Enhancing pulse productivity on problem soils by smallholder farmers: Challenges and opportunities

Workshop held August 14-18, 2011 at Penn State

Executive Summary

Pulses and other food legumes have traditionally been a source of high quality protein and micronutrients for poor people and are an important source of women's income in many low income countries. The Green Revolution in cereal grains has reduced the price of cereals dramatically since the 1970s but the absence of similar productivity gains in food legumes has increasingly put these high-protein foods out of reach for low-income consumers. The only sustainable, economic way to reverse this situation is to substantially increase the productivity of pulses and other food legumes through a focused, coherent research program directed at building the knowledge base for sustainable productivity gains. This document summarizes the deliberations of a three-day workshop in which 50 scientists considered the most effective avenues to attain substantial, sustainable gains in the productivity of pulses, by addressing edaphic and climatic constraints with a multidisciplinary approach of genetic improvement, phenomics, biological nitrogen fixation (BNF), and systems analysis and management.

1) Genetic Improvement

1a) Goals and potentials: Seed-based technologies have been at the heart of many of the innovations that have revolutionized agricultural production systems globally. Modern genetic technologies have created opportunities that were unimaginable a generation ago when the Green Revolution first addressed the issue of food security in the developing world. These technologies have rapidly evolved, and biology now stands at the threshold of the ultimate genetic tool: whole genome sequencing for individual organisms within a population, to reveal the genes and gene sequences behind the variability among lines or varieties for any given trait. As applied to tolerance to drought, heat, and edaphic constraints, phenotypic variability is documented for: root morphological traits; capacity to remobilize photosynthates to grain under stress; drought tolerance, heat tolerance; tolerance to low soil fertility including mineral deficiencies such as phosphorus (P) and to toxicities such as aluminum (Al) and manganese (Mn); among others. Knowledge of gene sequences, combined with modern phenomics and computing capacity, can propel legume improvement into a new age. Achieving the required advances across legume species will permit recognizing key genes and gene combinations in one species that can be sought in sister species. ***Our goal is to lay the genetic groundwork to address the edaphic and climatic constraints that limit legume yields in the developing world to a fraction of their genetic potential.*** Data generated will not only aid breeders to address the most important yield constraints of legumes in developing countries, but will provide feedback to physiologists about the utility of specific traits, and will serve as raw material for soil microbiologists, agronomists and modelers for improving BNF, system productivity and profitability in smallholder agriculture.

1b) Actions and outputs: Plant breeding communities must prepare for genome sequencing of carefully designed germplasm sets with promising traits and with sufficient size and structure for efficient analysis. To realize this potential, legume communities must develop breeding platforms that:

- Create networks of collaboration to evaluate large numbers of lines for multiple traits, across multiple environments, especially under stress of edaphic and climatic factors;
- Outsource genome sequencing of well selected germplasm sets;
- Implement the communication and analytical technology and skills to share, access and interpret information; and

- Convert this information into readily usable selection strategies, whether through genome wide selection (GWAS), marker assisted selection (MAS) or other approaches.
- Model and assess alternative breeding strategies.

Breeders in the USA, in the CGIAR centers, and in national programs of developing countries will develop common germplasm sets to be evaluated for key traits through phenomics. These sets will be evaluated in target environments and under managed stresses to create a foundation database for breeding and modeling across legume species. Computing capacity will be accessed through the iPlant facility. Populations will be developed for subsequent evaluation and QTL analysis to study stability of trait expression in elite genetic backgrounds. Furthermore, to understand how best to employ molecular markers in breeding programs, alternative breeding strategies will be modeled and assessed. These will examine tradeoffs inherent in selecting for multiple stresses, grain types and cropping-system constraints, and also consider the appropriate balance between conducting large single-location nurseries vs. more numerous, small trials that are better suited for on-farm, participatory experiments. Efficiency of GWAS will be compared with standard QTL selection for improvement of stress tolerance in legumes. This will lead to outputs of:

- sources of key traits to improve yield under stress, including traits associated with BNF, together with associated markers;
- greater levels of edaphic and climatic stress tolerance in elite lines;
- knowledge of interaction of genes and traits for superior trait expression;
- communication mechanisms for the exchange of data and information;
- capacity among partner institutions for the application of cutting edge techniques;
- core data to support modeling of crop and cropping system processes; and
- a platform incorporating GWAS (or alternative selection strategies) for the genetic improvement of legumes.

1c) Outcomes: Legume breeders will realize improved efficiency in breeding for tolerance to edaphic stresses in the face of climate change. Farmers (especially women) will access improved germplasm with greater, more stable yields under smallholder conditions. Modelers will create more accurate simulation models that incorporate response to edaphic and climatic stresses (especially low soil P) and that guide both ideotype development for breeding and dissemination of improved germplasm for integration into cropping systems. Physiologists will have access to additional germplasm for detailed characterization, to expand knowledge on mechanisms of stress tolerance. While focused on edaphic and climatic stress, the genetic analyses can benefit efforts for multiple breeding objectives, including disease resistance and biofortification of pulses with higher levels of iron and zinc.

2) Phenomics

2a) Goals and potentials: This activity seeks to define the mechanistic basis of legume adaption to low soil fertility, drought, and heat. This information is needed to guide focused breeding strategies, including the development of ideotypes as breeding goals for specific production environments, and the development of high-throughput phenotypic screens to identify adapted germplasm and molecular markers. This information is also useful in developing integrated crop management strategies that achieve synergies between genetic and agroecological technologies. Several key traits are already known, including root hairs for enhanced P acquisition, carboxylate exudation for Al resistance, and leaf antioxidant metabolism for Mn tolerance. Rapid and reliable screens are available for these traits and they are being deployed to a limited extent in common bean breeding programs. The basis of genotypic adaptation to drought, heat, and low nutrient availability have been more elusive, and breeding programs to address these constraints have relied primarily on yield screening, which is slow, costly, location-specific, and imprecise. Recent research advances provide the foundation for breakthroughs in the development of more drought-tolerant, nutrient-efficient crop germplasm. These include advances in our understanding of root biology, yield formation, and the advent of new phenotyping platforms. ***Our goal is to integrate modern phenomics and genomics to develop pulse genotypes with substantially improved performance in stressful soil environments in the face of climate change.*** These genotypes will be the cornerstone of improved pulse yields, sustainability and food security for smallholder agriculture.

2b) Actions and outputs: A comprehensive effort is needed to discover key traits, characterize their utility for specific stress environments, and phenotypically profile the diversity of pulse germplasm. For adaptation to low soil fertility (the specific case of BNF is treated separately below), research priorities include:

- Root traits enhancing acquisition of P and mineral N.
- Processes enhancing utilization of P and N in the plant, such as seed mineral composition.
- Understanding the basis of adaptation to low availability of soil K, Ca, and Mg.

For drought and heat, research priorities include:

- Root traits enhancing water acquisition under drought.
- Processes controlling fertilization, carbon partitioning and grain filling under stress.
- Understanding the role of phenology in resource acquisition, utilization, and stress avoidance.

Two cross-cutting themes with relevance to multiple abiotic stresses are 1) root biology: the utility of specific architectural, morphological, and physiological traits for soil resource acquisition, and 2) reproductive biology: the regulation of resource remobilization into developing seeds. In addition to these research opportunities, substantial impact can be realized by deploying traits of known value such as root hairs, Al resistance and Mn tolerance in pulse breeding programs.

For each of the priority research foci listed above, specific traits have been identified. To validate the utility of these traits for pulse breeding, physiological analysis of segregating genotypes is needed in managed stress environments. In some cases these analyses can be conducted by advanced labs in the US, in others the involvement of CGIAR centers and NARS partners is crucial because of their access to appropriate target environments. Powerful new tools for crop simulation modeling (Activity 4) will be useful in understanding how specific traits may affect performance in specific environments and phenotypic backgrounds. As these traits are validated, high-throughput phenotyping platforms can be used to profile pulse germplasm, identifying sources of useful variation. This will lead to the following outputs:

- validated ideotypes for focused crop improvement, encompassing interactions among traits in specific environments;
- high-throughput phenotyping platforms for germplasm evaluation;
- sources of key traits to improve yield under stress;
- greater levels of abiotic stress tolerance in elite lines;
- enhanced capacity among partner institutions to address abiotic constraints; and
- integration of optimal germplasm to achieve synergies with management technologies in Integrated Crop Management systems.

2c) Outcomes: Outcomes include all of those listed under (1) Genetic Improvement above, including improved efficiency of breeding programs, improved germplasm, and improved understanding of relevant processes that will guide model development and Integrated Crop Management strategies.

<u>3) BNF Plant/Microbe interactions</u>

3a) Goals and potential: The primary limitation for smallholders is declining soil fertility and inefficient cropping systems that are unable to effectively and efficiently utilize available resources. This limitation is particularly challenging for women farmers who often have limited access to inputs such as fertilizer and pesticides. Incorporation of legumes capable of supporting BNF into these cropping systems has provided a modest benefit for production. However, despite considerable investment in basic and applied research aimed at improving BNF, legumes grown by smallholders on degraded soils continue to produce only a fraction of their genetic potential. ***Our overall goal is to identify and capitalize on favorable microbial – plant interactions to improve legume productivity in degraded soils common to priority cropping systems in Sub-Saharan Africa.***

Potential for BNF is determined by a host of interacting factors including rhizobial strain(s) infecting the plant, the receptivity and support provided by the host plant, the local environment affecting plant growth and microbial function, as well as the management system used to produce the legume. As such, improving BNF and legume performance in these soils and cropping systems requires:

- research that integrates greater knowledge of the microbial populations available for symbiosis with legumes with understanding of the impact of environmental and management conditions on those populations;
- a more systematic breeding methodology to identify superior legumes and rhizobial strains, and to establish the genetic basis for superior plant-microbe interactions; and
- a commitment to capacity building encompassing training, germplasm curation, and inoculum standardization through a regional Rhizobium Resource Center to serve the scientific, agricultural, and business communities.

3b) Actions and outputs: Actions under this initiative will utilize the rapidly expanding knowledge of soil microbial systems, applying state-of-the-art molecular methodologies to select plant germplasm with enhanced BNF (see Activity 1), and training a new generation of young scientists to promote plant-soil microbe interactions that enhance legume BNF and grain yield. New knowledge about rhizobial/soil/environment/crop interactions will be used to predict rhizobia populations in degraded soils, and identify yield enhancing interactions between microbes and plants. Dissemination of this new knowledge and capabilities will be managed through a Regional Rhizobia Resource Center.

Outputs related to predicting rhizobia populations in degraded soils include:

- identification of beneficial microbes in soils of priority cropping systems;
- relation of current microbial population structures to predominant soil conditions and crop management systems;
- identification of soil biological factors (microbial exudates and volatiles) that vary with microbial population structure, soil conditions, and cropping systems and their potential impact on plant growth and yield;
- identification of genetic markers for persistent rhizobia in adverse soils that can be used to select superior strains;
- development of models to predict inoculant success as related to previous cropping history, as well as current and future soil conditions;
- development of a practical decision tool for farmers on profitable use of inoculants in their management systems; and
- identification of enabling interactions between a broader array of soil microbes and legumes that promote favorable plant growth and suppress soil-borne diseases.

Outputs related to identifying yield enhancing interactions between microbes and plants:

- creation of a set of “Differential Bean Genotypes” to characterize and screen candidate rhizobia strains for superior BNF, including molecular and phenotypic characterization;

- development of a set of promiscuous inoculants that perform well across multiple soil types with multiple legume hosts;
- enhanced efficiency of selection for superior rhizobium/plant genotype combinations;
- determination of how new root ideotypes (branching, depth, etc) and plant type (climbing bean v. bush bean) affect nodulation, nitrogen fixation, and yield;
- quantification of effects of plant removal (e.g. for animal feed, green manure) on soil N and microbial dynamics;
- characterization of host response with and without environmental stress, to explain a “BNF-gap” under stress that inhibits reaching fixation potential; and
- cross-legume comparisons to reveal host traits explaining differences among legume species in BNF efficiency.

Outputs related to establishing a Regional Rhizobia Resource Center:

- a germplasm resource for rhizobia and favorable soil microbe collection and curation;
- training for small business owners producing and distributing inoculant, students, lab managers, farmers, and extensionists;
- mini-grant program to develop skills in inoculant preparation and management; and
- industry standards for inoculant quality control, quality control detection, and inoculant production at large scale and on-farm.

3c) Outcomes: The primary outcome of these integrative research activities will be substantially increased pulse production by smallholder farmers. New knowledge about the effects of crop management and soil conditions on soil microbial dynamics will direct needed changes in cropping systems management to optimize production with limited resource inputs. Establishing the genetic basis for superior plant-microbe interactions will speed development and deployment of improved varieties with greater yields in degraded soils. Creation of the Regional Rhizobium Resource Center to serve the scientific, agricultural, and business communities will provide the highest standards for training, germplasm curation, and inoculum production, which are critical for improving BNF on a regional scale.

4) Systems analysis and management

4a) Goals and potentials: Improved crop and soil management are fundamental to ensuring that gains through genetic improvement attain their full potential and that such gains are truly sustainable. Productivity increases through agronomy must emphasize improved utilization of the existing natural resource base over increased use of external inputs as fertilizers or irrigation. Nonetheless, appropriately scaled fertilizer deployment and irrigation systems will still have a role. Critical constraints to the required research evolve from the inherent complexity of identifying and adapting promising to specific edaphic, climatic and cropping system conditions and then promoting the most promising technologies in a cost-effective manner. ***Our goal is to identify and promote promising crop management options for grain legume-based agricultural systems that emphasize more efficient use of existing or readily available resources and that ultimately improve the productivity, profitability and sustainability of smallholder agriculture.*** Five advances and innovations can support the required transformation of legume systems agronomy in Africa:

- Simple, robust ecophysiological models can simulate growth and estimate seed yield of target pulse crops. These models provide opportunities for scientists to evaluate the potential impact of different crop and soil management scenarios on the productivity of maize/bean and cowpea cropping systems commonly used in Africa. The cost and time required to generate a similar set of data using conventional agronomic trials is prohibitive.
- Extensive geospatial data on climate, soils and cropping systems allow use of crop models in conjunction with other geospatial tools in order to map potential productivity as well as likely effects of specific constraints.

- Advances in fundamental understanding of soil processes.
- Widespread recognition and acceptance of farmer participatory research as a means both to adapt promising technologies to needs and expectations of producers.
- Networking tools based on information technology, including smart phones and Internet kiosks, offer avenues for ensuring that producers have access to information in a timely and location-relevant manner and can provide feedback to the research community in a cost-effective manner.

4b) Actions and outputs: Quantitative systems analysis (QSA), which combines simulations with other geospatial analyses, can generate maps that identify specific edaphic constraints such as soil acidity, low P or Al toxicity in pulse production regions. Crop models can estimate the likelihood of the occurrence of unfavorable climatic conditions such as drought, flooding and periods of high temperature over a period of 20-30 years, thus allowing experimental results from two or three seasons to be placed in the context of climatic risk. QSA can draw on data across environments (Activity 1) and can be used to evaluate the potential benefit of different pulse crops, plant traits (characterized in Activities 2), and management alternatives in target environments. This approach permits the development of maps and diagnostic tools to evaluate pulse crop and system productivity. These diagnostic tools can be used by decision-makers to identify biological and conservation management techniques that enhance the efficiency of water and nutrient utilization, for example, through improved access to nutrients in deeper soil layers or through increased capture of precipitation by reducing runoff. Crop and soil management scenarios (basins, tied ridges, doubled-up legume rotations, mulch/residue management, species mixtures, long-duration and deep rooted species for improving soil organic matter) identified by QSA to have the potential to increase productivity or to improve the efficiency of use or the conservation of natural resources will be evaluated by participatory research teams in the target environments. Diagnostic and decision tool kits for farmers, extensionists and NGOs and maps can be refined based on feedback from these participatory studies. *Ex-ante* and *ex-post* socio-economic analyses will be conducted to evaluate the impact of promising crop management technologies. African scientists will be trained in the utilization of both QSA and participatory research techniques to help identify crop and soil management techniques that will increase productivity, improve the efficiency of the utilization of water and soil nutrients and conserve natural resources. Plant breeding programs and scientists can use QSA to evaluate the effect of a specific trait on crop development or seed yield. In addition, QSA can identify target environments for pulse cultivars with specific combinations of traits, while accounting for climatic risk or if deemed appropriate, climate change. The likelihood estimates of the occurrence of a specific edaphic or climatic constraints generated by QSA can help plant breeders to identify traits that should be selected for different target environments or specific crop and soil management systems.

4c) Outcomes: QSA conducted in coordination with participatory research teams will accelerate locally-appropriate adaptations to cropping systems for pulses in Africa that are more diverse, productive and resilient to edaphic and climatic constraints. This research approach also permits the development agronomic practices that are more attuned to the needs and limitations of specific target environments.