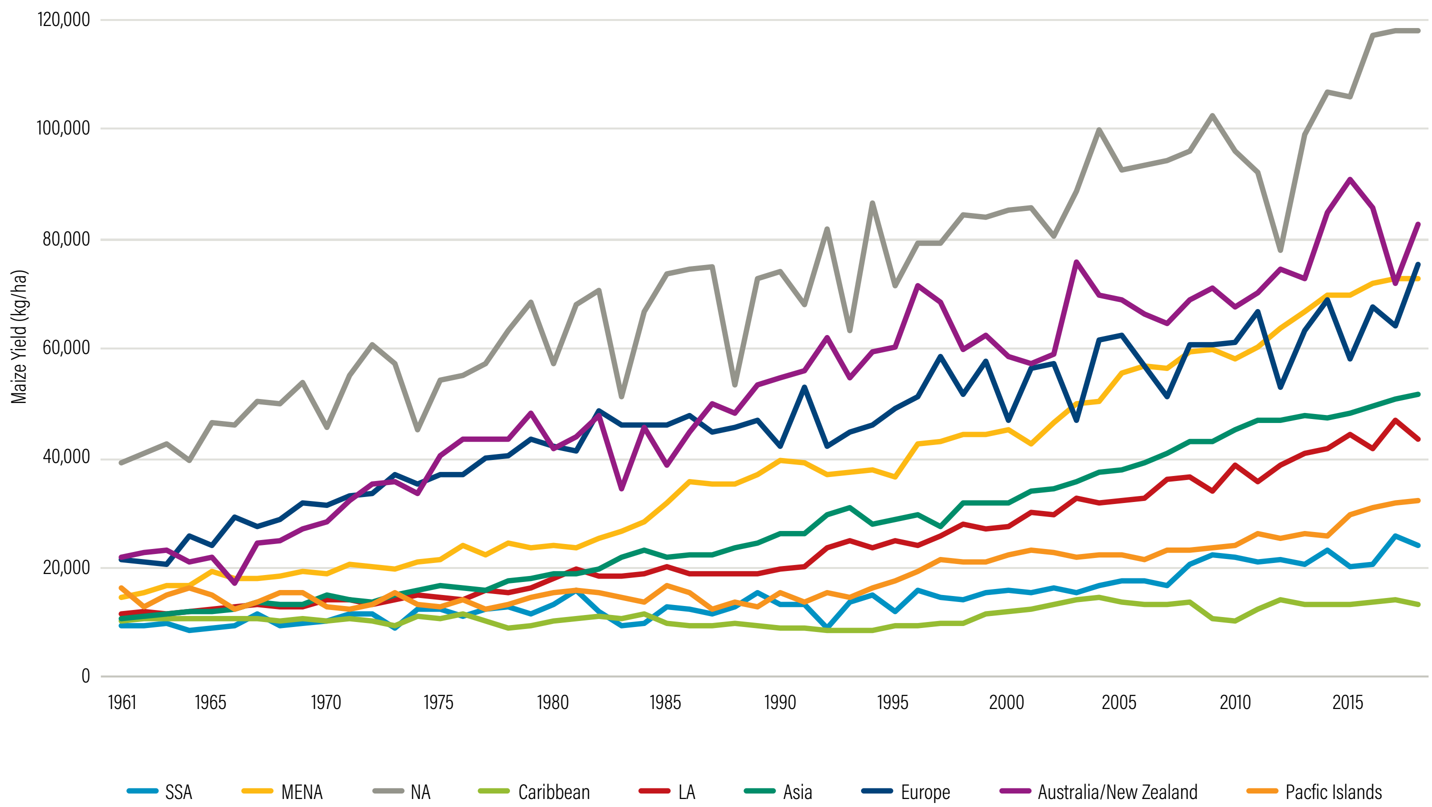
Reasons for such long-time horizons in breeding are myriad (see Challinor et al. 2016 for a nuanced discussion). One is that R&D for crop technologies and methodologies in Africa faces a lack of physical infrastructure (laboratories, genetic technology, etc.), soft infrastructure (data sharing platforms, institutional coordination, etc.), and human capital (the number and type of qualified experts to breed and disseminate crops). This includes the lack of representation of women in crop R&D, which can affect which types of crops receive the most attention and which traits are considered priorities (Beintema and Stads 2017). This lack of infrastructure and capacity is even more concerning considering the need to include new and unfamiliar crops that will be needed in transformative adaptation scenarios and require greater R&D investments.

Major research institutions are working to reduce the time it takes to develop new seed varieties for major crops both for maintaining yield and in consideration of other climate changes such as drought and increased pest and disease pressure. The International Maize and Wheat Improvement Center (CIMMYT), a branch of the CGIAR system, is now able to develop new seeds for maize and wheat in six to seven years by taking advantage of multiple crop cycles each year in greenhouses, through shuttle breeding (i.e., growing two or more harvests per year by shifting cultivation sites), and by applying technologies such as rapid phenotyping. In addition, CIMMYT is working with seed multiplication enterprises to release near-final varieties during the final stages of field trials so that seeds can be multiplied and put into the market faster when the trials are successful (CIMMYT 2016).

Even with these advances, rapid changes in farmer needs due to changes in climate conditions, shifts in pests and disease, and other factors are already straining many cropping systems. Cycles of two to three years may be feasible and a more realistic target for keeping up with climate change impacts than the current decades-long time frames (Cobb et al. 2019).

Genetic diversity is critical for breeding crops that are resilient to different climate conditions. The selection of genetic traits is hindered by lack of germplasm and limitations in data platforms and sharing, available genetic technologies and phenotyping platforms in field conditions such as precision phenotyping (Kumar et al. 2015). In genetics, the phenotype of an organism is the composite of the organism's observable characteristics or traits. Although many genetic information platforms exist, the information available does not cover the entire BDA cycle (genotypic, phenotypic, and market information, etc.). Information is lacking on climate-resilient traits. While attention to gene banks and germplasm

Figure 2 | **Global Maize Yields 1961–2018 by Region**



Note: SSA = Sub-Saharan Africa, MENA = Middle East and North Africa, NA = North America, LA = Latin America While most regions saw a clear increase in maize yields over the past several decades, yield gains in the Caribbean, sub-Saharan Africa, and the Pacific Islands were minimal

Source: Data retrieved from the FAOSTAT database (FAO 2019b).

preservation is increasing, crop submissions and diversity in global gene banks from Africa and South America are notably fewer than those from North America, the Middle East, and South Asia (Westengen et al. 2013). As such, plant breeding during this past century is associated with a narrowing of genetic diversity in germplasm (Tester and Langridge 2010). Expanding gene banks will allow breeders more flexibility in the future to breed crop varieties that can be grown in different parts of the world where they may not currently be viable.

More recently, participatory plant breeding (PPB) has emerged as an approach that may help to avoid the pitfalls of uniform modern plant breeding and an increasingly consolidated seed industry by promoting agricultural biodiversity and climate-resilient traits. PPB refers to farmers' involvement in defining breeding goals and priorities, selecting or providing germplasm, hosting trials, selecting plants, and engaging in research design as well as commercialization of selected crops (Agriculture for Impact 2020). PPB addresses not only the challenges of breeding for climate resilience but also the adoption of climate-resilient crops, since users' participation in seed development may increase adoption (Ceccarelli et al. 2014). Additionally, PPB may emphasize traditional and wild crops (Box 1), which are not globally traded but are important for local and regional food systems (Searchinger et al. 2014). However, while PPB is beneficial for promoting farmer's needs, continual farmer engagement in

Box 1 | **Traditional and Wild Crops in a Changing Climate**

Traditional and wild crops are important for regional food production and food security but are typically not traded internationally (Naylor et al. 2004). Since the majority of traditional crops are grown by women and smallholder farmers, this oversight has profound impacts on these populations (Oyugi et al. 2015). Examples of traditional crops include amaranth, jute mallow, desert date, and Shona cabbage. Wild crops include any harvested wild edibles that can contribute to the diet. Traditional crops are a significant portion of production in many low-income countries compared with the world's major crops of rice, maize, and wheat. For example, in Niger, where the top three produced crops are millet, cow pea, and sorghum, traditional crops are produced at a ratio of 235 to 1 compared to major world crops (Varshney et al. 2012).

Given their absence in international trade, breeding programs for traditional and wild crops have historically received little public and private investment (Naylor et al. 2004; Varshney et al. 2012). New advances in breeding technologies offer great potential to improve breeding in traditional crops, which could have major impacts in many low-income countries that heavily rely on them (Varshney et al. 2012). Using new breeding technologies and platforms in traditional crops could be particularly important for women, who often produce them (Oyugi et al. 2015). Such efforts could also improve household nutrition for children.

Traditional and wild crops may also be particularly important for transformative adaptation, as they may be more resilient to drought and other expected climate changes, and are often nutritionally dense (Kole et al. 2015; Tadele and Assefa 2012). For this reason, traditional and wild crops should be an explicit component of transformative breeding, delivery, and adoption efforts, with particular emphasis on crops that are important to women and children.

crop breeding can be expensive and logistically difficult. Innovations in developing commercial product profiles that incorporate farmer preferences may be more efficient, reducing breeding cycle times while promoting adoption of new varieties.

As a leader in plant breeding, CGIAR centers have developed a strategy for modernizing plant breeding programs that can serve as an example for other crop R&D institutions. Although not explicitly focused on the components of plant breeding that aim to enhance climate resilience, the CGIAR system's eight recommendations highlight many of the gaps in the current plant breeding landscape (Box 2). For optimal, sustained outcomes, all eight of these components should be instituted. Climate change should be more thoroughly incorporated, including the need for transformative adaptation, through actions such as ensuring that product profiles explicitly consider climate-resilient and climate-sensitive traits. Long-term climate change impacts should be considered when identifying obsolete varieties. The use of product profiles in these recommendations creates an opportunity to introduce new crops systematically into plant breeding programs that will be needed under transformative adaptation scenarios.

Beyond the technical aspects of crop research and development, the regulatory environment is also important. In many circumstances, regulations, certifications, and intellectual property rights (IPRs) are meant to protect producers and consumers. However, the current policy architecture in some regions may be hindering the capacity of crop R&D systems to produce methodologies and technologies that will promote long-term, systemic resilience to climate change. A part of this problem relates to the knowledge and awareness of the regulated technologies (e.g., gene editing) and their outputs, as well as cultural perspectives on their use. A meeting of more than 500 representatives in November 2019 that aimed to resolve long-standing tensions over the International Treaty on Plant Genetic Resources for Food and Agriculture, a 2004 accord intended to protect the global food supply, broke down over how to manage the treaty obligations related to access to genetic materials (Gewin 2019). A successful agreement would have allowed poorer countries better access to and exchange of improved seeds and genetic materials. In the absence of such an agreement, national research organizations must improve their strategies for communicating to policymakers and users the importance of new crops and crop technologies.

Crop Selection and Adoption

The release of a new crop is not successful if the crop is not selected and adopted by farmers who could benefit from growing it (Evenson and Gollin 2003). Yet not all farmers have the same capacity for adoption. Farmers who are lower-income, food insecure, lacking in land tenure, and limited in access to credit, capital, and the infrastructure necessary to grow and market new crop varieties may be less able to adopt different crops. Many new crop breeds require fertilizers, fumigants, and other inputs to be successful, limiting the capacity of poorer farmers to adopt them, and potentially forcing them to seek additional capital in the short- and long-term to buy inputs. In addition, without market incentives, crop switches will be extremely difficult and unsustainable. Farmers will produce and sell only products that are immediately economically feasible to sustain their families and livelihoods, rather than experiment with new crops that may serve them better as climate impacts intensify.

For new crops to be successfully adopted, especially by smallholders, seed systems must be strengthened, novel crops must be selected in participatory processes that engage farmers and other actors in the food system, and solutions to financial and market barriers to adoption must be created. While formal, institutionalized seed systems are generally weak in developing countries, a number of emerging practices offer promising foundations for supporting transformative adaptation.

Recognizing that in many low-income countries formal, institutionalized seed systems generally have fewer and less diverse high-quality seeds (World Bank 2015), governments and their development partners are investing in seed systems that connect researchers and breeders with farmers. For example, in Ethiopia, the Ministry of Agriculture and Livestock Resources, with support from Irish Aid, is working with women and youth to establish community seed multiplication enterprises. As these microenterprises have developed, they have come together in seed production unions that have invested in laboratory and quality-control capacities to support their members. In turn, these unions are better able to connect with larger seed multiplication enterprises and research institutions, which provide improved staple crop varieties that are then adapted to local conditions. Improved relationships between seed production unions and crop breeders have increased the speed of dissemination of new seeds and the communications between farmers and researchers. An estimated 60 percent of the seeds planted in the Tigray region of Ethiopia now come from this type of seed system. Without such a seed system in place, it would be very difficult for farmers to shift to new crops when needed, even with adequate crop breeding and research capacities.

The program Gender-Responsive Researchers Equipped for Agricultural Transformation (GREAT), housed at Cornell University, and the CGIAR Gender and Breeding Initiative are two examples of programs that aim to create more inclusive and effective breeding systems that enable more women to participate in crop selection and adoption decisions. GREAT delivers training to plant breeders from sub-Saharan Africa in the practice of gender-responsive research, while the CGIAR Gender and Breeding Initiative brings together breeders and social scientists to develop gender-responsive breeding strategies. For example, the CGIAR initiative has established local agricultural research committees in Honduras, which have encouraged shifts in power dynamics allowing more women to take the lead in deciding what to grow and where to grow it (Humphries 2016).

Another promising method of promoting adoption of crop switches is through strengthening private output and input markets for new crops. For example, FAO has analyzed crop diversification in Zambia to develop policy options that are relevant for market reform, which could be used as models for other contexts. One of these policy options in Zambia included reforming the Farm Input

Box 2 | CGIAR System Recommendations for Modernizing Plant Breeding Programs

In its initiative "Crops to End Hunger," CGIAR (2018) outlines eight key components of modernizing plant breeding programs:

- Systemic use of product profiles (i.e., a set of targeted attributes that a variety is expected to meet) based on market intelligence and stakeholder consultations
- Promoting institutional accountability of CGIAR centers through institutional ownership of product profiles and product advancement systems
- Optimizing breeding pipelines through use of rapid breeding cycles
- Mechanizing and digitizing phenotyping and data collection systems
- Integration of breeding information for crop genetic selection decision-making
- Improving variety testing (on-station and on-farm) to clearly demonstrate superior varieties
- Strengthening linkages with seeds systems and messaging on the need to replace obsolete varieties
- Building stronger partnerships with national agricultural research systems for codesign, joint testing, and joint dissemination

Subsidy Programme by allowing for a greater diversity of seeds and other inputs as well as providing preplanting extension advice to voucher recipients on recommended crop choices (FAO 2019c).

Incentive schemes, such as grants, can also help farmers transition to new crops. For example, the California Department of Food and Agriculture's Healthy Soils Program offers grants to qualifying producers to adopt soil health practices such as introducing cover crops (Schapiro 2019). Although focused on GHG mitigation, similar programs could be designed to provide incentives for adopting climate-resilient crops in regions facing climate extremes.

Supporting Farmers' Adoption of New Crops

Just as crop breeding itself has changed over the past century, the ways that innovations are diffused have also rapidly changed, offering farmers and crop researchers new ways to support transformative adaptation in crop production systems.

A critical component of dissemination and adoption is the accessibility of quality extension services, whose funding is being cut in high-income countries and remains low or stagnant in low-income countries (GFRAS 2012). Evidence from the International Food Policy Research Institute suggests that extension and education components of agricultural research were only 2.8 percent of the total share of agricultural research in 2014 (Beintema and Stads 2017). Additionally, these services typically do not reach women as effectively as men, reducing overall adoption of beneficial technologies and services.

While traditional extension models used a top-down approach of channeling information from universities or research facilities to farmers, new models—collectively referred to as "Extension 3.0" (Lubell et al. 2014)—now acknowledge the central role of farmer networks and new technologies in disseminating information. Such platforms and networks may be critical for providing farmers with information required for agricultural system shifts.

With public investment in research and extension services declining, the private sector has become increasingly interested in providing these services. Both public and private extension services are now essential in promoting new, climate-resilient crops and supporting farmers to grow and market these crops. Between 1990 and 2014, annual global private sector funding for research and extension services increased from $5.1 billion to more than $15.6 billion in nominal U.S. dollars (Fuglie 2016). Accordingly, the innovation and finance that is available in the private sector can be leveraged for developing climate-resilient technologies and methodologies at scale and providing the application support necessary for farmers to effectively and equitably use them. However, many barriers still exist to meaningful private sector involvement, including regulatory issues related to intellectual property rights (Box 3).

Developing and Sharing Crop Information

The CGIAR Excellence in Breeding Platform is a good example of a platform that has started to focus on information sharing, collaborative learning, and access to tools and services for national research systems, research centers, and the private sector (EIB 2017). However, this platform, like many others, has yet to emphasize the identification of systems that will reach climate thresholds and develop crop varieties and alternatives accordingly. Such an emphasis would allow project and program designers and implementers to base crop introductions, switches, or other fundamental agricultural changes on transparent data and information collaboration, and funders to more easily base their investments on scientific evidence. As climatic thresholds are reached, particular production systems may need to incorporate genetics from regions with climates similar to the new one in the target region. Therefore, mechanisms for sharing genetic information must be established. Patent pools may be a critical component to enable such a platform as genetic information is often privatized and made inaccessible.

RECOMMENDATIONS

Advancing BDA that is sustainable, equitable, and results in long-term resilience will require long-term planning and investment across multiple public, civil society, and private sector actors. Governments and funders need to collaborate with farmers, private sector agricultural operations, nonprofits, and consumers throughout adaptation planning processes that aim to shift crop production. Aligning the priorities and pathways to transformative approaches will be critical for systems actors to compound investments such that system-level analyses, inclusive planning, and implementation processes and value chain and market preparation are possible. Below we outline recommendations for research, policy, and investment priorities.

Research Priorities

Research organizations, governments, and funders need to urgently scale up crop viability and options research, especially in low-income countries, to inform policy, planning, and adaptation action.

While there is a growing body of scientific research on the impacts of climate change on crop production, much more localized and specific analysis of crop viability and options for new crops is needed to inform adaptation planning. Research needs to go beyond crop viability and assess the cost benefits of new crops, the socioeconomic impact on different communities, on women and men, on marginalized groups, and on the markets and policies needed for new crops to translate into viable livelihoods and economic development.

Research organizations (public and private) should expand data and technology platforms to provide the necessary information for facilitating transformative adaptation in cropping systems, especially information related to genetics and seed adoption.

Performing the research behind what crops may be suitable in which climates is not enough. Platforms that can integrate the entire BDA process (i.e., tracking the breeding and phenotyping with extension, adoption, and delivery, including real-time farmer adoption and feedback to the lab) could significantly help guide decision-making about transformative approaches. Open access data and software platforms, building on lessons from existing platforms like the CGIAR Excellence in Breeding Platform, could enable standardization and integration of data, genomes, phenomes, germplasm, and breeding across entire crop R&D pipelines so adoption, use, and feedback data can be directly linked to crop traits and varieties. Additionally, such platforms can help to share information related to identification of crop-climate thresholds and, accordingly, of potential alternative crop varieties. Patent pools are critical tools to enable open access data platforms. At the same time, facilities that collect crop genetics (i.e., gene banks) should be connected to open access data platforms that gather climate-resilient traits, especially from traditional and wild crops.

Box 3 | Barriers to Transforming Cropping Systems: Patents and Other Intellectual Property Rights

New crop varieties and tools for genetic improvement will be necessary to help agriculture become resilient as the climate changes. However, such efforts will be influenced by intellectual property regulations. Intellectual property can involve patents, trademarks, trade secrets, copyrights, and other related legal statuses granted to inventors (Caseiro 2000).

Today, many crops and genetic processes (e.g., clustered regularly interspaced short palindromic repeats [CRISPR]) are patented or have other intellectual property rights associated with them, which can limit the ways other companies, governments, and individuals can use them. Intellectual property (IP) is usually transferred to others through sale or licensing (use contracts), which makes them expensive for some and beyond reach for others.

Traditional licensing does not have a mechanism for the transfer of technologies that can foster global adoption easily and affordably. However, several emerging options could help increase the speed of adoption and the availability of new crop varieties and technologies for adaptation (Nocito 2018). These include patent pools and humanitarian licensing. Patent pools are agreements between IP owners to share or transfer IP through conditional licensing and can enable limited use. CRISPR is currently undergoing a potential review for a patent pool (Mika 2017). Humanitarian licensing, a concept first used in the pharmaceutical industry, involves transferring IP but maintaining some rights and financial opportunities. It has been defined as "technology likely to preserve human life by meeting basic needs that if unmet due to poverty or disaster would likely ultimately result in death within six months or be the direct cause of death. Such needs include food, medicine, medical supplies, sanitation, healthcare and the like" (Allen 2011).

Given crop breeding's potential to transform agriculture for climate resilience, and to strengthen food security, it is well within the bounds of this definition to consider new varieties bred for climate resilience for such licensing. Indeed, efforts to adapt the humanitarian licensing definition to explicitly consider extreme events and climate change, and to integrate these two licensing options into future Conference of the Parties agreements, are gaining traction (Nocito 2018).

Furthermore, both national and international government bodies have significant capacity to influence laws and regulations relating to intellectual property. National governments can reshape laws or set limitations on intellectual property for factors that may include national security or public health, among others. Internationally, the UN-affiliated World Intellectual Property Organization, with 191 member states, could further explore opportunities for IP agreements and other arrangements that can best facilitate transformative adaptation in agricultural systems.

Policy Priorities

National, subnational, and local governments should incorporate the need for new climate-resilient crop R&D in key agricultural planning initiatives.

Out of 196 countries that submitted NDCs, only 13 (approximately 7 percent) described an adaptation option that could be considered transformative in regard to cropping systems and related R&D. While this does not mean that countries are not considering the potential needs, it does illustrate the limited policy attention being paid to this important issue. The institutions that support governments' development of adaptation plans can address this gap by providing planning tools and decision support systems for identifying whether, when, and how agricultural system shifts will need to take place. Policymakers can build on plans that already incorporate interventions that may be considered transformative, and those who have yet to formulate strategies that consider transformative adaptation can learn lessons from those that already have (see Appendix A). For example, Burkina Faso highlights an adaptation strategy of "abandoning certain crops in favor of those which are more resistant to climate shocks" in its national adaptation plan (NAP). Providing analysis on how Burkina Faso, or other nations, are prioritizing and planning for agricultural system shifts will help to promote such types of adaptation that may also be required in other regions facing similar climate impacts.

National and subnational policymakers must proactively consider redesigning market incentives for the climate-resilient crops required in transformative adaptation scenarios.

Investment in crop R&D, as well as what farmers decide to grow and what consumers choose to buy, is often dictated by the market. Based on current and future research that indicates which crops may be suitable where (considering climate impacts), policymakers can help to create market incentives for climate-resilient crops, including traditional crops. Redesigning subsidy structures for new crops and their inputs, promoting marketing campaigns, and encouraging selective seed market intensification are all options to encourage adaptive crop switches.

International and national regulation bodies should reform regulatory processes, IPRs, and crop certification processes to facilitate the development and adoption of new crops needed in transformative adaptation scenarios.

Regulatory and trade policy can have a significant impact on the viability of new crops and cropping systems. Governments, regional institutions, and trade and scientific organizations should assess how they can best support transformative adaptation through reforming policies that hinder the introduction of new crops. Governments must weigh the potential promise of some of the technologies that current regulations address against their potential unforeseen consequences, and work with scientists and regulators to optimize regulatory frameworks. Human rights impact assessments can be used to evaluate how plant variety protection laws may affect smallholder farmers. Additionally, design of regulatory processes around plant genetic materials should consider the linkages between formal and informal seed systems so as to not restrict farmers' rights to use, save, exchange, and sell farm-saved seeds (De Schutter 2009). Emerging options include patent pools and humanitarian licensing.

Adaptation funders, policymakers, and practitioners must explicitly include gender and social equity components in policies, projects, and programs related to crop transformations.

Transformations in crop BDA must explicitly consider gender and social equity, including the critical differences in the choices among different actors concerning what to grow, sell, and consume. Certain crops are produced and consumed by certain people, and this must be recognized when trying to improve crops or introduce new species. In cropping systems, the risks of consolidation of power and wealth during system shifts are particularly high due to factors such as tenuous land ownership and rights, variable access to credit, presence of inequitable subsidy or tax structures, gender-differentiated reliance on particular crops, and a variety of other critical factors. Policymakers can address these challenges by ensuring inclusion of a range of stakeholders in the planning process from the start, especially those who are the poorest and most vulnerable. To successfully transform cropping systems requires working collectively with farmers, processors, distributors, marketers, input suppliers, consumers, and funders to understand diverse contributions, needs, and perspectives across the value chain. Since the needs of producers and consumers vary drastically from place to place, project planners and implementers who lead transformations in cropping systems must consider all stakeholders. Improving and scaling participatory plant breeding in a way that includes marginalized community members in decision-making dynamics may be a key to meeting stakeholders' needs.

Investment Priorities

Government and funders need to continue to scale up investments in improving seed systems, ensuring that these investments can support the development and dissemination of new crops needed for transformative adaptation.

Greater basic capacities in crop BDA are a prerequisite for transformative adaptation. Governments and adaptation funders should continue to invest in these capacities. These investments should explicitly address the challenges identified above, including decreasing breeding times, expanding the range of crops (e.g., traditional crops), expanding the diversity of genetic breeding material, scaling up participatory breeding approaches, speeding up distribution of new crops to farmers through public and private sector mechanisms, and so on. Leveraging the CGIAR's crop profile approach to new crops is one tool to support this practically.

National governments, adaptation funds, and the private sector should invest in shortening the time it takes for crop breeding from development to adoption by revamping crop R&D infrastructure.

Crop R&D infrastructure must drastically improve, especially in Africa, to achieve research outcomes and retain qualified researchers and scientists. The current crop R&D infrastructure in low-income countries is not sufficient to keep up with the intensifying impacts of climate change. As the impacts of climate change accelerate, governments and the private sector will need to become more agile in crop breeding and development and be able to go from trial to field with new varieties, cultivars, and crops faster, all while providing farmers with a greater range of climate-resilient crops. Lessons can be learned from what organizations like the CGIAR system are prioritizing in relation to breeding, such as strengthening messaging on the need to replace obsolete varieties. Although crop breeding technologies are rapidly improving, other areas require greater investment to develop critical technologies. These include precision phenotyping, crop suitability modeling, accelerated trialing, agronomic modeling, and farmer-accessible data platforms such as smartphone apps.

CONCLUSION

Agricultural systems will continue to face intensifying climate impacts, even with effective mitigation efforts, for the foreseeable future. As populations and demands on natural resources continue to grow, additional pressure will be put on these systems. This will threaten the viability of cropping systems in a growing number of regions. In some circumstances, incremental approaches will not be enough to maintain or achieve food security and promote sustainable livelihoods. Crop research and development will play a critical role in creating the knowledge, technologies, and methodologies necessary to shift agricultural systems and improve the prospects of these agricultural communities.

Currently, the level of investment in crop breeding, development, and adoption efforts is inadequate to keep pace with the changing climate. More must be done to identify where new crops will be needed, expedite breeding times, improve adoption rates, and strengthen data sharing and learning, all while better engaging farmers and food system actors in a participatory process. The adaptation community can build on what is already being done in this space as technology and breeding platforms continue to improve. Transformative adaptation in cropping systems will require adaptation policymakers, funders, and researchers to rethink the types of investments and actions that are prioritized in crop R&D to keep agricultural systems and communities from being pushed beyond biological, social, and market limits and instead embrace new adaptive opportunities.

APPENDIX A. INCLUSION OF TRANSFORMATIVE ADAPTATION IN CROPPING SYSTEMS IN POLICY DOCUMENTS AND SUBMISSIONS

Designing and implementing crop R&D such that it considers transformative adaptation is essential for countries to identify adaptation interventions in cropping systems that promote long-term, sustainable climate resilience. An analysis of available national adaptation plans (NAPs), nationally determined contributions (NDCs), and Koronivia Joint Work on Agriculture (KJWA) submissions revealed that the majority of contributing countries are only considering incremental climate change adaptation strategies for cropping systems. Out of 196 countries that submitted NDCs, only 13 (approximately 7 percent) described an adaptation option that could be considered transformative. Of the 9 NAPs made publicly available on the UN Framework Convention on Climate Change's NAP Central and the 48 KJWA submissions, 1 and 4, respectively, identified actions to transform their cropping systems in response to a changing climate. This is not to say that all countries will need to include transformative adaptation in their adaptation planning. Inclusion should be based on their given present and future climate contexts and related production systems. The lack of representation of transformative adaptation options for cropping systems in these documents may be partially due to a lack of suitable crop R&D systems that prioritize identifying, designing, and implementing adaptation interventions that include fundamental changes to cropping systems.

Table A1 lists entities that referenced transformative adaptation in either their NAPs, NDCs, or KJWA submissions. The table also includes the corresponding excerpts, the document in which they were found, and what type of transformative action it represents.

This analysis was completed by performing a keyword search for the following terms: ***crop***, ***breed***, ***genet-***, ***biotech***, ***selection***, ***phenotyp-***, ***relocat-***, ***cultivar***, ***orphan crop***, ***variet-***, and ***seed*** (all forms of these words were searched for; e.g., ***crop***, ***crops***, ***cropping***, ***cropped***, etc.). These search results were only further analyzed if they were discussed within the context of adaptation. Excerpts were considered to fall within the context of transformative adaptation if they reflected this paper's definition of transformative adaptation. Further analysis included scanning search results for references to food security, nutrition, gender, and social equity.

Table A1 | **Transformative Adaptation in Policy Submissions**

COUNTRY OR ENTITY	SPECIFIC EXCERPT	POLICY DOCUMENT/ SUBMISSION	TYPE OF TRANSFORMATIVE ADAPTATION
Brazil	"expand the use of drones as well as automated remote sensing equipment to enhance the resolution of data acquisition on diverse types of crop, crop systems and integrated crop systems"	KJWA	New technology/ methodology
	"due to genetic improvement of different crops and the shortening of production cycles, certain areas in the Cerrado region now produce during 365 days/year in rotation systems"	KJWA	Shift in type of production system
	"the introduction of cattle and trees in the rotation has led to the development of integrated cropping systems now being implemented in Brazil"	KJWA	Shift in type of production system
	"In the path of adaptation to climate change, a dedicated Research Center for Climate Change Applied Genomics (UMIP GenClima) was launched in 2017 and will have bioinformatics, molecular biology and breeding laboratories supported by large-scale phenotyping infrastructure to provide new technologies to the very demanding agricultural sector"	KJWA	New technology/ methodology
Burkina Faso	"abandoning certain crops in favor of those which are more resistant to climate shocks"	NAP	New technology/ methodology
Consumer Unity and Trust Society (CUTS International)	"There should be financial investments (through Green Climate Fund and other financial means to be supported by developed and developing members) to support the strengthening of alternative agricultural (crop and livestock) value chains, while clearly outlining the roles of private and public-sector players."	KJWA	Shift in type of production system; new technology/ methodology

Table A1 | **Transformative Adaptation in Policy Submissions (Cont.)**

COUNTRY OR ENTITY	SPECIFIC EXCERPT	POLICY DOCUMENT/ SUBMISSION	TYPE OF TRANSFORMATIVE ADAPTATION
Honduras	"introduction of insect repellant plants"	NDC	New technology/ methodology
International Fund for Agricultural Development (IFAD)	"Potential novel uses include linking PICSA (Participatory Integrated Climate Services) to Climate Smart Agriculture scenarios constantly updating estimated crop yields within changing climates to promote flexible, climate smart, long term adaptation"	KJWA	New technology/ methodology
Jordan	"introduction of salt-tolerant crops and application of saline irrigation"	NDC	New technology/ methodology
Laos	"research into new crops"	INDC/NDC	New technology/ methodology
Moldova	"assess the needs and opportunities of alternative crops"	NDC	New technology/ methodology
	"change the types of agricultural crops using those adapted to low water demand; introduce new crops"	NDC	New technology/ methodology
Morocco	"conversion of nearly one million hectares of grain crops to fruit plantations that are likely to protect agricultural areas from all forms of erosion"	NDC	Shift in type of production system
Pakistan	"introduce genetically modified crops that are more carbon responsive"	NDC	New technology/ methodology
State of Palestine	"introduction of new saline-tolerant crops"	NAP/NDC	New technology/ methodology
Somalia	"introduction and dissemination of pyrethrum to farmers; introduction of the moringa tree; introduction of karkade; introduction of napier grass for livestock feed; introduction of sudan grass and sorghum; introduction of sisal"	INDC	New technology/ methodology
	"develop charcoal production from the invasive prosopis and replace with crop production"	INDC	Shift in type of production system
Sri Lanka	"re-demarcating agro-ecological regions (AERS) maps with current climate and future climate and recommend appropriate crops for different areas to reduce vulnerability to climate change impacts"	NDC	New technology/ methodology
Uzbekistan	"development of biotechnologies and breeding new crop varieties adopted to conditions of changing climate"	INDC	New technology/ methodology
Vanuatu	"development of resilient crop species including traditional varieties"	NDC	New technology/ methodology
Youth Climate Movement (YOUNGO)	"Another avenue that deserves more thought is the return to traditional crops and diets. Moving aside from external influence that has modified behaviors could help (re)introduce a bigger diversity of more resilient crops, better adapted to local conditions that would allow a more balanced diet. Of course, behaviors and consumption patterns would need some reorientation if such crops and diets prove themselves beneficial. In this context, awareness should be raised both at the consumption end and at the production end so that supply and demand evolve harmoniously."	KJWA	New technology/ methodology

Source: Authors.

APPENDIX B. PLANNING QUESTIONS FOR LEVERAGING CROP RESEARCH AND DEVELOPMENT FOR TRANSFORMATIVE ADAPTATION

Given the potential need for transformative approaches for agricultural adaptation, we explore here the key challenges, planning questions, pipelines, and pathways to achieve transformative adaptation. In this working paper, ***pipelines*** refers to key components of the process of transformative change, such as planning, financing, and implementation, which require additional factors such as investments in human capital, extension, delivery, and adoption. *Transformative pathways* are sets of discrete actions and strategies that can be sequenced to create a general trajectory toward transformation, with sufficient flexibility to change course if needed and include potential alternatives as they become available.

We focus on crop relocation, fundamental shifts in agricultural systems, and new technologies at scale. We propose that these pipeline and pathway frameworks can be used in conjunction with the process set forth in "Transforming Agriculture for Climate Resilience" (Carter et al. 2018), such that key actors can begin the preparatory actions necessary to achieve transformative adaptation across a long-time horizon, should it be necessary. We further acknowledge that women and girls should be explicitly considered in the pipeline and pathway framework, and in all transformative and incremental adaptation planning and implementation.

Crop Relocation

Shifting crops to fundamentally new locations may be required if temperature, precipitation, pest, and other thresholds are exceeded in their current locations. Crop relocation is a complex and intensive process that requires significant investment and planning and considers potential trade-offs and the effort's impact on marginalized communities, women, and smallholders. It involves farmers growing new crops in new regions and shifting from growing familiar crops to another viable crop or agricultural product. These shifts require investments in human capital and education, infrastructure, supply chains, and markets. In Table B1 we detail the key challenges, planning questions, and pipeline activities that can facilitate transformative adaptation whenever crop relocation is necessary.

New Technologies and Methods at Scale

Crop breeding for transformative adaptation may entail implementing new technologies and/or methodologies. Technologies and methodologies for increasing breeding times, promoting adoption of new crops, and providing the necessary support tools and services will be necessary transformation. Challinor et al. (2016) cover the multiple factors that influence the breeding process, including potential strategies to reduce the breeding to development to adoption time to account for rapid onset climate changes. In Table B2 we explore the key challenges, planning questions, and pipeline activities that can facilitate crop breeding for transformative adaptation. These components can be considered for breeding new cultivars for new regions to facilitate crop shift or new introduction, as well as for more incremental strategies, including crops bred for climate resilience (e.g., ones that are drought- or saline-tolerant) as well as those bred for nutritional content as a result of anticipated climate change impacts.

Fundamentally New Crop and Agricultural Systems

Another form of transformative adaptation can involve a completely new crop and agricultural system. Shifts of this type could take myriad forms; for example, shifting from a pastoral system to a crop system or shifting an entire region's crop type to another crop (e.g., from cereals to horticulture). Such fundamental changes will require long-term planning and investment, as well as potential changes in infrastructure, supply chains, and consumer education. In Table B3 we detail key challenges, planning questions, and potential pipeline strategies for this type of shift, using a transition from cereals to horticulture as an example.

Table B1 | **Key Challenges, Planning Questions, and Pipeline for Crop Relocation**

TRANSFORMATIVE STAGE	KEY CHALLENGES	PLANNING QUESTION(S)	PIPELINE ACTIVITIES
Discovery	Relocating crops to appropriate regions (considering agronomics, environment, social, cultural, and economic factors in both the new and old locations).	Under what future conditions can this crop be grown? How long can we expect it to remain viable as climate continues to change? What other factors may help or hinder the success of this crop in this region in the future? What crops and related livelihoods can replace the relocated crop production in the long term? Is this crop viable under future climate, social, or other market changes?	Identify future agronomically suitable areas. Assess appropriateness and potential consequences for economics, environment, and sociocultural systems.
Assessment	Ensuring that crops will perform adequately across multiple dimensions, including social and cultural conditions, and will continue to do so for a reasonable period of time as the climate continues to change; potential displacement or marginalization of populations in old and new regions; food security implications (e.g., from food to cash crop, markets); use of resources, including water and land, which may not currently be utilized for agriculture (trade-offs for ecosystem services).	Does this crop perform equally or better than existing crops in this region across multiple dimensions? What other crops will be displaced and what effect will this have on the local region and people? Will this crop change the economic structure of the region? Will this relocation displace or marginalize certain people or populations, and, if so, what strategies can overcome this? How will this relocation affect women, girls, boys, and men differently? What new market and supply chain infrastructure is necessary for the new and old crop location?	Identify prime region(s) based on discovery. Trial and test crop types for agronomic performance and for impacts on economics, environment, and sociocultural conditions. Assess potential for displacement or marginalization and counterstrategies. Involve local stakeholders in the process, including the trialing of crops.
Delivery	Identification of new farmers or of farmers who would shift varieties.	What types of farmers may be most in need of new production systems due to vulnerability to impacts? What key networks, actors, and technologies can be used to share information with potential adopters?	Data-driven delivery that communicates adoption criteria through innovation networks and key actors across new platforms. Use of multiple knowledge systems (farmer groups, extension, input dealers, social media, etc.). Explicit consideration of women or disadvantaged farmers.
Adoption	Technical, financial, and other assistance for farm viability; market information for new crops; displacement or marginalization; assessment of farm types that adopt.	What technical, financial, or other assistance may be necessary to facilitate farmer adoption? What kinds of farmers are adopting these new crops? Does this adoption lead to marginalizing nonadopters?	Funding mechanisms that facilitate technical and financial assistance both up front and ongoing. Assessment of adopters and nonadopters, and potential unforeseen consequences for both populations.
Monitoring and Evaluation (M&E)	Agronomic, economic, environmental, and sociocultural M&E to assess changes; need for future shifts with other climate, social, or market changes.	What are the short- and long-term impacts of this crop shift on the crop/agronomic system, economics, environment, social inclusion, and sociocultural structures? Are new strategies necessary?	Ongoing M&E to analyze agronomic performance and benefits and challenges for adopters and nonadopters, changes in sociocultural systems, markets, and financing. Potential for innovative data platforms to track and share data. Use data to inform future discovery and shift to new systems if necessary.

Source: Authors.

Table B2 | **Key Challenges, Planning Questions, and Pipelines for Transformative Crop Research**

TRANSFORMATIVE STAGE	KEY CHALLENGES	PLANNING QUESTIONS	PIPELINE ACTIVITIES
Discovery	Availability of germplasm, molecular and genetic data; use and acceptance of varying breeding technologies; available platforms; breeding cycles per year; availability of molecular markers and secondary traits; number and quality of trained plant breeders; involvement of end users in breeding process; need to breed for multiple outcomes (climate resilient, low nitrogen, etc.).	Is there adequate access to data, germplasm, traits, and molecular markers necessary to breed new crops that are resilient to long-term climate risks? Are there appropriate platforms and technology to facilitate breeding of new crops, including precision phenotyping? Will consumers and markets accept the technology used to develop these crops? Are there enough plant breeders to breed crops? How can end users be involved in the breeding process? Are traditional and wild crops adequately considered?	Expansion and diversification of gene banks for climate-resilient traits and/or traditional and wild crops. Expansion of open access breeding platforms and data and/or precision phenotyping technologies. Market and consumer research to assess technology acceptance. Investment in agricultural researchers and plant breeders. Farmer groups and stakeholders integrated into breeding development.
Assessment	Varying national regulations; long-term impacts may be unknown; complexity of potential costs and benefits (beyond agronomic); economic, environmental, and sociocultural impacts often not considered; germplasm availability and breeding technology; phenotype availability; crops bred for local conditions.	Do national regulations facilitate accelerated crop breeding? Will our trading partners accept changes to our regulations? What are the potential economic, environmental, and sociocultural impacts of these crops in the short and long term? Are farmers involved in trialing and testing these crops?	Trial and testing of crops with multilevel assessment and testing of crop for agronomic, economic, environmental, and sociocultural impacts. Farmer stakeholder groups involved in trialability. Policy analysis of potential regulatory changes to accelerate breeding with market acceptance.
Delivery	Seed and market infrastructure; capacity of companies and/or governments to commercialize products; sociocultural or economic restraints on seed access; patents or other intellectual property that hinder seed distribution/saving; need to demonstrate the five innovation characteristics in Rogers (2003) (relative advantage, trialability, observability, compatibility, and complexity); number of extension or other outreach professionals.	Is there infrastructure and capacity within (a given region) to commercialize and distribute new seeds? Can farmers easily access and afford new seeds and accompanying inputs? Who may not be able to? Does the seed license prevent or hinder transformative adaptation? How can seed and new crop information be effectively delivered? Are there enough extension and other professionals to communicate about these new seeds?	Investment in seed distribution infrastructure and markets. Integration of input dealers and technical assistance from private sector. Potential incentives or assistance in promoting and delivering seeds and management information. Addition of and effective training and capacity of public sector and private sector extension to demonstrate five innovation characteristics. Data-driven delivery with new innovation platforms.
Adoption	Seed costs and other inputs necessary; technical, financial, and other assistance; market information for new crops, consumer research, and education for market demand and new value chains, especially if bred without traditional methods (consideration of regulatory issues); potential for displacement/marginalization among nonadopters; assessment of farm types that adopt.	What technical, financial, or other assistance may be necessary to facilitate farmer adoption? What kinds of farmers are adopting new crops? Do these new crops have markets and can farmers access them? Are there any farmers or actors who can't access these new crops and/or are marginalized in this process?	Funding mechanisms that facilitate technical, financial, and market assistance both up-front and ongoing. Potential incentives for farmers to adopt. Assessment of adopters and nonadopters, and potential unforeseen consequences for both populations.
Monitoring and Evaluation	Agronomic, economic, environmental, and social assessments to assess changes; need for future shifts with other climate, social, or market changes.	What are the short- and long-term impacts of these new crops on the agronomic, economic, environment, social inclusion, and sociocultural structures? Does this new crop continue to be viable under future climate, social, or other market changes? Are new strategies necessary?	Ongoing monitoring and evaluation to analyze agronomic performance and benefits and challenges to adopters and nonadopters, changes in sociocultural systems, markets, and financing. Potential for innovative data platforms to track and share data. Use of data to inform future discovery and shift to new systems if necessary.

Source: Authors.

Table B3 | **Key Challenges, Planning Questions, and Pipelines for System Change: Shift from Cereals to Horticulture**

TRANSFORMATIVE STAGE	KEY CHALLENGES	PLANNING QUESTIONS	PIPELINE ACTIVITIES
Discovery	Irrigation need and water availability; potential consequences and impacts from irrigation; seed availability for horticultural crops in local conditions; market demand for horticultural crops; potential shifts in food security.	Is irrigation necessary for successful long-term horticultural production? If yes, can this region support current and long-term irrigation considering long-term climate risks? What local conditions do new horticultural seeds need to be bred for? Are current breeders trained to breed horticulture crops? Are there market opportunities and supply chain infrastructure for horticulture crops? Will additional inputs be necessary for growing horticulture crops? What are the potential food security implications?	Hydrological assessment about water availability, use, and long-term capacity. Seed stock assessment of relevant crops for local conditions. Assessments to determine best horticultural crop types for irrigation and market demand and food security shifts. Cost/benefit analysis on infrastructure investment and technological capacity, including human capital.
Assessment	Timely horticultural crop selection, breeding and trials; availability of germplasm and seeds bred for local conditions; involvement of key stakeholders in process.	What are the key technological barriers for effective breeding? Is open source germplasm available? What open source platforms and gene banks can contribute? Are crops being bred for farmer and market demands?	Agronomic trials for yield and other local conditions as deemed necessary. Sociocultural, economic, and environmental assessments on the potential long-term impacts of shift to horticulture production. Promotion of local stakeholder involvement.
Delivery	Seed distribution networks and seed multiplication networks; substantial information delivery.	Who are the key seed dealers and multiplication networks? Do they have the capacity to deliver horticultural seeds? What other private sector actors may be necessary to provide additional inputs? Are additional inputs necessary? What costing structures are necessary and who can afford them? How can information be effectively delivered to users?	Seed multiplication and delivery through private sector and community seed organizations. Data-driven delivery that communicates key information through multiple knowledge systems (farmer groups, extension, input dealers, social media, etc.).
Adoption	Technical, financial, and other assistance for horticultural adoption; market information; displacement or marginalization; assessment of farm types that adopt.	What technical, financial, or other assistance may be necessary to facilitate farmer adoption? What additional inputs may be necessary for horticultural crops or this seed variety, and which farmers can afford them? What kinds of farmers are participating in horticulture and who may not be able to participate? Does horticulture production marginalize nonadopters?	Funding mechanisms that facilitate technical, financial, and market assistance both up-front and ongoing. Assessment of adopters and nonadopters, and potential unforeseen consequences for both populations.
Monitoring and Evaluation (M&E)	Agronomic, economic, environmental, and sociocultural assessments to assess changes; need for future shifts with other climate, social, or market changes.	What are the short- and long-term impacts of horticulture on the crop/agronomic system, economic, environment, and sociocultural structures? Is horticultural production viable under future climate, social, or other market changes? Are new strategies necessary? What has happened to nonadopters?	Ongoing M&E to analyze agronomic performance and benefits and challenges for adopters and nonadopters, changes in sociocultural systems, markets, and financing. M&E also necessary to understand long-term impacts on environment and economics, particularly if additional inputs are necessary. Potential for innovative data platforms to track and share data. Use data to inform future discovery and shift to new systems if necessary.

Source: Authors.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.