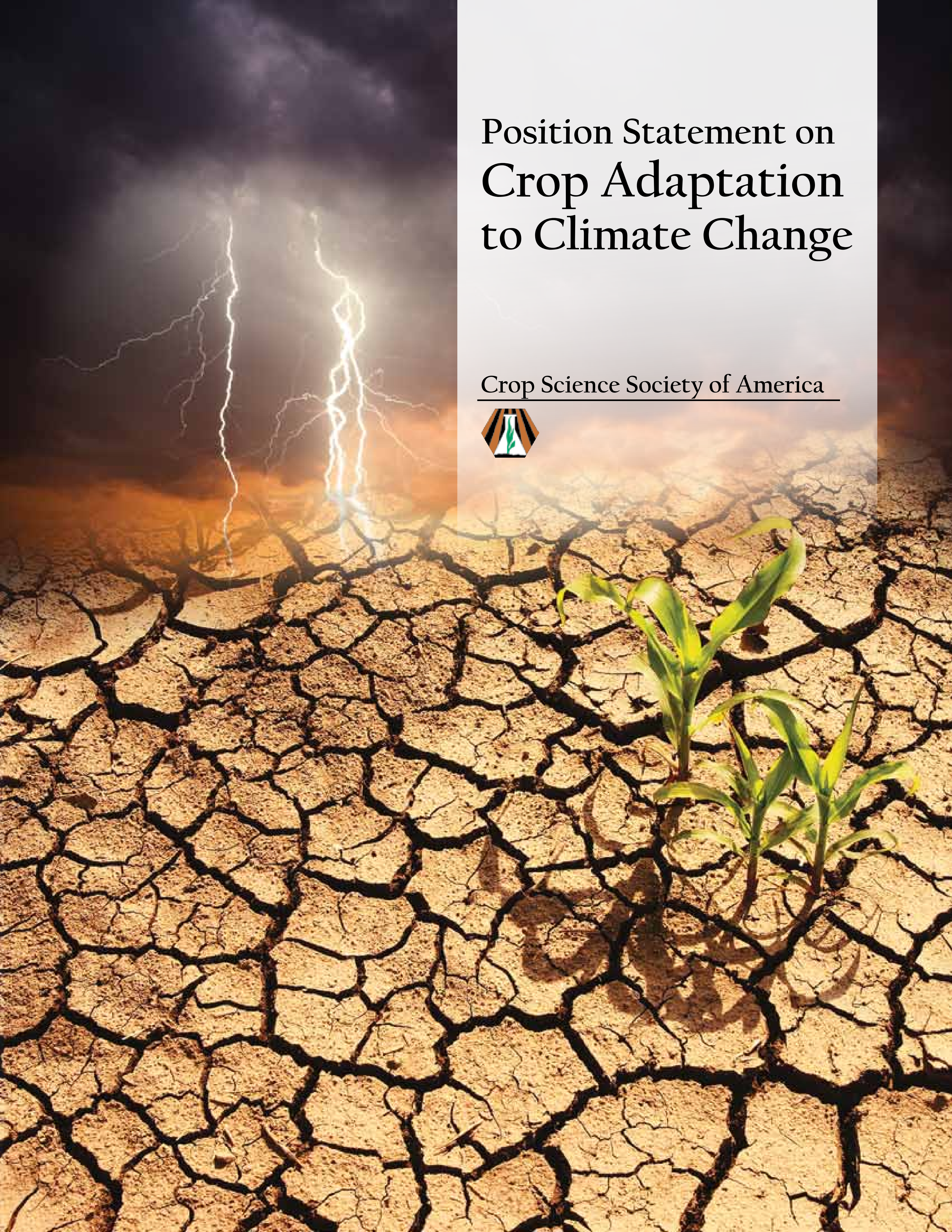
Position Statement on Crop Adaptation to Climate Change

Crop Science Society of America



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The Crop Science Society of America (CSSA), founded in 1955, is an international scientific society comprised of 6,000+ members with its headquarters in Madison, WI. Members advance the discipline of crop science by acquiring and disseminating information about crop breeding and genetics; crop physiology; crop ecology, management, and quality; seed physiology, production, and technology; turfgrass science; forage and grazinglands; genomics, molecular genetics, and biotechnology; and biomedical and enhanced plants.

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Summary

The Crop Science Society of America's (CSSA) position statement—Crop Adaptation to Climate Change—was researched and assembled by a working group of scientists from academia and industry. The statement 1) reviews the impacts of variable weather conditions arising from climate change on cropping systems, 2) reports the progress to date in adapting crops and management practices to new conditions, and 3) offers focus areas for increasing the speed at which global agricultural systems can adapt to climate change.

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Introduction

Throughout history, farmers have adopted new crop varieties and adjusted their practices in accordance with changes in the environment. But as global temperature continues to rise, the pace of environmental change will likely be unprecedented. More frequent and intense precipitation events, elevated temperatures, drought, and other types of damaging weather are all expected to impact crop yield and quality (Hatfield et al., 2011), making the challenge of feeding an estimated 9 billion people by 2050 exceedingly difficult. Extreme weather events are already affecting agricultural systems around the world. For example, after a 10-year drought, Australia experienced catastrophic floods during fall 2010 and winter 2011, leading to loss of an estimated $6 billion in grain harvests. Unpredictable and severe weather can also leave the most volatile regions of the world even more vulnerable to instability due to greater hunger, poverty, and food insecurity (CNA, 2007). Thus, learning to adapt our food production systems to a rapidly changing climate is critical to ensuring security of the global food supply and political stability.

Policy Statement

Climate change has far reaching implications for food security, health and safety, and approaches are required for adapting to new climates. Impacts of climate change are becoming evident and there is no indication that these will reverse in the foreseeable future; action must be taken now to adapt in a timely manner and prevent unpredictable and undesirable outcomes. New crop varieties, cropping systems, and agricultural management strategies are needed to provide options to farmers to counterweight these changes.

The world population, currently at 6.9 billion, is predicted to increase to 8 billion by 2025 and peak at about 9 billion in 2050

Source: Bengtsson et al., 2006; O'Neill et al., 2010.

How will climate change affect cropping systems?

Beyond its direct effects on weather, climate change will increase both abiotic stresses, such as drought, and biotic stresses, such as pest and crop disease pressures, on agricultural systems. Of greatest concern and largely unknown, are the influences that interactions among different types of stresses will have on crops.

Adaptation Needs

India, currently a producer of about 15% of the world's wheat crop, might be forced to turn away from a high-yield potential, irrigated, low rainfall mega-environment to a heat-stressed irrigated, short season production environment because of changes in climate (Ortiz et al., 2008). If crop adaptation strategies are not developed and implemented, India, the second largest (FAO, 2011) and historically self-sufficient wheat producer, may fail to provide enough wheat to meet the needs of its own people.

Photo: Istock

Drought is expected to limit the productivity of *over half* the earth's arable land in the next 50 years (Cattivelli et al., 2008; Sinclair, 2010), and competition for water between urban and agricultural areas will compound issues of water availability (Rosegrant et al., 2009). While the use of brackish and saline water could also help alleviate the world's water problems, this option is only possible with the development of salt-tolerant crops or management practices that alleviate salt stress. As a result, to limit the impact of drought, there is an urgent need for crop varieties and cropping systems that conserve water and retain yield during periods of water scarcity. Developing these crops is difficult, however, because of the interplay of crop response systems to drought at the genomic, metabolic, biochemical, and physiological levels. To make drought-tolerant varieties available to farmers, interdisciplinary teams of scientists working at the cellular, plant, and field scales must collaborate to discover ways to manipulate these complex, multi-level processes and improve crop response.

Temperature influences the growth and development of all crops, shaping potential yield throughout the growing season. Current temperatures in the Midwest of the U.S. are optimum for production, while the Southern U.S. temperatures already exceed the optimum. Temperature events higher than normal are expected to reduce cereal and grain legume yields (Hatfield et al., 2011). Elevated temperatures are known to shorten the grain-filling period, for example, and to reduce pollen viability and weight gain in grain (Boote and Sinclair, 2006; Hatfield et al., 2011). Moreover, temperature changes can result in warmer, less severe winters, which sometimes allow diseases and pests to survive and overwinter, increasing the likelihood of reduced yield during the next cropping season. For all these reasons, adapting crops and cropping systems to new seasons and temperatures will require region-specific **crop adaptation strategies.**

Spotlight on Changes in Seasonal Temperatures

In Canada's Northern Great Plains, where the growing season has lengthened in recent decades, spring frosts now occur about one day earlier with the passage of every 10 years, whereas the frost-free season increases about two days (Cutforth et al., 2007). These shifts coincide with earlier spring warming and runoff as well as decreased winter snowfall (Cayan et al., 2001; Cutforth et al., 2007).

Photo: Forest & Kim Starr, Starr Environmental. Bugwood.com

Carbon dioxide (CO_2) is fundamental to crop carbohydrate production (important for crop productivity and yield) and overall plant metabolism. It also plays an important role in climate change. Atmospheric CO_2 concentrations have risen dramatically over the past 200 years and may reach 450–1,000 μmol by the end of this century, according to the Intergovernmental Panel on Climate Change (IPCC, 2007). Rising CO_2 levels will likely boost the overall productivity of many crops; although important tropical grasses like maize, sugarcane, and sorghum, and some cellulosic biofuels crops, don't respond as well to elevated CO_2 levels (see sidebar on C3 and C4 crops). Increases in productivity could be offset, though, by pressures such as insect and fungal pests, ozone, and more variable precipitation, although the degree to which this occurs will depend on the physiology and biochemistry of each crop (Ziska, 2008; Taub, 2010). Crop adaptation will be critical to ensure that crops can maintain, or even increase, productivity amidst a CO_2-enriched environment.

Spotlight on CO_2 and C3 and C4 Crops

Crops with C3 photosynthesis (soybean, rice, and wheat) respond more positively to increasing CO_2 than C4 crops (maize, sugar cane, and biofuel grasses such as switchgrass and Miscanthus). Crops also respond differently to temperature and water availability, e.g. C3 crops are more susceptible to increases in temperature. Given that environmental factors like CO_2 concentration, temperature, and water availability will likely change simultaneously (as well as impact biotic factors), it is therefore difficult to make accurate predictions about crop production under elevated concentrations of CO_2.

Impacts of CO_2 on Crop Quality and Nutrition

Research shows that increased CO_2 can reduce grain protein by 4 to 13% in wheat and 11 to 13% in barley (Jablonski et al., 2002; Ziska et al., 2004), while increasing the carbohydrates in grain (Erbs et al., 2010). Depending on the crop, micronutrients also appear to be somewhat diluted by an increase in carbohydrate in the grain. These effects are difficult to explain, and more difficult to separate from whole plant physiological changes. However, they suggest that increased emphasis on research evaluating crop composition, as well as yield, will be needed in the coming decades.

Photo: USDA-ARS

Ozone (O_3)—an important greenhouse gas and agricultural pollutant—continues to increase because of fossil fuel combustion (Staehelin et al., 2001; Krupa et al., 2000). While levels of CO_2 will rise rather uniformly around the globe, O_3 concentrations will vary regionally and exist to a greater extent around industrialized areas (Jaggard et al., 2010). Crops take ozone into their leaves during photosynthesis, where the gas lowers photosynthetic rates and accelerates leaf death, affecting crop maturity and productivity (Krupa et al., 2000). The rate at which crops take up O_3 depends on the O_3 concentration in the air as well as the opening and closing of the stomata or leaf pores. Present-day global yield losses due to ozone are estimated at approximately 10% for wheat and soybean, and 3–5% for rice and maize (Van Dingenen et al., 2009). Modern tools of crop breeding will help to inform scientists about different approaches for developing crops that can thrive despite exposure to increasing concentrations of O_3.

Biological stresses on cropping systems include weeds, insects, viruses, bacteria, and fungi. Temperature is considered the most important factor in determining how insects affect crop production and yield (Coakley et al., 1999). For example, some populations of insect species, such as flea beetles, are showing signs of over-wintering because of warmer winter temperatures (Harrington et al., 2001; Wolfe et al., 2007). Viral, bacterial, and fungal pathogens also respond greatly to temperature, as well as humidity and rainfall. Thus, as the growing season lengthens and winters moderate due to climate change, pressures from plant, microbial, and insect pests are expected to rise due to an increased capacity for over-wintering, greater movement of organisms, and expanded adaptation zones.

In summary, new crop varieties, cropping systems, and agricultural management strategies are needed to provide options to farmers to counterweigh these changes.

Origin and Domestication of Today's Popular Crops

Wheat—Middle East
Rice and Soybean—Eastern Asia
Sorghum—Africa
Potatoes—South America
Maize and Beans—North and South America

Source: Harlan, 1991

How can we adapt crops and cropping systems to climate change?

The climate has always been in a state of flux, but the current rate of change is much faster, and the range of weather variables much broader than ever seen before in modern agriculture. Today, two primary approaches exist for adapting crops to these conditions: 1) improving existing crop cultivars and developing new crops, 2) devising new cropping systems and methods for managing crops in the field. These approaches include the specific strategies discussed below.

Strategies for improving existing cultivars and developing new crops

- **Develop new crops.** New crops will likely play a key role in maintaining and increasing agricultural production. Domestication began only 5,000 to 12,000 years ago for our oldest crops such as maize, wheat, potatoes, and sorghum, while blueberries and wild rice were domesticated more recently (Harlan, 1991). Today, some scientists are crossing wild, perennial relatives of crops such as maize, millet, rice, sorghum, sunflower and wheat with their annual, domesticated counterparts, to develop perennial grain crops (Cox et al., 2006). Additionally, a growing interest in bioenergy has also encouraged the domestication and breeding of C4 grasses, including switchgrass, and *Miscanthus* (Bransby et al., 2010). Domestication and breeding of new crops is a long-term solution, requiring many years of effort before formal testing can be performed.
- **Integrate beneficial traits into existing crops through use of germplasm collections, related datasets, and breeding.** Historically, crop scientists have identified and selectively adapted crops to exhibit desirable traits that allow crops to achieve optimum yields while withstanding stresses, such as drought, heat, and water-logging. The success and speed of breeding efforts depend, however, on the ability of breeders to access optimal germplasm and quality information about germplasm material. Today's breeders rely on genetic and environmental information in both private and public germplasm collections, such as the U.S. Department of Agriculture (USDA) Agricultural Research Service's National Plant Germplasm System. To support continuous improvement of germplasm that can be used to develop cultivars adapted to climate change, there is a need to acquire, preserve, evaluate, document, and distribute plant genetic resources for a wide range of crops and their wild relatives. Additionally, well-preserved information can allow scientists to employ modern biotechnology methods to screen crop traits—these advances are already changing how germplasm banks are used. Expanded use of these resources and methods will help researchers more quickly identify adaptive traits, represented by genes or groups of genes, which contribute to stress resistance.
- **Use new technologies—image-based measurements, high-throughput DNA sequencing, databases, and statistical models.** These technologies are changing the way that germplasm banks are utilized and surfacing new ways to use information stored in germplasm banks to improve crop performance. For today's challenges, it is essential to have public access to accurate information, allowing for identification of **adaptive traits** represented by genes or groups of genes that contribute to abiotic or biotic stress resistance. Using crop breeding alone or in partnership with new biotechnology, scientists can more rapidly identify cultivars with enhanced productivity even in the presence of drought, heat, water logging, and frost pressures relative to the current cultivars available.
- **Identify crop germplasm that tolerates drought, heat, and water-logging.** Yield drops when crops experience drought, excessive heat, or surplus water deviating from the optimum for growth during key stages, including pollination, flowering, and filling periods, when carbohydrates and nutrients assimilate inside grain, tubers, or fruit. Multiple molecular markers can be statistically associated with some of these traits to allow selection to be performed without testing in the breeding environment. Cultivars are now being developed which are tolerant to excess heat during pollination for cowpea and corn, and flooding early in the growing season for soybean and rice (Hall, 2004; VanToai et al., 2010; Bailey-Serres et

al., 2010). Maize hybrids are now being developed that have a better synchronization of pollination and flowering under heat and water stress (Ribaut et al., 2009). Cultivar differences for heat tolerance exist in some crops such as rice, cowpea, and peanut, but knowledge about the effects of extremely high temperatures is very limited because diverse germplasm has not been extensively screened. Continued work in this area will provide new germplasm for plant breeders to incorporate into productive varieties for farmers.

Concerted efforts are needed for the screening of crop germplasm for susceptibility to many biotic and abiotic stresses. U.S. farmers already experience significant yield losses from pests despite the use of improved crop varieties and agrichemicals for pest and pathogen control. As the climate changes and becomes more variable, the interactions between crops, pests and pathogens will likely be complex, and need to be further studied. Continued work in this area will provide new germplasm material for plant breeders to incorporate into adapted varieties which are highly productive for farmers.

- **Expand field-level evaluations of crop germplasm.** The modern crop breeder's toolkit enables consideration of the entire world's genetic resources for use in crop genetic improvement. New technology in combination with large scale field phenotypic evaluations will likely help disclose previously unknown genetic sources and genomic regions on DNA associated with abiotic stress tolerance (Collins et al., 2008). These genetic resources and knowledge will foster important leaps in abiotic stress tolerance. This, in turn, will help scientists discern molecular to physiological mechanisms underpinning drought tolerance that are now poorly understood because agriculturally important stress tolerance is a relatively new area of science (Sinclair, 2011). Overcoming this 'knowledge gap' will unlock the ability of both applied and basic research groups to develop long term strategies that can maximize delivery of new, improved cultivars. Therefore, expanded field-based phenotypic research programs and related breeding efforts must be closely coordinated with the full spectrum of crop development sciences, engaging breeders, physiologists, and geneticists.
- **Employing new tools, techniques, and datasets to accelerate the delivery and release of proven varieties.** New technologies—made possible with use of computer imaging, robotics, and super

Definitions

Cross-breeding and self-pollinating plants: crossing pollen between parents that have desired traits—morphological, physiological, metabolic, and molecular characteristics—to facilitate new offspring that are improved cultivars.

Germplasm banks: the USDA Agricultural Research Service's National Plant Germplasm System (NPGS) serves as a warehouse of seed (physical DNA) that can be used to develop new cultivars and functions as a reservoir of information, e.g. genes and alleles, about the seeds (Tanksley and McCouch, 1997).

Germplasm is living tissue from which new plants can be grown. This can be a seed, or it can be another plant part—a leaf, a piece of stem, or pollen—or even just a few cells (USDA, 1996).

> CSSA publishes the *Journal of Plant Registrations* which publishes cultivar, germplasm, parental line, genetic stock, and mapping population registration manuscripts.
>
> The National Plant Germplasm System (NPGS) consists of a network of repositories of germplasm that provides the information stored in the Germplasm Resources Information Network's (GRIN) database.

Cultivar is a plant, cultivated for a certain purpose, which has been selected for because of its desirable characteristics, e.g., crop performance.

computers—such as *high-throughput screening* of crop genetic material, allow for fast and accurate identification of adaptive traits expressed in different environments (Richards et al., 2010; Tardieu and Tuberosa, 2010). These technologies allow researchers to identify adaptive traits expressed in different environments more quickly, and increase the probability of finding key clusters or groups of genes that control traits for resistance to drought and other abiotic stresses (Richards et al., 2010).

As the cost of genome sequencing drops, researchers will also be able to sequence more than one cultivar per crop. This will allow them to uncover the genomic basis of water, resource, and nutrient-use efficiencies in crops, and identify locations on the genome where breeders have most successfully selected and bred for adaptive traits in the past, providing additional knowledge to improve crop yield. Moreover, genome-wide prediction and breeding simulations are helping breeders make better selections in their programs because they can improve their prediction of the outcome of breeding decisions using forward breeding (Heffner et al., 2010; Jannink et al., 2010; Lorenzana and Bernardo, 2009; Podlich et al., 2004; Messina et al., 2010). High-throughput screening in combination with advanced genomics and prediction methods will likely enhance the ability of crop scientists to develop cultivars adapted to climate change at a faster pace, broadening the options that farmers will be able to choose from.

- **Identifying crop germplasm for tolerance to pathogens, insects, and nematodes.** Yield losses from biotic stresses are significant in the U.S. even with the use of improved crop varieties and agro-chemicals for control. Under climate change and climate variability the interactions between crops, pests, and pathogens will likely be complex and are currently poorly understood (Gregory et al., 2009). There is a need for concerted efforts to screen crop germplasm for susceptibility to many pest organisms. Such screening, coupled with molecular marker tools, will assist plant breeders in dealing with current and future pest outbreaks, and support producers by providing them with new cultivar options at a faster pace, and provide greater food security.

Advances in Drought-Resistant Varieties

Exciting advances have been made through modest germplasm screening projects that identified desirable old cultivars and landraces (naturally developed, local varieties) and subsequently used them as parent stock for breeding. As a result, drought-tolerant cultivars now exist for several crops including soybean, dry beans, rice, and peanut (Brick et al., 2008; Chen et al., 2007; Branch and Kvien, 1992). This initial success capitalizes on millennia of farmer adaptation of crops to particular climates and points the way ahead in adapting crops to future climate change.

Photo: USDA-ARS

An approach for devising new systems for managing crops in the field

New management systems are now being developed to increase crop resilience toward climatic stresses. Since not all regions are predicted to experience the same agricultural vulnerabilities to climate change, mitigation and adaptation strategies will vary. Appropriate, site-specific cropping system management practices can help alleviate the effects of abiotic and biotic stresses on crop productivity and yield. Crops are planted in sequences or rotations depending on their purpose, tolerance to prevailing temperatures and weather extremes, and economic return. Each crop has an impact on the successive crop planted. Because agriculture will not experience the same vulnerability to climate change in all regions, site-specific cropping systems and management practices are needed that match yield potential with inputs, soil fertility, and the range of climate variability in each area.

Growers have modified cropping systems in the past, of course, either in response to gradual climate change or as crops were moved into new geographical regions. This process of adaptation required extensive trial-and-error, disrupting farm economies, and sometimes food supplies (Olmstead and Rhode, 2011). However, research and development in the public and private sectors provides information allowing producers to adapt more fluidly. Research technologies and management tools that can accelerate the adaptation of cropping systems include simulation modeling and remote sensing. These technologies, combined with location-specific information and recommendations, will help to minimize the negative economic impacts that can otherwise accompany *ad hoc*, untested changes in cropping systems.

Photo: Dreamstime

Strategies for developing new cropping systems that address climate stresses

- **Use crop models in decision-making.** Crop models integrate important information about processes, and allow scientists to estimate the impact of changes in crop genetics, and crop and soil management methods. Models can also be used to compare crop management strategies, helping producers weigh both economic and environmental considerations as they make decisions about crop varieties, cropping dates, and management practices (Jones et al., 2003).
- **Apply remote sensing and precision agriculture technologies.** Remote sensing using both satellite and on-the-go field scanners can reduce the resources needed to measure crop characteristics like cover, leaf greenness, growth rate, and biomass across a broad range of cropping systems and environments. This information then allows researchers to assess the effectiveness of modifications in cropping systems, and can help producers make precision agriculture production decisions at the field scale. These tools will be of great use in understanding the effects of a changing environment at the field scale, and the appropriate agronomic methods needed to respond to such changes.
- **Monitor crop condition.** Short- and long-term monitoring of factors such as pathogens, changes in field conditions, crop productivity, and weather patterns is essential for building an information base on which future decisions and innovations can draw from. Remote sensing of crop, weather, and pest conditions, for example, can be used by farmers for adaptive management or by governments as an early warning signal for climate-based food security crises. Databases also permit modeling of both biotic and abiotic climate change effects on crops in specific regions. In short, long-term monitoring is needed to develop strategies for crop/cultivar deployment and associated management practices that offer farmers the best chance for a productive harvest.

- **Optimize water-use efficiency.** With climate change, water supplies are expected to become threatened in certain regions of the world, but water management strategies, such as drip irrigation, can conserve water and protect vulnerable crops from water shortages. To evaluate the effectiveness of these practices, agronomists often calculate the amount of crop yield per unit of water, or water productivity. Also known as achieving "more crop per drop," water productivity helps agronomists and cropping systems scientists evaluate management practices (French and Schultz, 1984; Passioura, 2006; Sadras and Angus, 2006; Grasini et al., 2011a/b). Water productivity considers the economic optimization of water use (Taylor, 1975) which can be improved through advances in cultivars, plant nutrition, and irrigation practices based on real-time crop need, and better drought and heat tolerance in crops grown in rain-fed systems.
- **Optimize land use.** Intensifying yields sustainably on existing arable land uses land more efficiently and avoids bringing new land into production. Higher yields have also been shown to reduce greenhouse gas emissions, thus helping minimize agriculture's contribution to climate change (Burney et al., 2010).

Policy Statement

Climate change has far reaching implications for food security, health and safety, and approaches are required for adapting to new climates. Impacts of climate change are becoming evident and there is no indication that these will reverse in the foreseeable future. Action must be taken now to adapt in a timely manner and prevent unpredictable and undesirable outcomes. New crop varieties, cropping systems, and agricultural management strategies are needed to provide options to farmers to counterweight these changes.

Needs for the Future

This CSSA Position Statement identifies the challenges that crop science can address to adapt cropping systems to climate change in the short-term. However, uncertainties and limited predictability in the long-term require an infrastructure that drives innovation and implements crop adaptation strategies in a sustainable manner. In particular, research investments and efforts are needed to further:

- understand the physiological, genetic, and molecular basis of adaptation to drought, heat and biotic stresses likely resulting from climate change;
- translate new knowledge into new agricultural systems that integrate genetic and management technologies (i.e., both breeding and agronomy will contribute to adaptation); and
- transfer knowledge effectively and make technologies and innovations widely available to increase food production and stability.

The CSSA recognizes that both private and public sector research and development are fundamental to building a sustainable approach to crop adaptation to climate change. Collaboration and communication between these sectors is also essential to create knowledge, and develop and transfer new technologies. Although the contributions of government, universities, and industry may vary with crop, region, and time, the roles of each can be tailored appropriately.

Both private and public sector research is vital to improving crops and production systems. However, the land-grant university system plays another critical role: It trains the next generation of crop scientists, agronomists, breeders, and growers. Without these human resources, society will have little or no capacity to adapt to climate change.

In summary, the Crop Science Society of America finds that an effective, planned response to climate change must include provisions for significant investments in and strengthening of crop science research that provides knowledge and information on adapting crops and cropping systems to our changing environment.

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