OPINION & POLICY

# The Scientific Grand Challenges of the 21st Century for the Crop Science Society of America

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## ABSTRACT

Crop science is a highly integrative science employing expertise from multiple disciplines to broaden our understanding of agronomic, turf, and forage crops. A major goal of crop science is to ensure an adequate and sustainable production of food, feed, fuel, and fiber for our world's growing population. The Crop Science Society of America (CSSA) identified key Grand Challenges which, when addressed, will provide the tools, technologies, and solutions required to meet these challenges. The Grand Challenges are: (i) Crop adaptation to climate change: Increase the speed with which agriculture can adapt to climate change by using crop science to address abiotic stresses such as drought and heat. (ii) Resistance to biotic stresses: Increase durability of resistance to biotic stresses that threaten yield and quality of major crops. (iii) Management for resource limited systems: Create novel crop cultivars and management approaches designed for problem soils and low-input farming to increase economic prosperity for farmers and overcome world hunger. (iv) Crop management systems: Create novel crop management systems that are resilient in the face of changes in climate and rural demographics. (v) Biofuels: Develop sustainable biofuel feedstock cropping systems that require minimal land area, optimize production, and improve the environment. (vi) Bioresources: Genotyping the major crop germplasm collections to facilitate identification of gene treasures for breeding and genetics research and deployment of superior genes into adapted germplasm around the globe. These challenges are intended to be dynamic and change as societal needs evolve. Available funding and national prioritization will determine the rate that they will be addressed.

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**Abbreviations:** CGCC, CSSA Grand Challenge Committee; CSSA, Crop Science Society of America; RFI, request for information.

In June 2009, the Crop Science Society of America (CSSA) set out to identify grand challenges for crop science related to the most pressing issues facing society. This charge resulted from a meeting in April 2009, facilitated by the CSSA Science Policy Office, which was attended by CSSA President Joe Lauer, colleagues from the American Society of Agronomy and Soil Science Society of America, and Dr. Rajiv Shah, who, at the time, served as Under

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Secretary of Research, Education and Economics (REE) and Chief Scientist at the U.S. Department of Agriculture (USDA). During the meeting, Shah appealed to the societies to identify *transformative questions* to guide science in solving issues related to climate change, food security, bioenergy production, human health and nutrition, and ecosystem health. He argued that concurrence on a set of grand challenges and related key scientific questions would help shape investments in innovative research aimed at problem solving. During the meeting, Shah outlined several societal challenges for the societies to address (Fig. 1).

In response to this charge, the CSSA Grand Challenge Committee (CGCC) was formed during the summer to develop and communicate the challenges (Table 1). The committee members were selected based on expertise, regional distribution across the United States, and private or public sector affiliation. The CSSA rapid response teams, run by the Science Policy Office, and the CSSA Executive Committee offered critical advice during the formation of the committee. With direct guidance from the CSSA Executive Committee, the CSSA Science Policy Office facilitated the work of the CGCC from June to late September.

In many respects, the meeting with Dr. Shah provided the Crop Science Society of America with a head start. Our approach for developing the grand challenges followed the model taken by the basic energy sciences, as described in Fleming and Ratner (2008). Accordingly, a grand challenge statement must

- be scientifically rigorous,
- be clear and well defined,
- be relevant to the broad portfolio of their sciences, and
- promise deliverables in the form of technologies or methods that can provide a secure future (adapted from Fleming and Ratner, 2008).

What we chose as grand challenges are fundamental problems with broad practical implications whose solutions would be enabled by the multidisciplinary application of agronomic, crop, soil, and environmental sciences. The leveraging of new and future technologies along with established research methods already in use will be essential for the successful accomplishment of each grand challenge.

## THE CSSA GRAND CHALLENGES

Crop science is a highly integrative science using the disciplines of conventional plant breeding, transgenic crop improvement, plant physiology, and cropping system sciences to develop improved varieties of agronomic, turf, and forage crops to produce feed, food, fuel, and fiber for our world's growing population. During the last century, crop science has achieved feats that are now part of everyday life and taken for granted.

Despite these scientific achievements, the world today faces ever-growing challenges of widespread food insecurity and malnutrition, negative impacts of climate change, environmental degradation, and dependence on fossil fuel energy. Solutions to these challenges will be found, in part, through sustained, federal investment in crop science to address these challenges. The CSSA organized a committee to identify key grand challenges associated with crop science that, when addressed, will provide the tools, technologies, and solutions required to address these challenges.

### Grand Challenge: Crop Adaptation to Climate Change

**Increase the speed with which agriculture can adapt to climate change by using crop science to address abiotic stresses such as drought and heat**

- *Bioenergy:*
    - The challenge of sustainably producing bioenergy feedstocks
- *Climate change:*
    - Mitigating greenhouse gas emissions in managed systems
    - Adapting production systems to be resilient in the face of global climate change
- *Human nutrition:*
    - Improving nutritional quality and safety of our food supply
- *Food security:*
    - Achieving global food and water security for developing nations

Figure 1. Dr. Rajiv Shah's societal challenges.

### Background

Drought is the number one limitation to crop productivity in the world. As climate changes, the incidence and duration of drought and heat stress on our major crops will increase in many regions, negatively affecting crop yields and food security. Solutions to this complex problem can best be found by forming research teams, bringing a spectrum of scientific expertise—breeders, physiologists, and molecular geneticists—to bear on the problem. Because the majority of the progenitors of most crops were developed under periodically dry conditions, drought tolerance genes already exist in most crop germplasm collections. These important genes have not all persisted in modern cultivars because agriculture has concentrated on breeding varieties adapted to favorable environments and responsive to irrigation. The need to incorporate genes for drought tolerance takes on new urgency with predictions of more wide-spread and severe drought. Agriculture must produce more "crops-per-drop" of water and develop strategies to share water resources at the rural–urban interface where water can be bought and diverted to nonagricultural uses.

### Key Questions

1. How can teams of breeders, geneticists, physiologists, and agronomists be created with sustained support to conduct research in abiotic stress tolerances through all phases of testing to produce economically viable tolerant varieties?
2. Can we develop networks of abiotic stress-prone fields (laboratories and/or sites) and efficient screening methods to identify genotypes tolerant of stresses such as drought and heat?
3. What economically important abiotic stress-tolerant genetic resources exist in germplasm collections and in applied breeding programs?
4. What are the physiological mechanism(s) by which abiotic stress tolerance genes interact with each other and with the environment to impart abiotic stress tolerance?
5. What are the physiological and genetic mechanisms by which temperature reduces pollen viability and seed set? Can genetic tolerance to temperature stress be achieved?
6. How can we exploit variation in the morphology, rooting depth, and/or functionality of roots, leaves, or stems to mitigate the effects of abiotic stress?

### Expected Outcomes

1. Fundamental knowledge regarding traits, genes, and breeding stocks that convey economically important levels of stress tolerance.
2. Cultivars genetically improved for stress tolerance will provide sustained or higher crop yields that will help stabilize crop production in the face of projected climate changes.
3. Adequate infrastructure (laboratories, personnel, and experience with integrated approaches) to mount a sustained long-term responsiveness to continuing abiotic stresses.

## Grand Challenge: Resistance to Biotic Stresses

**Increase durability of resistance to biotic stresses that threaten food security in major crops**

### Background

Organisms that cause biotic stresses in crop plants are continually adjusting their pathogenic mechanisms to take advantage of the plant's limited defenses. Unfortunately, with new intensive management practices being adopted and climate change altering environmental conditions,

**Table 1. The timeline for developing and communicating the Crop Science Society of America grand challenges.**

| | |
|---|---|
| 8 Apr. 2009 | Crop Science Society of America (CSSA) meets with USDA Research, Education and Economics Under Secretary Rajiv Shah. |
| 27 July 2009 | CSSA Grand Challenge Committee (CGCC) is formed. |
| 30 July 2009 | CSSA commences work on grand challenges. |
| 4 Aug. 2009 | CGCC splits into subcommittees to work on societal grand challenges. |
| 4 Aug. 2009 | Office of Science and Technology Policy (OSTP) releases its annual memorandum on "Science and Technology Priorities for the FY 2011 Budget" (OSTP, 2009). |
| 14 Sept. 2009 | CGCC completes draft grand challenges. |
| 21 Sept. 2009 | President Obama announced his innovation strategy (NEC, 2009). |
| 28 Sept 2009 | Grand challenges are sent to CSSA membership. |
| 5 Oct. 2009 | CSSA membership sends comments to CSSA Science Policy Office and a final document is developed. |
| 30 Oct. 2009 | CSSA develops the CSSA Grand Challenge Wiki (CSSA, 2009). |
| 10 Jan. 2010 | CSSA releases the 2010 grand challenges (CSSA, 2010a). |
| 4 Feb. 2010 | OSTP requests information on the 21st century grand challenges (OSTP, 2010a). |
| 14 Apr. 2010 | CSSA submits the CSSA grand challenges to OSTP. |
| 16 June 2010 | CSSA releases grand challenges to media, highlighting cropping system adaptation to climate change (CSSA, 2010b). |
| 21 July 2010 | OSTP releases its annual memorandum on "Science and Technology Priorities for the FY 2012 Budget" (OSTP, 2010b). |
| 11 Feb. 2011 | President Obama releases an updated *Strategy for American Innovation* (NEC, 2011). |
| 11 Apr. 2011 | CSSA releases the 2011 grand challenges (CSSA, 2011). |

the rate of adjustment by some pathogens has accelerated. Furthermore, crop uniformity can increase genetic vulnerability to various pests. For example, U.S. soybean [*Glycine max* (L.) Merr.] cultivars are almost uniformly susceptible to two relatively new U.S. biotic stresses: soybean aphid (*Aphis glycines* Matsumura) and soybean rust (*Phakopsora pachyrhizi* and *Phakopsora meibomiae*).

Contemporary best management practices that retain plant residues on the field result in increased soil organic matter, improved soil quality, and additional sequestered C; however, they also provide an environment where pathogens can prosper and cause reduced yields. Examples include pathogens such as gray leaf spot (*Cercospora zeae-maydis*) of corn (*Zea mays* L.) whose inoculum grows on previous crop residue. Carcinogenic aflatoxins are produced by fungi whose proliferation increases in stress environments of drought, high temperature, and/or high humidity. Therefore, there is a need for plant genomic tools that can identify novel resistance genes and assist in their rapid incorporation into improved cultivars.

### Key Questions

1. What are the molecular and physiological mechanisms by which various pathogens and pests interact with plants? How can these interactions provide novel and durable approaches for defense mechanisms?
2. How do we efficiently identify novel resistance genes in our extensive germplasm collections?
3. How do we incorporate resistance genes effectively without limiting progress for improving yield?
4. How can genomic tools be used with germplasm to uncover the molecular basis for resistance to biotic stresses?
5. How do we develop and use gene-specific markers to combine and deploy resistance genes so that the risk of crop loss is minimized?

### Expected Outcomes

1. Prevention of widespread crop yield and quality losses as plant diseases and pests evolve and spread due to climate change.
2. Enhanced year-to-year stability of food, feed, fiber, and biofuel production.
3. Improved human and animal health by increasing crop resistance to mycotoxins and aflatoxin.

## Grand Challenge: Management for Resource Limited Systems

**Create novel crop varieties and management approaches designed for problem soils and low-input farming to increase economic prosperity for farmers and overcome world hunger**

### Background

Agricultural productivity is limited in many areas by poor soil conditions and high fertilizer prices. However, soil tilth issues including high soil pH or toxic Al and salt levels are not easily remedied by conventional high-input approaches. As a result, new crop varieties and management practices are needed that reduce dependence on agricultural inputs and overcome common soil problems. Multidisciplinary research teams will be the key to success because they have the expertise to improve N fixation in legume crops and improve nutrient uptake and use and can develop crop varieties that are tolerant of such soil limitations. Team research should focus on efficient and reliable methods to identify desirable crop germplasm that has the right genetic makeup to deliver these improvements. When coupled with technology transfer, these efforts will increase yields and quality of food crops and ameliorate food security and nutritional deficiencies at home and abroad.

### Key Questions

1. How do soils, weather, genetics, and management practices interact and influence root growth and nutrient uptake and N fixation?
2. What are the most reliable, efficient, and inexpensive methods that accurately predict the worth of a genetic trait or gene in low input agriculture (for efficient use of limiting soil nutrients)?
3. Which genetic traits have the greatest impact on nutrient use efficiency, and how do these traits interact with each other and the environment?
4. How do we ensure optimal partitioning of limited nutrient resources to the economically important portions of the crop?
5. Can genomic methods provide better understanding of host plant–rhizobial strain interactions and rhizobial–soil interactions?
6. How might crop, nutritional, and soil factors be managed to sustainably and consistently improve crop performance and yields? Can commercial mycorrhizae applications improve plant nutrient uptake?

### Expected Outcomes

1. Reduced need for the application of N fertilizers through enhanced biological N fixation by microorganisms in association with crop plants.
2. Reduced need for P fertilization or use of other soil amendments if roots–mycorrhizae systems can more adequately provide nutrient uptake for the crop.
3. Improved energy balance for biofuel production.
4. More economically and environmentally sound farming systems.
5. Increased yields, crop nutrient quality, and food security in resource-scarce environments.

## Grand Challenge: Crop Management Systems

**Create novel crop management systems that are resilient in the face of changes in climate and rural demographics**

### *Background*

Agriculture is constantly adapting to change; consider the revolutions in agriculture due to irrigation, fertilizer, weed, insect, and disease control, and modern tillage systems. We will need to make similar changes to our cropping systems as we face future changes in our climate and an increased need for using resources efficiently.

Eighty to ninety percent of our food is produced on large-scale farms, usually operated by family entities. To ensure the greatest advances in productivity, environmental sustainability, and profitability, new crop management information and technology systems need to be adopted for farms of various scales. Such innovations should encourage integrated pest management and water and soil conservation in ways that are practical and convenient for large-scale farms. There are several tools that can make this possible, such as remote sensing and other off-site monitoring. The synergy between variety development and crop management research has been responsible for yield gains of the last 50 yr. The interplay between genetics (e.g., variety) and environment (e.g., cropping systems) must be continually optimized to produce food, feed, fiber, and fuel for the United States.

### *Key Questions*

1. How can we adapt the latest information on pest, crop, and soil management strategies to develop applications that are convenient and profitable in both small- and large-scale crop production systems?
2. Can crop growth simulation models and remote sensing be useful for advising mitigation strategies and be accurately parameterized for climate change factors, species, cultivar, soils, and management effects on crop growth and yield?
3. How do we best define complex, multilevel interactions involved in a full system analysis of producing food, feed, and raw materials for a specific ecological or market niche?
4. Can powerful applications be developed using massive multilayer data sets—including yield history and genetic, soil, and weather data—to create practical decision-making tools to enhance crop productivity, environmental sustainability, and management convenience for growers?
5. How can crop residue management be optimized in ways that balance crop productivity and water, soil, and energy conservation with consideration of C policy?

### *Expected Outcomes*

1. Crop management strategies that simultaneously improve multiple factors within cropping systems and allow sustained crop production under climate stress.
2. Cropping systems that conserve and protect soil resources, increase crop enterprise diversity, improve input efficiency, and increase production.
3. Practical and timely information delivery tools to help farmers make field-level management decisions with increased convenience and profitability.

## Grand Challenge: Biofuels

**Develop sustainable biofuel feedstock cropping systems that require minimal land area, optimize production, and improve the environment**

### *Background*

The role of crop plants as feedstock for biofuel production will increase in the coming years. Crops are a source of sugar, starch, and cellulose that can be converted to ethanol and seed oil that can be converted to biodiesel. All bioenergy crops will need to be grown in a way that optimizes biomass yield while minimizing inputs of fertilizer, irrigation, and pesticides.

It is important to minimize the competition between biofuel crops and human food crops. Therefore, in the future, ethanol-based biofuel crops probably will be nonfood crops grown on land that is marginal for other crop production. Since biodiesel is the product of seed oil, this biofuel must be produced using existing seed crops. Therefore biodiesel research needs to concentrate on oil seed crops that are less used for feedstock but very productive, such as peanut (*Arachis hypogaea* L.). The composition of biofuel crops will need to be modified to make them easy to convert for energy use, but these modifications may make them more vulnerable to stresses and pests. As a result, there is a need

- to modify crop compositions according to processing requirements,
- to increase yield in low-input production systems,
- to understand plant response to changes in the environment, in tandem with changes to composition for accurate modification,
- to understand the ecosystem services (C sequestration, water quality, wildlife habitat, etc.) from perennial bioenergy crop production on arable and marginal lands, and
- to develop new production systems that thrive in low-input situations.

### *Key Questions*

1. What genetic improvements to the composition and field productivity of biofuel feedstock crops optimize conversion processes while also improving production efficiency?

2. What steps do we need to take to develop or tailor biofuel feedstock cropping systems appropriate to diverse agroecosystems?
3. What crop management strategies can we develop and use to increase soil C, minimize production inputs, and ultimately increase economic return for the grower?
4. How do we optimize use of N-fixing plants into bioenergy cropping systems?
5. What biomass biofuel crops and cropping systems can be developed that are highly productive and reduce the total land area required to meet demand?

### Expected Outcomes

1. Reduced dependence on fossil fuels by providing sustainable renewable energy alternatives.
2. Increased number of crops and cultivars that have proven metrics for productivity and high fuel conversion efficiency rates.
3. Low-input management systems for the production of biofuel crops in diverse ecosystems.
4. Strategies to meet increasing global demand for food, feed, fiber, and fuel on a decreasing land base with fewer inputs.
5. Increased profitability for producers of bioenergy feedstocks.

## Grand Challenge: Bioresources

**Genotyping the major crop germplasm collections to facilitate identification of gene treasures for breeding and genetics research and deployment of superior genes into adapted germplasm around the globe**

### Background

Germplasm collections are a wonderful treasure trove of genetic diversity and the foundation for all crop improvement programs. A germplasm collection for a single crop species may contain more than 50,000 distinct genetic plant types, yet the genomic profiles are not readily available, limiting application of information contained in the collections. However, new inexpensive technologies offer a low-cost remedy for developing detailed genetic profiles to entire collections. As a result, new genomics information will enhance our ability to correlate a plant's genotype with its agricultural performance for plant breeding purposes in a way never before possible.

To translate the economically important diversity of germplasm collections into food and other agricultural products, it is critical that we integrate this new genomics information with a series of field-breeding positions specifically targeted at "mining" germplasm collections. Field breeders will use hybridization and selection, informed by genomics, to produce novel, agronomically important genetic types that work effectively in agriculture. As a result, development of crops will be accelerated to avoid famines and market-place catastrophes resulting from fluctuations in rainfall, diseases, and pests, therefore enabling greater food security in the United States and around the world.

### Key Questions

1. Can we develop a system and the resources to use high-throughput gene chip technology to create genetic profiles of individual entries within germplasm bank collections of major crops?
2. What information management systems and related protocols can we develop that enable breeders, geneticists, and biological information technologists to understand, access, and effectively use extensive DNA marker profiles for germplasm collections of major crops?
3. Can we capitalize on the value of novel gene discoveries by developing crop-specific molecular markers to facilitate rapid cultivar improvement?
4. Can improved methods for establishing genotype–phenotype relationships be developed for vital genes in all major crops?
5. Can genetic manipulation techniques and new genetic tools be customized for each major crop and incorporated into plant breeding practices (e.g., doubled haploidy, transformation, marker-assisted breeding strategies, and genome-wide selection) to accelerate the time to field evaluation stage?
6. Can the capabilities and capacities of regional and international research centers be enhanced to expedite new cultivar releases?
7. Can we create a new cadre of plant scientists and field-oriented plant breeding positions specifically targeted at "mining" the genetic diversity found in germplasm collections and integrating new genomics information above to produce novel agronomically important breeding materials?

### Expected Outcomes

1. Intelligent sampling strategies for gene mining within germplasm collections to expand the dangerously narrow genetic base of our major crops.
2. Higher crop yields through multiple, creative strategies using many genes from different sources for controlling diseases, combating insects, and minimizing climate stresses.
3. Enhanced food security, greater research efficiency, and production stability.
4. Efficient and sustained translation of products from gene discovery to agronomically adapted breeding materials for farmers' fields to proactively address shifts in pest dynamics and climate.

## INFORMING SCIENCE POLICY WITH THE CSSA GRAND CHALLENGES

Quickly after the release of their initial grand challenges booklet, CSSA submitted all six of the grand challenges to the U.S. Office of Science and Technology Policy, in response to their request for information (RFI) on the "grand challenges for the 21st century." In the resulting *Strategy for American Innovation*, released exactly 1 yr after the RFI, there was little mention of specific disciplines. The document focused rather on the broader issues underlying science education and workforce development, global competition for the skilled labor force, and U.S. economic stimulation.

The grand challenges document enabled CSSA to present a solid vision of the role of crop science in addressing the key societal challenge areas. The challenges have been used to communicate CSSA's priorities to the USDA, USDOE, and Agency for International Development as well as to the National Science Foundation, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration. Interagency efforts such as the Biomass Research and Development Technical Advisory Committee, which may have the capacity to drive research priorities, also were made aware of the CSSA grand challenges through the assistance of CSSA members. The U.S. Agency for International Development requested a copy of the CSSA grand challenges to help identify grand challenges appropriate to developing countries. As a result, the CSSA grand challenges project has been a great success; it has strengthened CSSA's voice when providing input to government agencies for their priority-setting activities and has provided a platform to launch discussions about maintaining and growing investments in research and development in crop science.

Even so, the process is not complete and it should be recognized that the process was intended, from the outset, to be dynamic. The CSSA believes that it is important to continue to revise prior grand challenges and develop new ones while also refining the development process. In the coming year, a new committee will be formed to assess the progress made on the current CSSA grand challenges and to identify new areas in which crop science can influence and induce solutions to challenging issues.

For the next process, CSSA will probably focus more on the impact that crop science can provide, not only to solving global challenges but also to providing new economic opportunities related to these solutions. The recent recession, along with increased globalization, has provided a clearer understanding of the need to remain competitive and the role that science in general will play in our economic future. With a greater emphasis on workforce and economic sector returns on investment, the essential information provided in the CSSA grand challenges will be buttressed by the potential that these sectors have to increase economic vitality. The key questions and related expected outcomes will, in effect, provide greater incentives for investment in research and education.

## CONCLUSIONS

These challenges, developed through a society-wide process, represent priority areas that have the potential to dramatically shape the future of humankind. They address fundamental issues that underlie basic human needs, including the availability of sufficient, consistent, and nutritious food, protection of the environment, and sustainability of natural resources. Furthermore, the CSSA grand challenges highlight advances needed to maintain a robust global economy. The full capacities of crop science and allied scientific communities will need to be marshaled to meet these challenges; however, success will be realized only if adequate resources are made available to public and private researchers. Because crop science provides systems and technologies fundamental to a vibrant society, these grand challenge statements can be leveraged to prioritize funding for these immensely important issues. As we foresee a growing population with unprecedented demands on our environment and natural resources, it is our goal to underscore the urgent task at hand and foster a dialog that will ultimately provision the resources needed for timely solutions.

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