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REPORT IN BRIEF

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Emerging Technologies
to Benefit Farmers in Sub-Saharan Africa and South Asia

Increased agricultural productivity is a major stepping stone on the path out of poverty in sub-Saharan Africa and South Asia, but farmers there face tremendous challenges improving production. Poor soil, inefficient water use, and a lack of access to plant breeding resources, nutritious animal feed, high quality seed, and fuel and electricity—combined with some of the most extreme environmental conditions on Earth—have made yields in crop and animal production far lower in these regions than world averages. This report identifies sixty emerging technologies with the potential to significantly improve agricultural productivity in sub-Saharan Africa and South Asia. Eighteen technologies are recommended for immediate development or further exploration.

The scientific and technological advances of the past century have greatly expanded the breadth and power of agricultural innovations. There now exists a remarkable array of technologies to improve crops and animal breeds, manage pests and diseases, provide nutrient inputs, and irrigate effectively and efficiently. However, many of these innovations were developed for farming in temperate regions in the industrialized world and are not always suitable for the needs of farmers in tropical regions in developing nations, who grow different types of crops and raise animals with different diseases and pests, and face unique soil, water, and weather conditions. Those farmers need innovations that can help them improve productivity and efficiency in the face of some of the world's most extreme environmental stresses and competing demands for natural resources—conditions that push science and technology to their limits.


A Pakistani woman and her vegetable seedlings. Source: USAID

Farmers in sub-Saharan Africa and South Asia currently experience yields in crop and animal production that are far below world averages and are too low to support the expanding populations in these regions. If production can be improved, the agricultural sector has the potential to foster economic growth and reduce poverty across these regions by vastly improving the outlook for the nearly 70 percent of the world's poor whose livelihoods are connected with the land on which they live and toil.

International donors and national governments are investing in the agricultural sectors of sub-Saharan Africa and South Asia to improve the agricultural economy and the structure of agricultural markets, provide financing for farmers, and make accessible inputs like seeds and fertilizer. To complement those investments, these organizations are also seeking ways to improve crop and animal production. Although technologies are not the only determining factors of farmers' success, having access to improved inputs, proven methods, and critical knowledge can make a significant contribution to agricultural production. In addition, recent advances in scientific disciplines not ordinarily associated with agriculture, such

Crop	Yield (kilograms per hectare)			
	Kenya	Ethiopia	India	Developed World
Maize	1,640	2,006	1,907	8,340
Sorghum	1,230	1,455	797	3,910
Millets	580	1,186	1,000	2,010
Rice (paddy)	3,930	1,872	3,284	6,810
Wheat	2,310	1,469	2,601	3,110
Beans, cowpea	378	730	332	1,790
Chickpea	314	1,026	814	7,980

Table 1. Yields of cereal and legume crops in 2005 were far lower in Kenya, Ethiopia, and India than in the developed world. Source: Compiled from data from the Food and Agriculture Organization.

as remote sensing, energy science, and nanotechnology, are expanding the scope of possibilities for new agricultural applications.

At the request of the Bill & Melinda Gates Foundation, the National Research Council's Board on Agriculture and Natural Resources convened an expert committee to look over the technological horizon and produce a report on the emerging innovations in science and technology most likely to help farmers in sub-Saharan Africa and South Asia.

Challenges Facing Farmers in Sub-Saharan Africa and South Asia

Agricultural yields in sub-Saharan Africa and South Asia consistently fall below world averages (see Table 1). Why are yields so low? A number of interacting factors play a role (see Box 1).

Soil quality was the primary constraint on agricultural productivity that was identified by scientists from sub-Saharan Africa and South Asia. Both regions also face water use and management challenges; inadequate resources to deal with pests and diseases; insufficient fuel and energy; a lack of high-performing crops and animals; and poor animal health, partially due to a lack of reliable and nutritious feed supply.

Agriculture in the two regions is also constrained by weak governments, insufficient investment in agricultural research and development, a lack of cash and financing for farmers, and insufficient basic infrastructure. There is also a lack of extension services for transferring new knowledge and technologies to farmers.

Sub-Saharan Africa

Most African crop and animal production is practiced under low-input agricultural systems, leading to poor quality soil and seeds, low plant and animal nutrition, and increased vulnerability to changes in weather and climate.

African farmers traditionally left lands fallow between plantings to restore soil nutrients, but as a result of high food demand, farmers now grow crops continuously with little or no nutrient input. Fertilizer use in the region is low, primarily due to its exorbitant cost—up to four times that paid by a farmer in the U.S.

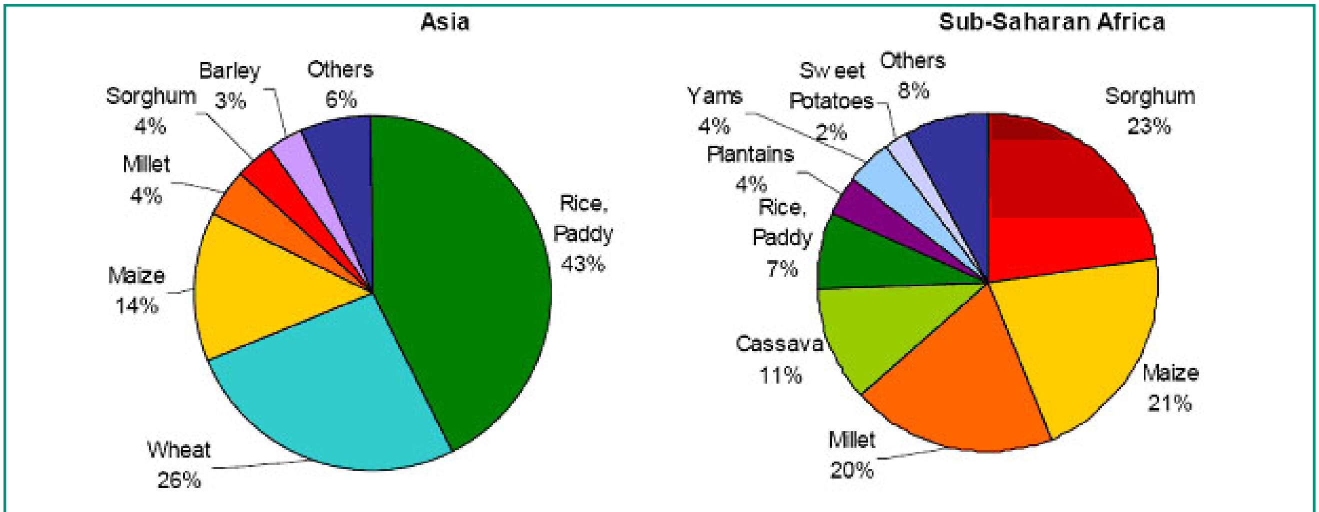
South Asia

In contrast with Africa, fertilizer use in South Asia is high, which should mean higher yields. However, farmers have recently seen decreases in the responses of some crops to fertilizers that have translated to yield drops. One possible reason for this decline is the loss of soil organic matter as farmers strip all organic matter from their fields—including weeds, roots, and manure—for animal feed or cooking fuel. Lacking inputs of organic matter, the soils have low holding capacities and often do not respond to the addition of fertilizer.

Water issues also present a major problem. Inefficient irrigation systems have led to water overuse and increased water salinity. It is estimated that in Pakistan, for example, over 50 percent of the groundwater is saline and not fit for irrigation. Other problems include arsenic in many groundwater sources, depletion of some major aquifers, and pollution from agricultural runoff.

Box 1. The Most Serious Agricultural Constraints in sub-Saharan Africa and South Asia: Perspectives from Scientists in those Regions

- Soil fertility, lack of fertilizer, soil degradation
- Drought, insufficient water, difficulties in managing water
- Animal nutrition, diseases, and arthropod vectors
- Insufficient markets and international regulation
- Weak government, institutions, and finance for small farmers
- Germplasm of plants and animals
- Education of farmers, extension, and information systems
- Need for biotechnology, other new technologies
- Weeds, plant diseases, and arthropod pests
- Lack of infrastructure and manpower
- Energy and mechanization for small farmers
- Climate change and related problems
- Information and resources for local scientists
- Postharvesting technologies
- Population growth



Major food crops of Asia and sub-Saharan Africa. Percentages refer to hectares harvested, averaged for 2000-2004. Source: Compiled from FAO, 2006 and de Janvry and Byerlee, 2007.

Priority Technologies for Development and Exploration

The report describes approximately 60 technological tools that could help farmers in sub-Saharan Africa and South Asia to increase agricultural productivity. Eighteen technologies are recommended as most worthy of immediate attention (see Table 2).

"Tier I" tools and technologies are those that should be given the highest priority for development into specific applications in sub-Saharan Africa and South Asia today. These technologies largely already exist and have been proven successful, but they are new from the perspective of farmers in sub-Saharan Africa and South Asia because applications specific to the needs of farmers in these regions have not been developed or widely used.

"Tier II" technologies include ideas that are emerging from advances in many fields that are considered a high priority for additional exploration. In concept, applications based on these technologies would have a great deal to offer farmers in the two regions. However, these technologies are not yet fully developed, so applications cannot be built based on them at this stage. Additional exploration is needed to determine their feasibility and how they could be implemented in the two regions.

In general, the technologies identified with great potential impact are those that help to: (1) manage the natural resource base supporting agriculture (especially soil and water); (2) improve the genetic profile of crops and animals; (3) reduce biotic constraints (such as disease, pests, and weeds) that decrease yields; and (4) provide affordable, renewable energy for farmers.

Technologies for Natural Resource Management

The Challenge: The future of agriculture in sub-Saharan Africa and South Asia depends on the management of crucial natural resources, primarily soil and water. Soil quality has been identified as the number one challenge to agricultural productivity in these regions, and the prospect of water scarcity is a commonly raised issue of concern for the future, especially given climate change projections. Sub-Saharan Africa currently has little installed irrigation, and South Asia faces inefficient water use and water degradation.

Tier I Technologies

Soil management techniques: Both soil and water management are integrative technologies—they require multiple methods for each particular site. Promising soil management techniques include controlled grazing; mulching with organic matter; applying manure and biosolids; use of cover crops in the rotation cycle; agroforestry; contour farming; hedgerows; terracing; plastic mulch for erosion control; no-till or conservation tillage; retention of crop residue; appropriate use of water and irrigation; and integrated nutrient management, including the judicious use of chemical fertilizers.

Integrated water management: Arrays of efficient, on-farm water capture, storage, pumping, field application and drainage technologies could help address water challenges in both regions. Water management technologies include tube wells, on-site storage tanks, and effective irrigation methods. Subsurface drip irrigation, in which buried tubing delivers water

A Zambian farmer stands with his maize crop, severely stunted by drought. Integrated water management could help farmers deal with water shortages. Source: USAID

directly to plants' root zones, is the most efficient form of irrigation technology, but it is currently expensive.

Climate and weather prediction: Increased climate and weather prediction capabilities would be a transformative development for farmers in sub-Saharan Africa and South Asia. If farmers could more accurately predict drought or the onset of the tropical rainy season, they would be better equipped to make pivotal timing and management decisions. Weather models, databases, and monitoring devices are taken for granted in many parts of the world, but these tools still need to be built for sub-Saharan Africa and South Asia. In developing these capabilities, specific attention is needed to ensure that farmers can easily receive and use the information that is generated.

Tier II Technologies

Soil-related nanomaterials: The emerging field of nanotechnology shows promise for developing innovative agricultural technologies, such as nanotechnology-based soil amendments that enable better control over the conditions for or timing of fertilizer release. These materials may also help remediate toxic substances in soil that can inhibit the growth of plants and beneficial soil bacteria.

Manipulation of the rhizosphere: Current research suggests that it is possible to manipulate plants' rhizosphere (where a plant's roots interact with the surrounding soil) by optimizing their root structures for better water and nutrient uptake and increased yields. In addition, it may be feasible to take advantage of the chemical signals emitted by plant roots to manipulate soil microorganisms in ways that reduce the need for off-farm nutrient inputs. To develop such strategies into applications, however, a better basic understanding of microbial ecology in major crop systems of sub-Saharan Africa and South Asia is needed.

Remote sensing of plant physiology: Remote sensing technologies could potentially allow farmers to monitor the biological status of their plants and make management decisions based on that information. Increasingly sophisticated optical imaging equipment (both hand-held and satellite-based) can detect subtle differences in plant physiology, such as the presence of disease or the rate at which the plant is using nutrients. Farmers could receive remotely collected information via cell phones or the Internet and take appropriate action, such as irrigate or fertilize their crops. Although today it seems an unlikely tool for poor farmers, remote sensing has the potential to become a practical and valuable decision-making tool.

Technologies for Crop and Animal Improvement

The Challenge: It takes years to develop high performing crops and animals, and efforts in sub-Saharan Africa and South Asia have fallen behind. However, powerful new tools are emerging that can help speed improvement in plants and animals. Using genomic technologies—those that examine the entirety of available genetic diversity in individual plants or animals and populations of those individuals—scientists can identify beneficial genetic traits and bring together new combinations of genes that enable crops and animals to perform well in specific environments.

Tier I Technologies

Annotated crop genomes (describing their genetic details): There is a need to establish baseline information about the genetic diversity of local crops in the two regions. Annotation of genomes—determining the genetic sequence and gene functions—of plants that are important to farmers in these regions would help speed crop improvement. Given advances in the rate of DNA sequencing, the full genetic code of key crops grown in the two regions could be built very quickly, and the identities and function of their genes could be determined by relying on similarities to the existing *Arabidop-*

Focus of Technology	**Tier I** *High Priority for Development*	**Tier II** *High Priority for Additional Exploration*
Natural Resources Management	• Soil management techniques • Integrated water management • Climate and weather prediction	• Soil-related nanomaterials • Manipulation of the rhizosphere • Remote sensing of plant physiology
Improving Genetics of Crops and Animals	• Annotated crop genomes • Genome-based animal breeding	• Site-specific gene integration • Spermatagonial stem cell transplantation • Microbial genomics of the rumen
Overcoming Biotic Constraints	• Plant-mediated gene silencing • Biocontrol and biopesticides • Disease suppressive soils • Animal vaccines	-
Energy Production	-	• Solar energy technologies • Energy storage technology • Photosynthetic microbe-based biofuels

Table 2. Priority technologies for development and exploration.

sis, rice, and sorghum sequences and the emerging maize sequence. A variety of genomic tools can then be used to analyze how the plants' genes function in different environments.

Genome-based animal breeding: Genomic tools can also be used to help animal breeders increase the quality of their livestock. It is feasible to generate reference genomes (complete genetic sequences that can be used to study and compare animals' genetic traits) for *Bubalus bubalis*—the Asian water buffalo—and other farm animals raised by subsistence farmers in the regions, such as goats and hair sheep. By taking samples of DNA from many animals throughout each region and observing and recording their traits ("good milk producer," for example), breeders would get a picture of the genetic diversity in the whole population of animals. By associating the DNA with the traits, breeders can construct the theoretical genetic pedigree of a farm animal with the most desirable traits. Armed with this information, conventional breeding methods can go forward at a much faster pace.

Tier II Technologies

Site-specific gene integration: Currently, new genes can be added to a plant for improved performance, but they are incorporated in a random fashion, and they often bring along linked genes that negatively affect the performance of a crop. A technology that would fulfill the dream of crop breeders to replace one gene with another in an exact location is called site-specific gene integration. This tool would allow breeders to more precisely and reliably control the genetic makeup of crops.

Spermatagonial stem cell transplantation: For animal improvement, one of the biggest hurdles is getting the right genes distributed throughout the herd. But a new approach is to harvest spermatogonial stem cells (which give rise to sperm cells) from genetically superior males and transplant them into many other males, who then distribute those genes to the females they encounter. This approach would circumvent the technical difficulties currently posed by artificially inseminating females.

Microbial genomics of the rumen: No matter how good its genetics, an animal that is poorly nourished cannot fulfill its production potential. Further investigation of the microbial diversity of the rumen (the multi-chambered stomach of cattle where microorganisms play a key role in digestion) could lead to methods that enhance animals' ability to extract nutrients from difficult-to-digest grasses that are the predominant animal foods in the two regions.

Technologies for Overcoming Biotic Constraints

The Challenge: Diseases and insect pests rob the world of more than 40 percent of the attainable yield of the eight most important food crops, and invasive species threaten both crops and native biodiversity.

The most damaging weeds to overcome in these two regions include *Striga* (witchweed) in grain and legume crops in sub-Saharan Africa; *Echinochloa*, an herbicide-resistant weed in rice; and *Phalaris minor*, the major weed of wheat in South Asia. Farmers also face threats from viruses, including Cassava Brown Streak; Cucumber Mosaic Virus; African Cassava Mosaic Virus; and Cotton Leaf Curl, as well as major insect pests such as weevils and stem, fruit, and grain borers, and insects that serve as vectors for disease transmission.

There are several promising technologies to mitigate biotic threats. All of these are listed as Tier I, as they have been proven effective but not yet made available for application in the two regions.

Tier I Technologies

Plant-mediated gene silencing: Using plant-mediated gene silencing, scientists induce plants to transfer pieces of genetic material to other organisms, targeting and interfering with the interactions between plants and their pests at the genetic level. This approach takes advantage of the recently discovered powerful molecules known as small RNA, which play a role in plant development and resistance to stress. Plant-mediated gene silencing has shown promise for control of viruses, nematodes, and certain insects.

Biocontrol and biopesticides: Approaches involving biocontrol and biopesticides focus on using natural means to fight diseases, pests, and weeds. Biocontrol involves the release of a pest's specific natural enemies to control its population. Biopesticides are types of pesticides that use toxins that are naturally produced by some organisms, instead of synthetically-produced chemicals.

Disease-suppressive soils: The use of disease-suppressive soils involves management practices that encourage crop-associated microbial communities that naturally reduce plant diseases and pests. These practices might include manipulating carbon inputs, using crop rotation sequences that increase the presence of beneficial organisms, or inoculating the soil with disease-suppressive microorganisms.

A veterinarian vaccinates a chicken in Afghanistan. Source: USAID

Animal vaccines: Vaccinating animals against common diseases could greatly improve livestock productivity in the two regions. A range of approaches to vaccine development could be supported, from attenuated bacteria (bacteria whose virulence has been reduced) to DNA vaccines (in which an animal is injected with genetically engineered DNA to produce a specific immune response). The control of diseases such as brucellosis, leptospirosis, bovine virus diarrhea and other respiratory and intestinal diseases in young, preweaning animals could significantly improve the long-term productivity of important livestock animals in the two regions.

Technologies for Energy Production

The Challenge: In the majority of the poorer countries in sub-Saharan Africa and South Asia, less than 25 percent of rural households have access to electricity, and only 5 percent of the rural population is connected to the electric power grid. Agriculture in these regions is therefore energy-limited. It is critical that cost-effective, clean, renewable energy sources replace the fuels that are currently used. Moreover, the climates in parts of the two regions make them good locations for certain types of renewable energy systems, such as solar power and microbe-based oil production.

Energy production technologies are listed as Tier II because, although they show great promise, additional research and development is needed to determine which approaches will be most feasible and effective in the two regions.

Lack of fuel and energy is a significant constraint on agricultural productivity in the two regions.

Tier II Technologies

Solar energy technologies: Solar energy technologies are advancing rapidly, are potentially scalable and inexpensive to operate, and would provide a source of off-the-grid energy for rural communities in the two regions. A wide variety of new semi-conductor materials are being explored that will reduce the cost and boost the efficiency of solar panels. In addition, these two regions are potentially ideal locations for novel solar thermal devices that use mirrors and lenses to concentrate heat from sunlight and convert it into mechanical and electrical energy.

Energy storage technology: The need to store energy produced by solar and other off-the-grid technologies presents a challenge. Batteries are made of toxic metals and chemicals and eventually lose their ability to be recharged. An alternative emerging method for energy storage is the super-capacitor, which operates through static energy, rather than chemical energy—making its ability to be recharged virtually limitless. Supercapacitors are expected to replace batteries in the future and could be used to store energy as well as to power rechargeable, small-scale mechanical devices used for agricultural production and processing.

Photosynthetic microbe-based biofuels: The warm and sunny regions of sub-Saharan Africa and South Asia may be well suited to grow photosynthetic microbes, such as algae and cyanobacteria, that produce much larger quantities of biodiesel than palm oil, Jatropha (a leading biofuel crop native to central America), or soybean. These microbes also have simple input requirements and can grow in saline waters that are not suitable for agriculture or drinking.

Essential Considerations in the Development of Agricultural Technologies

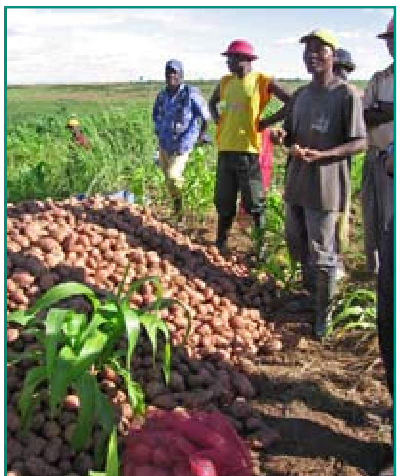
As the context for examining the potential impact of different agricultural technologies, the report identifies several underlying considerations to inform development of applications for improving agricultural productivity in sub-Saharan Africa and South Asia. These include:

- **A system-wide approach:** Technological innovations in agriculture provide fixes for specific problems, but they are not comprehensive solutions by themselves. Agricultural production is a complex system; consequently, agricultural technologies are interdependent. For example, it is difficult to increase meat or milk production if farm animals are chronically infected with pathogens and are fed low-quality, poorly digestible foods. Solving the problem of poor agricultural productivity requires a multifaceted approach to address deficiencies throughout the farming system.
- **Local expertise and participation:** Technologies must meet local needs and conditions, a requirement that is best fulfilled when farmers and local scientists participate in research, development, and implementation. For example, crop breeding requires the evaluation of traits under local environmental conditions; similarly, accurate weather prediction needs data collected at the ground level. These tasks require a trained, local workforce. Engaging farmers in remote areas will require the development of novel ways of communicating.

A woman works in a laboratory to improve seed productivity in Afghanistan. Local expertise and participation is needed to improve agricultural productivity.
Source: USAID

• **Innovations not necessarily limited to "low" technology:** Technological applications must be more than just affordable; they should be cost-efficient. For example, although it is cheapest for farmers to save seed from a previous year's harvest, that may not be the best choice, given that hybrid seed has a high germination rate and is free of pathogens and weeds. In this sense, the best choice for farmers in these regions does not necessarily have to be limited to "low-tech" approaches like saving seed from year to year. Furthermore, there is a need to develop solutions specific to these regions. Incentives to build applications that address the specific problems in these reigions could deliver benefits faster than waiting for market forces to propel technology development in industrialized nations first.

• **Attention to the implications of climate change:** Farmers in sub-Saharan Africa and South Asia already face severe environmental constraints. By all predictions, their livelihoods will be imperiled by the future consequences of global climate change, especially water scarcity. Comprehensive planning to alleviate the economic and ecological impacts of drought will be needed, as well as technologies that increase the availability of water and efficiency of water use.



Conclusions

Together with improvements in the structure of agricultural markets, scientific knowledge and technology can improve agricultural productivity and offer hope to poor communities in developing countries. If farmers can more reliably produce greater quantities of staple crops, they can ensure their own food supply. If they can sell the surplus of what they do not consume, they can improve their income while meeting the needs of a growing regional population. If they can produce a diversity of high-value products, they can capitalize on the demand for a greater variety of food by urban dwellers whose incomes are rising.

A whole suite of approaches—some technological and some not—must come together for farmers to realize the benefit of any innovation. Scientists from all backgrounds have an opportunity to become involved in bringing these and other technologies to fruition. The opportunities suggested in this report offer new approaches that can synergize with each other and with the many other activities supported by the Bill & Melinda Gates Foundation and other actors to transform agriculture in sub-Saharan Africa and South Asia.

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This report brief was prepared by the National Research Council based on the committee's report. For more information or copies, contact the Board on Agriculture and Natural Resources at (202) 334-3062 or visit http://dels.nas.edu/banr. Copies of *Emerging Technologies to Benefit Farmers in Sub-Saharan Africa and South Asia* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.

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