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Strategic research, education and policy goals for seed science and crop improvement

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ABSTRACT

Genetically improved varieties and their delivery through high quality seeds have been essential contributors to yield increases that have allowed crop production to keep pace with population growth. However, as global population continues to expand and economies improve, crop production will need to double again by 2050 to meet demand. To do this without markedly expanding cultivated area will require new breakthroughs in plant breeding. This article, based upon a consensus developed at a broadly based American Seed Research Summit in 2008, identifies critical research topics, educational priorities and policy issues that were considered essential to this effort. Research targets focus on germplasm conservation and characterization, seed production and quality, fundamental genetic mechanisms, advanced breeding strategies, and knowledge systems to manage data and information to support development of crops with improved resource use efficiency and stress tolerance. A diverse pool of high quality plant breeders and researchers must be educated to carry out this work. An effective and efficient regulatory system should support innovation in variety improvement by balancing risks and benefits. Public–private partnerships are a key component of achieving these goals.

1. Introduction

The remarkable increases in food production that resulted from the Green Revolution advances in crop varieties and production systems, led by genetic improvements in wheat, rice and maize, as well as application of fertilizer, irrigation and pest control, allowed food supplies to keep pace with population growth from the 1960s until recently with minimal increases in planted area [1] (Fig. 1). In addition, the yield gains in agriculture since 1961 have avoided carbon emissions equivalent to 34% of the total released by humans between 1850 and 2005, largely by limiting conversion of additional land to cultivation [2]. However, a historic combination of factors, including food shortages and price increases in 2007 and 2008 followed by an economic crisis, has emphasized the vulnerability of our global agricultural production systems [3,4]. During 2007, localized crop failures, exacerbated by protectionist market responses, resulted in food shortages and 50–70% increases in grain prices [5,6]. The global economic downturn exacerbated these problems, with high domestic food prices, lower incomes and increasing unemployment resulting in over 1 billion undernourished people worldwide in 2009 [3]. Continued population growth and the expectations of millions of people in rapidly developing countries for economic advancement have elevated global demand for food, feed, fiber and fuel. As the world population is predicted to increase 34% by 2050 and become further urbanized, food production must increase by 70% to feed the larger and richer population [7].

Achieving these increases in productivity will need to occur largely through elevating yields per unit area, as the best agricultural lands are already in use and expanding to additional lower quality areas faces both environmental and resource (e.g., water) availability constraints [2,8]. In the past, increasing yields were dependent upon comparable increases in inputs, particularly fertilizer, irrigation and pest control. However, while many parts of the world can still benefit from additional resource inputs, particularly sub-Saharan Africa [9], the primary challenge in the developed countries is to maintain the rate of yield growth while reducing total resource inputs (particularly fertilizers and fuel) due to their scarcity, cost or environmental impacts [10]. These challenges must be met in the face of anticipated global climate changes that are predicted to have an overall negative impact on agricultural productivity [11]. An overriding social and scientific issue for the coming decades is how to meet the increasing demand for agricultural products in a sustainable manner while reducing inputs. Yet, with fewer people directly engaged in farming (e.g., less than 2%

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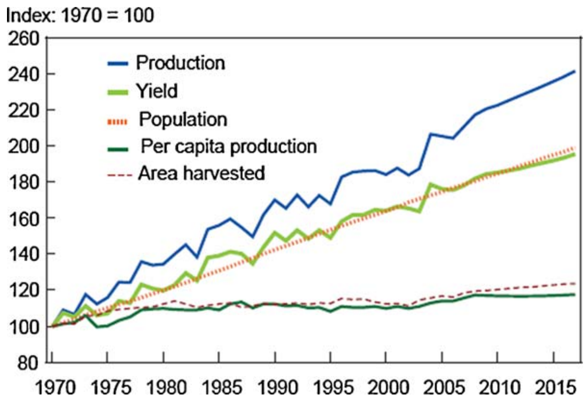

Fig. 1. Total world grain and oilseeds production, 1970–2017. Production and yield of global grains and oilseeds (soybeans, rapeseed, and sunflowers) have continued to increase at similar rates to the world population from 1970 through recent projections to 2017. This has maintained the per capita production of food and total area harvested virtually flat over the past 30 years. However, the rate of growth in productivity is on the decline, averaging 2.0% per year between 1970 and 1990 and only 1.1% between 1990 and 2007.

Figure reproduced with permission from "Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices" [5].

of the U.S. population), and the seed sector *per se* representing and even smaller fraction of agriculture (e.g., less than 5% of the total crop value in the U.S.) [12,13], few outside of the agricultural community are aware of the critical importance of continued genetic improvement of crops and distribution of new varieties via seeds to meet the global demands for food, feed, fiber and fuel.

A key input into increased productivity is the genetic improvement of crop plants. Overall, it is estimated that at least half of the yield increases attained in wheat and rice between the 1960s and 1990s was due to the utilization of genetically improved varieties [14,15]. Continuous improvement of crop varieties has supported the steady increase in crop yields over the past several decades (Fig. 2). The impact of improved breeding methods is evident in the changes in the slopes of these yield curves upon the introduction of hybrids in corn, for example (Fig. 2). Further yield increases (or reductions in inputs) have resulted from the application of biotechnology to engineer varieties with resistance to herbicides or insects [16]. Advances in genomics and DNA marker technologies have enabled marker-assisted breeding strategies that can reduce the time and expense associated with development of improved varieties [17,18]. Together, the integration of these technologies has revolutionized plant breeding in the past decade, making it feasible for some seed companies to set lofty goals such as to double corn, soybean and cotton yields per hectare by 2030 while using one-third less inputs [19].

Research and development in plant breeding are conducted in both public and private institutions. Universities conduct basic genetic and genomic research and many maintain plant breeding programs, although the latter are declining in number. Government research organizations, such as the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) and its counterparts in other countries, as well as international organizations like the Consultative Group on International Agricultural Research (CGIAR) also conduct fundamental research and develop germplasm and varieties for public release. While 95% of agricultural research and development expenditures in developing countries are from public sources, over half, or $35 billion annually, of R&D expenditures in North America and Europe are from private firms that breed and sell improved plant varieties [20]. While plants can be propagated both vegetatively (i.e., by tubers, cuttings or grafting) and by seeds, the majority of crop acreage is planted to annual crops that are replanted each year by seed. Thus, the largest fraction of private investment in variety development is in the seed industry, which is involved in crop variety development and in seed production, distribution and marketing. The seed industry is therefore a primary developer and user of plant breeding technology to create varieties that can yield more while requiring fewer inputs. In addition, seeds can serve as the delivery system not only for improved genetics, but also for new planting and production methods and crop protection strategies that improve overall agricultural efficiency [21–23].

Recent studies have concluded that expanded investment in agricultural research is critical for meeting the challenge of sustainably increasing global crop productivity [3,9,24,25]. Since breeding and seed production are central to this effort, an American Seed Research Summit was held in September 2008 to identify and prioritize a seed research agenda for the next decade. The workshop was sponsored by the American Seed Trade Association (ASTA), the American Seed Research Foundation (ASRF) and the National Council of Commercial Plant Breeders (NCCPB), with the support of the Seed Biotechnology Center at the University of California, Davis and the USDA Cooperative State Research, Education and Extension Service (CSREES). Scientific leaders from industry, government and academia (participant list is available at www.amseed.com/meeting_asrf_summit.asp) discussed the scientific goals and policy issues that should be addressed to enable continued advances in plant breeding and seed production. Key goals and strategies for accomplishing these priorities were identified and paired with specific action items to move these agendas forward. As most participants were from the U.S., the policy issues reflect a bias toward the situation in that country. However, the U.S. domestic seed market represents over 25% of the global seed value, and U.S. seed exports are 16% of total global exports [26], so developments in the U.S. have significant international impact. While not claiming to represent all stakeholders in agriculture, a conscious effort was made to balance different constituencies and crops in order to reach a broad consensus on the most pressing issues in seed research and policy that should be addressed to allow the agricultural system to meet future demands in a sustainable manner. Here we describe the consensus research and policy goals that were identified at this Summit.

2. Research, education and policy goals and strategies

2.1. Research goals and strategies

A broad agenda of research goals that were identified at the Summit will be briefly described below; additional detail on the scientific goals is included in Table 1. These goals were not specifically prioritized, as all were judged to be important.

- *Conserve, characterize and utilize novel germplasm*. As advances in breeding are dependent upon genetic diversity, preserving and characterizing existing germplasm resources and expanding collections are essential to future crop improvement [27]. Changing agricultural practices, including adoption of improved varieties, can result in loss of genetic diversity that exists in native landraces [28]. Both *in situ* and *ex situ* conservation must be encouraged as well as genotypic and phenotypic characterization of the diversity present [29].
- *Understand basic genetic mechanisms*. Genetics, genomics and molecular cytology have the potential to uncover important gene functions underlying phenotypic traits. A better understanding of the fundamental mechanisms of heredity, including meiosis, recombination and heterosis, will support more efficient and directed breeding strategies [30–32]. Mechanisms related to transgenic technologies also need to be studied in detail,

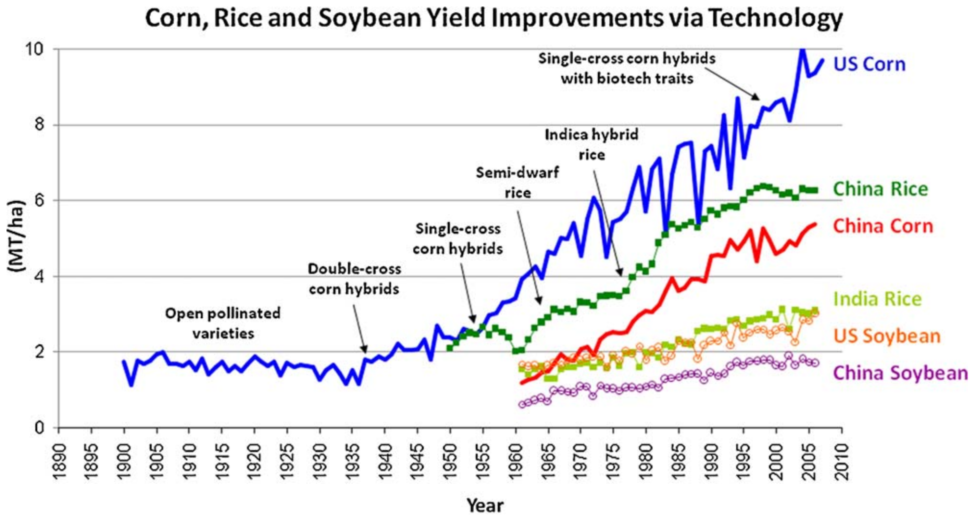

Fig. 2. Historical trends in production yields (metric tons per hectare) of corn, rice and soybeans in the U.S., China and India. The approximate dates of introduction of important plant breeding improvements are noted.

Graph prepared by Bill Niebur [DuPont/Pioneer] from data of USDA, International Rice Research Institute, and the Food and Agriculture Organization of the United Nations.

Table 1
Research priorities and scientific or policy goals identified at the American Seed Research Summit (not in prioritized order).

Research priority	Scientific or policy goals
Conserve, characterize and utilize novel germplasm	Conserve and curate existing germplasm resources and expand collections Characterize germplasm resources genotypically and phenotypically Preserve biodiversity in both agricultural and natural environments Utilize genetic diversity for improved productivity and yield stability
Understand basic genetic mechanisms	Determine how to manage and direct genetic recombination Determine the basis of heterosis and combining ability Develop site-directed transgene insertion methods Identify the determinants of gene expression efficiency Develop gene switches for controlling trait expression Design safe and efficient platforms for protein production in seeds
Develop efficient, high-throughput analysis systems	Develop systems for high-throughput phenotyping of multiple traits Develop molecular markers and high density genetic maps Develop efficient and high-throughput marker analysis systems Integrate phenotypic and genotypic databases and analyses
Create knowledge from information	Improve systems for management and analysis of large data sets Apply intelligent information technology and systems analysis to genetic analyses Develop standardized formats for distribution of information Create interactive / interoperable databases Develop and utilize simulation models of biological systems
Manage complex traits, including quantitative traits	Analyze the genetic basis for complex, multi-gene traits Determine modes of action of genes and physiological processes in producing phenotypic traits Analyze regulatory mechanisms for gene expression and metabolic networks Control plant architecture to increase productivity
Decipher the genetic basis of plant environmental responses	Identify and improve plant responses to abiotic stresses (drought, heat, cold, nutrients, etc.) Identify and improve plant responses to biotic stresses (insects, pathogens, nematodes, etc.) Analyze the basis of genotype by environment by trait interactions
Increase plant efficiency and quality	Identify traits and methods to reduce inputs (water, nutrients, energy) while maintaining productivity Increase nutritional content and/or product quality for end uses Increase "value density" of products per unit of production area Enhance sustainability and reduce ecological impacts of the complete agricultural system
Improve seed health, quality and performance	Develop and implement production methods that maintain seed health and eliminate pathogens Analyze the effects of new traits on seed physiology and quality Develop new seed technologies for improved performance Utilize seeds as multi-purpose delivery systems for diverse technologies Investigate mechanisms of seed deterioration to improve seed longevity and germplasm conservation
Develop cost-efficient risk analysis systems for products of new technologies	Regulate traits on the basis of actual risk, not due to the breeding methods employed Standardize regulatory data and analysis requirements Understand the social science of consumer issues regarding agricultural technologies Standardize relevant indices of sustainability

including plant transformation, site-directed insertion, artificial minichromosomes, gene expression efficiency, epigenetics, controllable gene switches and design-driven genetic engineering platforms [33–36].

- *Develop efficient high-throughput phenotyping and genotyping systems*. The ability to genotype multiple genetic markers in parallel has increased exponentially in recent years, making the efficiency with which samples can be collected and prepared more limiting than the analyses themselves. While new techniques are being developed for elucidating the genotype to phenotype relationships, particularly through utilization of quantitative trait locus mapping, phenotypic characterization for trait evaluation is increasingly the limiting factor as larger numbers of traits need to be analyzed simultaneously [37,38]. High-throughput phenotyping systems were identified as a critical need to take advantage of current and anticipated genotyping capacity. The integration of phenotypic and genotypic databases and analyses was also identified as a key enabling research area.
- *Create knowledge from information*. Plant breeders are facing a flood of genotypic and phenotypic information that must be analyzed and converted into usable knowledge, often on very short time scales. Intelligent systems, interactive databases and simulation modeling are all needed to efficiently extract actionable knowledge from large datasets [39,40].
- *Manage complex multi-gene traits*. Many agronomic traits are determined by multiple genes in a quantitative manner and must be managed simultaneously to achieve the full benefit. Better methods to manage multigenic traits in breeding programs and a better understanding of the gene expression and metabolic networks underlying the physiological processes that result in phenotypic traits are needed [41,42]. The ability to manage complex traits would enable enhanced utilization of quantitative traits and modification of plant architecture to increase productivity.
- *Decipher the genetic basis of plant environmental responses*. Environmental stresses, both biotic and abiotic, often constrain yields below their potential. Increased knowledge of plant responses to abiotic (drought, heat, cold, nutrients) [43] and biotic (insects, pathogens, nematodes) [44–47] stresses can be used to preserve or enhance yield in the face of environmental stress and climate change. More generally, genotype-by-environment interactions are the norm in plant breeding; understanding the basis for these interactions would allow development of varieties with greater yield stability across environmental variation [48].
- *Increase plant efficiency and quality*. Resource use efficiency is a key component of both productivity and sustainability. Improving the inherent efficiency of photosynthesis or of nutrient acquisition would increase potential yield limits without increasing inputs [49]. Developing plants that can maintain yield with reduced inputs (e.g., water, fertilizer, pest control) will enhance sustainability and limit ecological impacts [50]. Similarly, increasing end-product utility or nutritional quality will result in greater usable product or nutrition per unit of production [51,52].
- *Improve seed health, quality and performance*. Seeds are the delivery system for multiple technologies applied through breeding and through seed enhancement technologies [53]. Research is needed on seed production, processing, storage and enhancement methods to produce and market high quality, disease-free seeds [21,54].

This is an ambitious but necessary research agenda that will provide the knowledge and tools needed to breed crops for higher yields, quality, resource efficiency and stress tolerance and to deliver high quality seeds with these improved traits to farmers.

2.1.1. Engage diverse stakeholders to support stable funding for seed and breeding research

The ambitious research agenda outlined above cannot be accomplished without substantial and stable financial support. The plant genomics and plant sciences programs in the U.S. at both the National Science Foundation (NSF) (www.nsf.gov) and USDA (www.csrees.usda.gov) are critically important sources of public research support. However, the total investment in competitive peer-reviewed plant biology research of all types in the U.S. is less than $1 billion per year, roughly 30-fold less than for research programs focused on human health [55]. In addition, the relatively limited funds available and the highly competitive nature of those programs means that many worthy scientists and projects go unfunded, particularly those focused on practical plant breeding and seed quality.

As plant genetics and breeding are long-term enterprises requiring dedicated expertise and infrastructure, substantial and stable funding sources are needed to support public research and germplasm development programs. For example, the U.S. federal research system represents an ideal locus for large-scale coordinated investments in crop research infrastructure across state and regional boundaries that can link frontier genomic analyses with large scale evaluations of field performance in characterized environments. A positive recent development is a partnership between NSF and the Bill and Melinda Gates Foundation to boost agricultural productivity in developing countries, with each program providing $24 million over 5 years to support competitive research [56]. In addition, the Alliance for a Green Revolution in Africa (AGRA) is investing $150 million through its Program for Africa's Seed Systems to improve the availability, variety and quality of seeds for African farmers [57]. While still relatively short term, these programs have the potential to engage new partners in the development of seed systems for rural farmers and lead to more stable sources of support.

Internationally, the CGIAR institutes have been engaged in public seed and breeding research for the last four decades. The CGIAR functions as a strategic partnership of 64 members and 15 international Centers to foster germplasm conservation and improvement for sustainable agriculture (www.cgiar.org). While the CGIAR expenditures of $572 million in 2009 were the largest investment worldwide to utilize science to benefit the rural poor [58], the average annual net investment to deliver the necessary production increases in developing countries is estimated to be $83 billion [7]. Furthermore, for every $1 invested in research, approximately $9 worth of additional food is produced within developing countries, and economic studies consistently show high societal returns on agricultural research expenditures [25,59]. However, donor support for the CGIAR system is in crisis and core funding levels have faltered, particularly from the U.S. and Japan, resulting in decreased support for productivity-enhancing agricultural research of 6.5% annually in real terms between 1992 and 2001 [60]. In 2009, CGIAR began a process to embrace change through a new strategic framework to enhance their consortium of Centers and address funding issues by leveraging existing strengths and capacities through new collaborations. As one example, CGIAR centers could address the need for a series of coordinately managed field sites providing high-throughput phenotyping and genotyping capacities together with infrastructure for precise characterization of environmental variables. The CGIAR, together with the private sector, government and academic research communities, have a unique opportunity now to design a comprehensive approach to enhance global crop improvement efficiency and productivity.

Stakeholders in the private seed and breeding industry are exploring new ways to support public research and its infrastructure both directly through collaborative partnerships and indirectly by expanding public research funding programs. These stakeholders and their counterparts in public research institutions share the objective of creating stable funding mechanisms to invigorate and sustain seed biology and plant breeding research. A unified and coordinated message from the seed industry and public seed and breeding researchers, in conjunction with a compelling economic justification, can generate support for seed research in the broad sense as an essential investment to meet growing societal demands on agriculture.

2.1.2. Strengthen public and private partnerships to accomplish seed research priorities

As the issues facing us are not confined to either the public or the private sector, the answers will require partnerships and collaboration for success. The private sector relies on fundamental research and proof-of-concept demonstrations of feasibility from the public sector, and the public sector expects their discoveries to be expanded and implemented commercially by the private sector. Issues such as intellectual property, competition and privacy can complicate public–private interactions, but effective partnerships between the two sectors have proven to be highly synergistic [61]. With a set of unified priorities (above) and new models for cooperation and collaboration, the strengths of both sectors can be brought to bear on the significant challenges we face.

Pre-competitive research in the public sector, jointly funded in some cases by private resources, can "lift all boats" and provide tools and resources for accelerating plant breeding improvements. Mechanisms are needed to allow the significant private investments in fundamental research, such as genome sequences and genetic maps, to be available to public researchers. Cost-sharing programs, with public funds matching private investments in public research, are excellent models for encouraging direct public/private research collaborations [62]. A number of public sources of research funding now require matches from private industry or commodity groups, making private partnerships even more critical for public research. Creating a shared vision that supports systemic change increases the opportunities for success. These new approaches need to focus on leveraging the potential for synergy between the collaborators and set the foundation early in the arrangement to manage the risks and dangers that are of greatest concern [63]. A number of such public/private partnerships are tackling the challenge of improving crops specifically for Africa and other developing countries, such as the Drought Tolerant Maize for Africa (http://dtma.cimmyt.org), Water Efficient Maize for Africa (http://aatf-africa.org), Africa Biofortified Sorghum (http://biosorghum.org), BioCassava Plus (http://biocassavaplus.org) and Golden Rice (www.goldenrice.org) projects.

2.2. Education goals

2.2.1. Attract and develop a pool of diverse, high quality plant researchers

The science of plant breeding has been revolutionized in the past decade due to the integration of genomics and molecular markers into "classical" genetics and selection programs. However, capitalizing on this opportunity will require a continuous supply of educated and motivated plant scientists at a time when companies throughout the agricultural sector are having difficulty filling open positions. The number of agricultural universities with strong plant breeding programs is declining [64,65] even as demand for plant breeders, agronomists, pest control advisors and plant scientists is increasing [20,66]. We must ensure that the global plant breeding enterprise has a robust infrastructure for the education and training of plant researchers.

A key starting point is the development of workforce needs assessments for the agronomic, seed and plant breeding industries. Through the support of the Global Partnership Initiative for Plant Breeding Capacity Building (GIPB), national consultants from 74 developing nations or regions completed plant breeding and related biotechnology capacity surveys of their countries. These reports each summarize the current agricultural systems with an emphasis on plant breeding and biotechnologies [67]. For example, an analysis of capacity building opportunities in Africa found that in nearly all countries there is less financial support for breeding programs than there was in 1985 and that education of breeders is insufficient to allow them to carry out effective breeding programs [68]. Similar assessments for developed nations can also illustrate the diverse skills and talents in demand in this field, thus improving the professional appeal of plant sciences [66].

Diverse agricultural industries are anticipating a large cohort of retirements in the next decade, and are uncertain where their replacements will be found. In the U.S., an estimated 2130 plant breeders were employed in 2001 (75% in private industry) [20], and it has been projected that at least 110 breeders per year will be needed to replace retiring professionals and provide for the growth of the breeding industry [69]. Ironically, the success of private plant breeding programs, along with research emphasis on fundamental genetics and genomics at public institutions, has resulted in fewer university positions in plant breeding and loss of many public plant breeding programs [66]. Novel approaches, such as establishment of Centers of Excellence in plant breeding at public institutions and increased incentives for students, are needed to replenish the pool of high quality plant researchers to meet the current demands and establish a pipeline for the future. A promising sign is the recent funding of competitive grants focused on Plant Breeding and Education through the USDA, which also include outreach components targeted toward recruiting young people into plant science and breeding. Professional education programs such as the UC Davis Plant Breeding Academy (http://pba.ucdavis.edu) and similar programs at other institutions that educate professionals in the seed industry for positions in modern breeding programs can be expanded regionally and nationally.

In the U.S., the Plant Breeding Coordinating Committee (http://cuke.hort.ncsu.edu/gpb/pr/pbccmain.html), the National Association of Plant Breeders (www.plantbreeding.org) and the National Council of Commercial Plant Breeders (www.nccpb.org) are committed to increasing excellence in training and education programs for breeders. The infrastructure of the USDA-ARS and similar national agricultural research systems represents a rich training environment that is vastly under-utilized in educating the next generation of agricultural researchers. From student internships to graduate and post-graduate training to sabbatical and research exchanges, the historic divisions between "education" as a strictly academic endeavor and "research" as a governmental responsibility should be reduced. On an international scale, the GIPB partners with national programs to support agricultural research to create stronger and more effective plant genetic resources for development (http://km.fao.org/gipb).

The scientific and professional opportunities in plant sciences in general and plant breeding in particular need to be better communicated to prospective students along with expanded opportunities and funding for pursuing advanced degrees. Internships in the seed industry and graduate level assistantships supported by the industry not only provide additional educational opportunities to students, but also are incentives to attract high quality people to the field. Several programs have been initiated in recent years by the private sector to promote graduate education in plant breeding. For instance, a number of institutions throughout the U.S. (e.g., University of Wisconsin, University of Illinois, North Carolina State University, Texas A&M) have benefited from private company gifts primarily to support graduate student stipends. In addition, the Monsanto Beachell-Borlaug International Scholars Program, which has pledged $10 million in funding, selected its first recipients in 2009 for student fellowships pursuing doctorate degrees in plant breeding disciplines [70]. In the first 2 years of the program, a total of 24 fellowships have been awarded with recipients representing 17 countries. Often these fellowships and assistantships also support complementary experiences such as international engagement, industry internships and cross-institution conferences focused on current topics and issues of relevance. In addition, the African Center for Crop Improvement, in partnership with AGRA and the University of Ghana, offers prestigious scholarships to young African scientists training as plant breeders [71]. This program aims to train 120 Ph.D. plant breeders within 10 years through a $13 million grant, helping to create the critical mass of breeders needed to address the food crisis in Africa. AGRA is also providing $4.5 million over 3 years to the Seed Science Center at Iowa State University, the International Maize and Wheat Improvement Center and private business experts to establish a Seed Enterprise Management Institute in cooperation with the University of Nairobi in Kabete, Kenya [72]. These and other similar programs are essential to expanding educational opportunities for training plant scientists if we are to successfully double food production in the coming decades.

2.2.2. Develop an education and advocacy program to communicate the value of seed and crop research to the public

Citizens receive multiple benefits from seed and crop research, including new products, lower food prices, agricultural sustainability and ecosystem services. Crop genetic improvement and distribution via seeds are the original “green” technologies. Between 1992 and 2002, U.S. crop output value increased by 26%, while the land area used for crop production actually decreased slightly [13]. Similarly, further increments in productivity will come largely from crops that are more efficient in using resources such as sunlight, water and nutrients, rather than from expanding agricultural land use.

Seeds are the wellspring of products to nurture both the body and the spirit, yet plant breeding in general and the seed industry in particular are often portrayed as part of the problem rather than the source of solutions to enable a sustainable future. The advantages of and potential for increasing agricultural productivity via crop genetic improvement must be better communicated to the public and to policymakers through more active outreach and advocacy programs by both public and private stakeholders. Scientists should be enabled to utilize our best knowledge and technology in the service of agriculture and of society in general.

2.3. Policy goals

2.3.1. Develop an effective and efficient regulatory system to support innovation in variety improvement

Recombinant DNA technology (genetic engineering) has enabled the development of crops with increased productivity while reducing pesticide and fuel use and providing a range of environmental and economic benefits. In the first 12 years since genetically engineered crops were introduced on a wide scale, an estimated $44.1 billion in economic benefits were realized by farmers around the world [16]. This is based almost entirely upon only two categories of traits thus far, herbicide tolerance and insect resistance. New products in the developmental pipeline will expand on the current range of traits, at least for crops in which transgenic varieties are available [73]. New traits such as improved nitrogen use efficiency and drought tolerance promise to shift productivity/input ratios positively, assuming they are allowed to be commercialized. However, the current U.S. and particularly E.U. and international (e.g., Cartagena Protocol) regulatory systems severely limit the pace at which new genetically engineered traits can be introduced into commercial use, or in fact prevent their introduction entirely for most crops and many locations [74,75]. The high cost of satisfying biotechnology regulatory requirements is prohibitive for most specialty crops [76,77], restricting the commercial availability of this powerful technology to a few commodity crops such as cotton, maize, soybean and canola. In addition, high regulatory hurdles reduce or eliminate opportunities for small companies and public institutions to commercialize products that might appeal directly to consumers or address humanitarian needs. The lost opportunity costs and reduced innovations due to underutilization of modern biotechnology methods in variety development are significant, particularly in light of the documented benefits of these products [78–81]. Thus, Summit participants proposed a policy goal to develop cost-efficient benefit/risk analysis systems for products of new technologies (Table 1).

Several programs have been developed to ensure the safety and quality management of modern agricultural innovations. The Excellence Through Stewardship program of the Biotechnology Industry Organization (BIO) is an industry-coordinated effort to enhance the management of agricultural biotechnology from development through commercialization (www.excellencethroughstewardship.org). It provides guidelines for the adoption of stewardship principles as well as third-party audits of quality management practices. The U.S. Biotechnology Regulatory Service is similarly offering a Biotechnology Quality Management System and audit program to facilitate compliance with regulatory guidelines (www.aphis.usda.gov/biotechnology/news_bqms.shtml). A collaborative, public–private effort to assist developers of biotechnology-derived specialty crops, the Specialty Crops Regulatory Assistance (SCRA) program, seeks to increase market access for a wider diversity of crops and traits (www.specialtycropassistance.org). Most critically, establishment of pragmatic thresholds for low level presence of engineered genes across all markets would largely prevent economic disruption without compromising safety [74]. Regulators, the seed research community and diverse stakeholders must work together to streamline the regulatory system and harmonize it internationally while assuring the appropriate level of oversight.

3. Conclusions

Continual increases in agricultural productivity and sustainability are essential to feed the growing world population, which is anticipated to include over 9 billion people by 2050 [82]. However, productivity growth has slowed since the mid-1990s and food prices have increased sharply [5], contributing to a rapid rise in food insecurity [3]. Reductions in public investment in agricultural research have raised questions regarding the prospects for agricultural productivity growth in the future [25]. The American Seed Research Summit focused on identifying key research topics, educational programs and policy issues that would enable future progress in crop improvement to help keep pace with population growth while preserving the environment. Dedication, persistence and partnership between public and private stakeholders will be required to ensure that the resources needed to accomplish this goal are available in the coming decades. Scientific developments in the past 25 years have outlined clear paths for accelerating the pace of crop improvement to meet the dual demands of growing populations and rising standards of living. Through continued research and development, plant scientists and breeders can envision ways to achieve dramatic improvements in crop productivity and quality while reducing overall inputs and promoting sustainability. The question is not whether these achievements are possible, but rather whether the financial and human resources will be available to achieve that vision, and whether society will allow the full application of current knowledge and technology to the task.

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