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Global Food Security: Emerging Technologies to 2040

NATIONAL INTELLIGENCE COUNCIL REPORT

NICR 2012-30, 28 August 2012

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Scope Note
Global Food Security: Emerging Technologies to 2040

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In July 2011, the National Intelligence Council (NIC) asked Strategic Business Insights (SBI) to identify emerging, potentially breakthrough technologies for agriculture—grains, fruits, vegetables, meats, and fish—by 2040. This effort was targeted towards agriculture products that can be used for human consumption, animal feed, energy production (biofuels), and other industrial processes (e.g. corn resin). Research was focused on technologies that would impact medium-to-large enterprises in developing and developed countries; not considered were technologies that would be exclusively used in subsistence farming in the underdeveloped world. The developed world is the most likely source of new technology that could be employed in the most advanced agriculture sectors. SBI reviewed their existing publications (*Scan*, *Signals of Change*, and *Technology Maps*) and other open-source material to identify emerging technologies. The timelines implied in the report reflect deployment in the developed world unless specifically stated otherwise.

The year 2040 was selected as the target end point for this research to enable consideration of longer-term impacts from climate change, growing populations, continued global economic development, and technology development and deployment.

This report is the third of four external efforts the NIC will conduct during 2012 to explore global food security. The first report—*Global Food Security: Key Drivers*—was a conference report introducing the topic of food security. The second report—*Global Food Security: Market Forces and Selected Case Studies*—explored market forces that will affect food security to 2040. Finally, the fourth report will be a 20-plus nations study of global food security and the potential impacts on US national security. Following these external studies, the NIC will lead an Intelligence Community (IC) analytic effort to report on food security and potential impacts on US national security.

Food Security Definition

The World Food Summit of 1996 defined food security as a condition "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life." Commonly, the concept of food security is defined as including both physical and economic access to food that meets people's dietary needs as well as their food preferences.

Global Food Security: Emerging Technologies to 2040

Executive Summary

Our Bottom Line: Technology will certainly be one of the primary means for improving agricultural productivity necessary to meet the demands of an increasing world population. However, the complex factors that affect productivity do not point to a single or even a handful of new technology innovations that can markedly impact agriculture. The technologies that will have the largest impact on agricultural productivity in the next 10 years include the use of existing genetically modified crops, soil and water management, pest control, and post-harvest processing. By 2040, the tools and advances of molecular biology applied to plants, livestock, and microorganisms will most likely have the greatest impact on agricultural production.

The principal challenge facing world agriculture is finding the means of increasing agricultural productivity—producing more with fewer resources (land, fertilizer, water, and pesticides)—to meet the demands of an increasing world population. **However, the complex factors that affect productivity do not point to a single or even a handful of new technology innovations that can markedly impact agriculture.**

- The application of existing technologies (genetically modified crops, soil and water management, pest control, and post-harvest processing) will have the largest impact on agricultural productivity in the next 10 years.

- By 2040, the tools and advances of molecular biology applied to plants, livestock, and microorganisms will most likely have the greatest impact on agricultural production.

Out to 2040 the extent of development and deployment of new technologies will be varied among the different agriculture sectors—grains, livestock, water and soil management, aquaculture, precision agriculture, biofuels, and post-harvest processing.

- **Grains.** The productivity of the grain segment of the agricultural industry is key to meeting global food demands. To meet the food needs of the world population in 2030, the agricultural sector will have to produce an additional billion tons of grain per year, which is roughly a 50-percent increase over the production of 2.2 billion tons in 2011. **With the molecular biology tools now available, plant breeders will possibly be able to achieve grain yields sufficient to meet world population grain needs in 2040.**

  - The advances in plant genomics come at a cost to the farmer. The cost of genetically transformed seed can be five to seven times higher than conventional seed.

- **Livestock.** Similar to plants, livestock breeding is taking advantage of the developments in molecular biology to accelerate development of highly productive and healthy animals. Genetic analysis of animals through molecular biology has also improved the quality of livestock agriculture.

- **Water and Soil Management.** Because agriculture consumes 70 percent of the freshwater supply, and 40 percent of the world's agriculture depends on irrigation, any sustained increase in agricultural productivity by 2040 will require efficient water management. To be more efficient, some farmers in developed countries are applying subsurface drip irrigation. This technology has higher installation costs than conventional surface irrigation but will likely become the norm by 2040. Most of the fertilizer technology in use today was developed in the 1950s through the 1970s. Because publicly funded fertilizer research has mostly ceased, significant development and deployment of new and more efficient fertilizers and fertilizer manufacturing technologies will not likely occur between now and 2040.

- **Aquaculture.** Demand for aquaculture will continue to grow to meet the world's demand for protein. Based on a 2006 World Bank report, aquaculture producers will likely see growth rates ranging from 1.4 percent to 5.3 percent per year in the next 20 to 30 years. The key technologies required to produce this growth are all feasible today.

- **Precision Agriculture.** Because of its history, precision agriculture—the use of soil sensors and geolocation technologies for planting, watering, feeding, and harvesting—is bound up heavily with the large-scale industrial-agriculture practices. They predominate in regions like the midwestern United States, southern Brazil, and parts of Canada, Germany, and Australia. For precision agriculture technologies to diffuse on a wide scale in the future they will need to scale down to work well for small plots in the developing world where the greatest potential productivity gains can be made.

- **Biofuels. Over the next several decades, a transition to next-generation technologies that convert biomass (rather than food crops) to advanced biofuels and chemicals will be essential to improve the security and affordability of the world's food supplies.** Developers are just beginning to scale up the new biofuel technologies to commercial production and still face significant technical and financial risks.

- **Post-Harvest Processing.** Most of the technologies deployed in the post-harvest processing sector are mature and reasonably effective. Application of existing irradiation technology could reduce crop losses that can be as high as 50 percent in developing countries. However, the technology has met with public resistance to its application because of fear the basic food properties will be altered.

Currently many of the biotechnologies that have been commercialized face resistance from the public and regulatory agencies. This is because of concerns that pollen from the genetically modified plants will spread the transformation to non-transformed plants in nearby fields and that genetically modified foods will be harmful to human health. In addition, for many of the emerging technologies to be deployed globally, they will have to be adapted to the mix of commodities produced, production practices, and environmental conditions of different localities. Local implementation might require additional factors such as investments in agricultural research at the developing-country level as well as in agricultural human capital and infrastructure.

Further, agricultural productivity improvements will require advances in other fields beyond molecular biology, including chemistry, electrical engineering, remote sensing, and computer science. The tools from these fields are not necessarily developed specifically for agriculture, but their application can make improvements in controlling the management of soil, water, crop, and energy inputs to agriculture.

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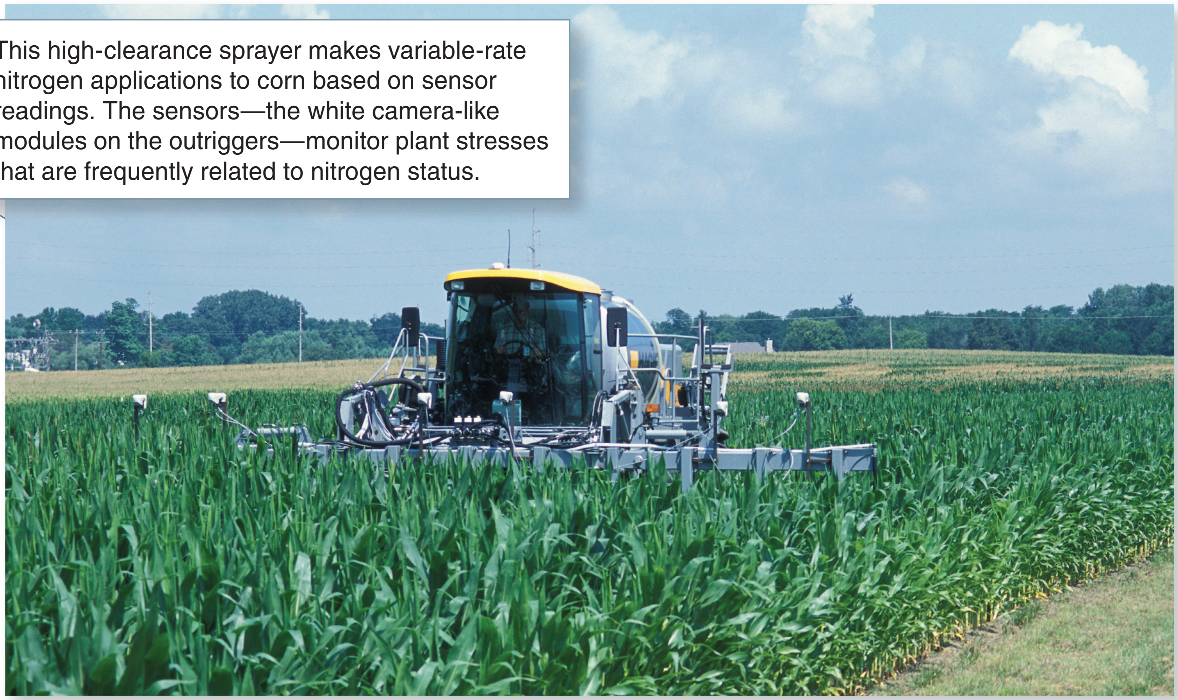
Contents

This report was prepared by Strategic Business Insights (SBI) under the auspices of the Director of the Strategic Futures Group. It is not an IC-coordinated report.

Use of Sensor To Adjust Fertilizer Application



This high-clearance sprayer makes variable-rate nitrogen applications to corn based on sensor readings. The sensors—the white camera-like modules on the outriggers—monitor plant stresses that are frequently related to nitrogen status.

Use of Global Positioning System (GPS)

In Missouri, an agricultural engineer examines corn from this combine's grain flow sensor. The combine is linked to the satellite-based GPS, allowing precise yield and location data to be correlated with soil samples taken earlier throughout the field. This information will help growers plan best fertilizer rates for the next crop.

Source: USDA Agriculture Research Service (ARS).

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Discussion

Introduction and Background

The principal challenge facing world agriculture is finding the means of increasing agricultural productivity—producing more with fewer resources (land, fertilizer, water, and pesticides)—to meet the demands of an increasing world population. **Technology will certainly be one of the primary tools for accomplishing agricultural productivity improvements, but the complex factors that affect productivity do not point to a single or even a handful of new technology innovations that can markedly impact agriculture.**

Although plant breeding was the key technology of the highly successful "Green Revolution" between the 1940s and the late 1970s, other technologies—fertilizer, water management, and pest control—were among those required to achieve the phenomenal increases in agricultural productivity experienced in developing countries from 1960 to the late 1990s. Similarly a combination of technological innovations will likely be required to achieve future increases in agricultural productivity and product quality.

- The primary goal of the application of technology is increased agricultural productivity. Improving nutrition of agricultural products is the secondary goal.

The technologies that will have the largest impact on agricultural productivity in the next 10 years include the use of existing genetically modified crops, soil and water management, pest control, and post-harvest processing.

Molecular biology applications to plants and animals are the technology advances most likely to have the greatest impact on agricultural productivity by 2040. Enhancing plant and animal traits by the conventional methods of cross-pollination, grafting, and cross-breeding is a slow trial-and-error process. **Advances in molecular biology provide a means of making specific changes relatively quickly through over-expression or deletion of genes or the introduction of foreign genes.**

- The advances in plant molecular biology are supplementing the classical plant genetics used in the Green Revolution to improve plant productivity. The developments stemming from advances in animal molecular biology are supplementing conventional breeding practices to improve livestock productivity.

- The developments of molecular biology can lead to more effective plant and animal breeding by examining the entire genome of all organisms for potential improvements to crops and livestock.

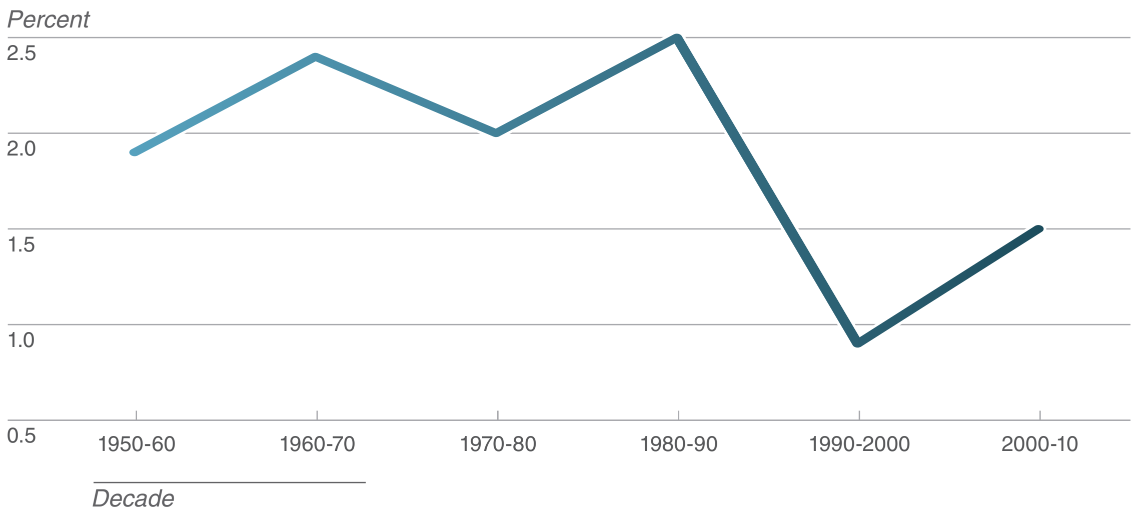
Emerging Technologies

Grains

The productivity of the grain segment of the agricultural industry is key to meeting global food demands. The United Nations Food and Agriculture Organization (FAO) estimates that to meet the food needs of the world population in 2030, the agricultural sector will have to produce an additional billion tons of grain per year, which is roughly a 50-percent increase over the production of 2.2 billion tons in 2011.

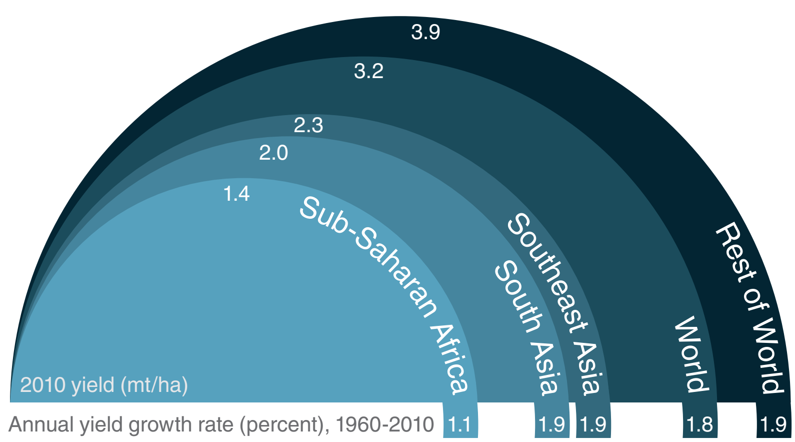
Grain Yields

World Average Annual Increase in Grain Yields



Source: Calculated from Masters, Will, "Africa's Turnaround," presentation at "Research Day on Sustainability," Tufts University, 3 May 2011.

Grain Yields and Annual Growth Rates for Different Regions of the World



Source: Calculated from Masters, Will, "Africa's Turnaround," presentation at "Research Day on Sustainability," Tufts University, 3 May 2011.

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With the molecular biology tools now available, plant breeders will possibly be able to achieve grain yields sufficient to meet world population food needs through to 2040.

Although many agricultural products are grown, grain crops are the most important source of food in the world. Grains are used not only for direct human consumption but also for the production of livestock and biofuels. From 1960 to 2010, annual cereal production increased by 270 percent from 800 million to 2.2 billion tons even though the hectares under cultivation increased by only 8 percent. Over those five decades, the average grain yield for the world increased from 1.3 to 3.2 metric tons/hectare (see chart on facing page). Technology advances resulting from the Green Revolution that were introduced in the 1960s more than doubled the yield and added more than a billion tons of all grain types to the world food supply. As the graphic on the previous page shows, the rate of increase in grain yield from the advances spurred by the Green Revolution is tapering off. This indicates that yield increases through 2040 will require some new technological advances to assure the needed 50-percent increase in grain production.

The graphic at the bottom of the previous page shows the yield and yield growth rates for different world regions. The similar annual growth rates indicate the introduction of technological advances during the Green Revolution in most of the regions. The growth rate in Sub-Saharan Africa is lower because the advances during the Green Revolution were not adapted to the different soil, climate, and geomorphic conditions of that region. Furthermore, economic conditions within the region did not support the investment in new technologies. The Rest of the World includes mostly the developed countries, and the difference in yield indicates that there is potential for some increase in the other regions.

Geneticists have developed specialized seeds by mapping plant DNA that can improve the control of crops by increasing yield with fewer inputs. As biotechnology tools develop through 2040, the cost of conducting transgenic[1] research projects will probably decrease substantially and the productivity of transgenic plants will spread from developed countries to developing countries. Although the cost of identifying a gene in a single plant was $2 a few years ago, it now is about $0.15 and developments now taking place could reduce this to $30 for one million genes. By 2040 gene identification might become routine and no longer a significant plant development hurdle.

- Molecular breeding in plants will likely accelerate the commercialization of new plant cultivars[2] that have higher grain yields and better agronomic traits. The cost of gene sequencing and mapping is steadily declining to the point where these technologies will likely become routine by 2040. Drought-tolerant maize, which received regulatory approval by the United States Department of Agriculture (USDA) and European Commission, is an example of the application of marker-assisted selection technology that accelerates the plant breeding process.

- Transgenic plant technology has advanced remarkably with a number of technical breakthroughs in pesticide and herbicide resistance. However, its application has been slowed because of public and regulatory concerns about the potential harmful effects of the technology. It is unlikely to be fully developed and deployed by 2040.

The advances in plant genomics come at a cost to the farmer. The cost of genetically

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[1] Transgenic technologies transfer genes with specific traits from one species or organism into another species or organism.

[2] A cultivar is a plant or group of plants selected for desirable characteristics that can be maintained by propagation.

transformed seed can be five to seven times higher than conventional seed. However, based on US experience, herbicide and pesticide-resistant crops pay off. In 2011, 88 percent of the corn crop and 94 percent of the soybean crop in the United States were genetically transformed. As efficiencies in developing genetically transformed crops continue to increase to 2040, the economic advantages of using these crops will also increase.

Livestock

Similar to plants, livestock breeding is taking advantage of the developments in molecular biology to accelerate development of highly productive and healthy animals. Genetic analysis of animals through molecular biology has also improved the quality of livestock.

Transgenic technology provides the means of inserting a desirable gene or set of genes from one animal species to another. *E. coli*, transgenically modified with the genes from a cow that generate the hormone bovine somatotropin (BST), produces BST by fermentation. The injection of transgenic BST into dairy cows enhances the production of milk and is now widely used in US dairy farming.

Marker-assisted selection, another use of advanced molecular biology, gives scientists the tools to identify genes that can enhance beneficial traits in livestock. These include controlled growth rate, resistance to disease, tolerance of heat and cold conditions, lower cholesterol in eggs, and an increased lean-to-fat ratio in pigs.

Water and Soil Management

Besides solar radiation and soil, agriculture depends on two other major inputs—water and fertilizer. Over the last few decades, half the increases in yield resulted from increased use of fertilizer and irrigation.

Because agriculture consumes 70 percent of the freshwater supply, and 40 percent of the world's agriculture depends on irrigation, any sustained increase in agricultural productivity by 2040 will require efficient water management. Current irrigation practices waste 60 percent of the water drawn from freshwater sources. Because water scarcity can limit the productivity of major agricultural crops, some farmers in developed countries are applying subsurface drip irrigation technology. However, the technology has higher installation costs than conventional surface irrigation. **As the price of water used for agriculture rises in response to increased demand for scarce water resources, subsurface drip irrigation, because of its high water efficiency, will likely become the norm by 2040.**

- Advanced drip-irrigations systems, vapor-transfer irrigation, and hydroponic greenhouse technologies are being developed and employed to enhance the efficiency of water utilization in agriculture.

- Drought-tolerant and salt-tolerant plants, which are being developed by using molecular biology techniques, employ emerging technologies that can reduce the consumption of freshwater sources.

Global fertilizer consumption per hectare had an annual increase of 5.5 percent in the 1960s and is projected to grow 1.2 percent annually from 1990 to 2020. **Most of the fertilizer technology in use today was developed in the 1950s through the 1970s. Because publicly funded fertilizer research has mostly ceased, significant development and deployment of new and more efficient fertilizers and fertilizer manufacturing technologies will not likely occur between now and 2040.**

- Research work currently underway focuses on agronomic efficiency and minimization of environmental impacts from fertilizer use.

- A breakthrough achievement would be the genetic alteration of non-legume plants so that they could convert nitrogen from the atmosphere into ammonia and greatly reduce the need for chemically synthesized fertilizer. The large number of genes involved in the symbiotic relationship between soil microorganisms and legumes results in a very complex problem that has only achieved a glimmer of scientific insight at this time. Research is progressing in this field, however by 2040 farmers will likely still be using conventional plant nutrient approaches.

Aquaculture

As an excellent source of affordable, high-quality animal protein, fish accounted for approximately 16 percent of the global population's intake of animal protein in 2010 and approximately 6 percent of all protein consumed. As the fastest growing animal-food-producing sector, aquaculture—the growing of aquatic animals and plants—contributed 46 percent of total food fish consumption in 2008, up from less than 10 percent in 1970. It will soon account for more than half of the world's supply of food fish. Major increases in aquaculture productivity through the entire production and distribution cycle have driven this growth. Prices of many aquaculture products, including large-quantity products like carp and tilapia, have fallen steadily over the last 20 years. **Demand for aquaculture will continue to grow to meet the world's demand for protein. Based on a 2006 World Bank report, aquaculture producers will likely see growth rates ranging from 1.4 percent to 5.3 percent per year in the next 20 to 30 years. The key technologies required to produce this growth—all of which are feasible—are genetically improved fish, new feed and feeding practices, closed recirculating systems, and open ocean systems (large cages in deep-ocean waters).**

Precision Agriculture

Precision agriculture supported by information technology is increasingly employed by farmers. These technologies allow farmers to precisely control crop and livestock production. Existing precision agriculture techniques tend to focus on discovering how factors like soil quality, water availability, and drainage patterns vary within a single field. They are then used to adapt planting, harvesting, and management strategies to address those variations. Because of its history, precision agriculture is bound up heavily with the large-scale industrial-agriculture practices. They predominate in regions like the midwestern United States, southern Brazil, and parts of Canada, Germany, and Australia.

For precision agriculture technologies to diffuse on a wide scale in the future and in a manner that will have a substantial impact on global food production and resource consumption, the kinds of automated systems that are emerging on large farm vehicles will have to decrease in size and price. They will also need to scale down to work well for small plots in the developing world where the greatest potential productivity gains can be made.

Biofuels

The use of biofuels—primarily ethanol and biodiesel—for transportation has grown rapidly worldwide. However, according to many government, academic, and industry experts, today's biofuels have drawbacks. They provide little environmental benefit, consume food crops, and are expensive. US corn-based ethanol production reached 13 billion gallons in 2010, but consumed nearly 30 percent of the US corn crop while supplying only 9 percent of US gasoline demand. **By 2030, a transition to next-generation technologies that convert biomass (rather than food crops) to advanced biofuels and chemicals will be essential to improve the security and affordability of the world's food**

supplies. Such a transition would also reduce global dependence on petroleum fuels.

- **Developers are just beginning to scale up the new biofuel technologies to commercial production and face significant technical and financial risks.**

- One of the biggest drivers of advanced biofuels is government policies. Both the United States and the European Union have aggressive biofuel regulations in place that include sustainability standards.[3] We do not know yet whether nations will be able to meet their targets for producing advanced biofuels using nonfood crop feedstocks.

The long-term viability of advanced biofuels depends on relative prices for competing petroleum-based gasoline and diesel fuels. In addition, very high-efficiency vehicle technology, including hybrid and pure electric vehicles and hydrogen-powered fuel-cell vehicles, will help to reduce fossil-fuel use and carbon emissions and thus will also compete with advanced biofuels.

Post-Harvest Processing

Post-harvest losses of grain are 10 to 20 percent. Fruit and vegetable losses can be as high as 50 percent in developing countries and as low as 5 percent in developed countries. Post-harvest research receives only about 5 percent of the total agriculture Research and Development (R&D) funding. **Most of the technologies deployed in this sector are mature and reasonably effective. Existing irradiation technology might reduce losses substantially, but the technology, like transgenics, has met with public resistance to its application.** FAO and the International Atomic Energy Agency (IAEA) have been active in regulating food irradiation. Through 2011 more than 60 countries had allowed the use of food irradiation on at least one product. Since the technology is already dispersing throughout the world, it might have a bigger role by 2040 in disinfestations and shelf-life extension.

Preparing for the Long Haul

Technological innovation in agriculture is complicated by the multiplicity of parameters that affect the productivity of crop or animal herds. This means that no one breakthrough technology can assure an increase in the productivity of world agriculture. Improvements in plant and animal genetics need to be cost-effectively integrated with new technologies in the management of pests and diseases, soil, animal nutrition, and water. Furthermore these technology developments have to be adapted to a wide variety of local agricultural conditions.

- For many of the emerging technologies to be deployed globally they will have to be adapted to the mix of commodities produced, production practices, and environmental conditions of different localities. Global research efforts of USDA and the Consultative Group on International Agriculture Research (CGIAR) are critical to lifting global production. Local implementation might require additional factors such as investments in agricultural research at the developing-country level as well as in agricultural human capital and infrastructure.

- The rapid advances in molecular biology are providing the tools to delve into the complexities of plant and animal traits. These

[3] The EU Renewable Energy Directive requires 10 percent of transportation energy from renewable energy by 2020 and that the lifecycle greenhouse gas emissions of biofuels consumed be at least 50 percent less than the equivalent emissions from gasoline or diesel by 2017 (and 35 percent less starting in 2011). Also, the feedstocks for biofuels "should not be harvested from lands with high biodiversity value, from carbon-rich or forested land, or from wetlands." The US Renewable Fuel Standard (RFS) requires at least half of the biofuels production mandated by 2022 should reduce lifecycle greenhouse gas emissions by 50 percent.

Technology Hurdles

Assessing how new technologies will affect agricultural productivity includes an examination of the hurdles to their adoption. Currently many of the biotechnologies that have been commercialized face resistance throughout the world from the public and regulatory agencies. Transgenic technologies that have produced pest-resistant corn, genetic transformation of crops for herbicide resistance, and bovine somatotropin (BST) produced by genetic engineering have all been banned in some parts of the world. If public and regulatory resistance continues through to 2040, the pace of agricultural productivity gains will slow down.

The cost of introducing new technologies into agriculture might also limit their widespread application. Although transgenic technology research is an ongoing activity in many agricultural research institutions, application in a particular region is quite costly. For example, the Insect Resistant Maize for Africa (IRMA) project cost $6 million over a five-year period, and a transgenic sweet potato research project cost $2 million.

Annex J shows the cost of US production of corn, soybeans, and wheat. The higher cost of seed for genetically engineered crops will probably come down by 2040, but until the prices do come down, there will be a slow application of genetically engineered crops in developing countries where grain yields are in need of the most improvement. The more complex wheat genome and its relatively lower economic value have also hindered the development of genetically engineered wheat and will likely continue to do so.

Although precision agriculture is at an early stage in developed farm economies, its potential for increased widespread deployment by 2040 may be limited. The present capital recovery costs for the three crops shown in Annex J account for 15 to 24 percent of the production cost. Precision agriculture would likely add considerably to these existing costs, and it may be that the yield increases with this added technology cannot compensate for the added costs.

advances have already had significant impacts on agricultural productivity and are likely to continue providing improvements in agricultural practices.

- **However, to examine the impact of emerging technology on agriculture, one needs to look beyond the advances in molecular biology to other fields including chemistry, electrical engineering, remote sensing, and computer science. The tools from these fields are not necessarily developed specifically for agriculture, but their application can make improvements in controlling the management of soil, water, crops, and energy inputs.**

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Annex A

Emerging Technologies for Crop Productivity Improvement

As occurred during the Green Revolution, the most likely technology breakthroughs to appear in agriculture through 2040 will likely come from plant breeding to improve desired plant traits. The difference in plant breeding now as opposed to 50 or more years ago is the availability of the tools based on molecular biology, which have provided many insights into the genetic makeup of plants and its relationship to important agronomic traits related to plant productivity. Plant scientists use these molecular biology tools, most of which have been developed in the medical sciences, to introduce desirable agronomic traits in plants. The molecular biology tools include rapid sequencing, gene cloning, gene mapping, recombinant DNA, polymerase chain reaction, and biochips. In addition, bioinformatics, which uses applied mathematics, informatics, statistics, computer science, artificial intelligence, chemistry, and biochemistry, is essential to making the plant breeding process much more efficient.

Historically crop improvement has been done by selecting the best performing plants or seeds and using them for planting in the following year. As genetic science becomes better, plant breeding will be done by modifying the genetic composition of a plant through cross breeding, then selecting plants that exhibit improved traits. Conventional plant breeding has limits in that it can be applied only to plants that sexually mate, limiting traits that already exist in a species. Additionally when plants are crossed, traits besides the one of interest are transferred, some of which might negatively impact the desired trait or the yield potential of the plant.

Molecular biology for crop improvement has two approaches:

- **Gene technology** converts the conventional breeding process to a molecular plant breeding process. The tools of molecular biology have produced a major breakthrough in plant breeding by using gene technology to identify the genetic origin of a trait or group of traits. This technology can accelerate the process of developing improved plant cultivars from two or three decades long to less than a single decade.

- **Transgenic technology** transfers the genes from other plant species or organisms into the genome of a plant. Transgenic technology allows a single trait from any living organism to be introduced into a plant. This technology enables the introduction of new traits not found in a particular species of plant that can provide agronomic benefits.

Molecular Crop Breeding Technology

Numerous molecular biology tools are used in modern plant breeding technology. By and large, these technologies have been developed in the medical sciences. The technologies flowing from the Human

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Genome Project[4], which was sponsored by the US Government, have been essential elements of molecular crop breeding.

Gene Sequencing determines the nucleotide sequence of the entire DNA in a genome. It is a formidable task with the genome of maize having 2.3 billion base pairs of DNA in 32,000 genes in 10 chromosomes. Scientists have also sequenced the genomes of rice, sorghum, cassava, and poplar, and the sequencing of other plants is underway. Because highly automated sequencing innovations are simplifying the task and reducing the cost, sequencing of a particular species of plant by 2040 might become a routine task costing only thousands of dollars. The research effort on maize conducted at Washington University in 2009 cost approximately $30 million. Automated sequencing instruments now have the capability of generating 500 million DNA base pairs per day.

Annotated Plant Genomes follows the completion of gene sequencing. Annotation is the process in which the DNA sequences are analyzed to determine a gene location in the chromosome, the gene structure (open reading frames, exons, introns, and regulating regions), and gene function (the role of gene products and regulatory features). By using the existing genomes in databases, e.g., *Arabidopsis* and rice, as models, the annotation of a particular crop in an agricultural region can be more rapidly developed. By 2022, the complete sequences of many crops will likely be known, all genes will be identified, alleles (variants) of important genes will be known, and the association of relevant genes with traits will be established to increase yield or establish other important agronomic characteristics.

Proteomics complements DNA technology. Because DNA sequences alone are not sufficient for understanding how genes are transcribed and translated into functional proteins, another emerging technology derived from molecular biology—*proteomics*—provides a tool for further annotation of the structural and functional characteristics of a genome. The direct identification and quantification of the proteins from a genome has been made possible by advances in chromatography, electrospray ionization of peptides, tandem mass spectrometry, bioinformatics, and computer technology. These technologies have enabled the monitoring of 8,000 or more proteins of whole plants with reproducible quantitative comparison of different samples. Peptide mass spectrometry has the ability of identifying single amino acid polymorphisms derived from alleles, which facilitates the detection of genetic markers.

DNA Markers are sequences of DNA known to be related to particular genes or traits. Using marker assisted breeding to determine the best cross breeding and progeny shortens the time of having a crop cultivar with improved characteristics by two to five years when the relationship of a gene variant to a trait is known, then the variant gene can be used as a marker of that trait. A plant for cross breeding can then be identified by the presence of the marker in its genome without the need of testing for the expression of a trait. This helps the selection of diverse parents for development of a specific trait and reduces the number of breeding generations.

Although great strides have been made by geneticists in locating on genetic maps the loci linked to a particular trait using genetic markers, the measurement of phenotypes (observable characteristics such as morphology, crop or product development, biochemical or physiological properties, and product composition) nevertheless remains a lengthy process. Plant breeders need to assess hundreds of thousands of progeny from many plant crossings in multiple environments to show which loci on a

[4] The Human Genome Project matured technologies, instrumentation, and robotics for more efficient DNA sequencing.

chromosome move together in heritable associations (haplotypes). *Quantitative Trait Loci* (QTL) technology is a method that can reduce the effort required to establish gene-trait associations. QTL analysis uses the statistical frequencies of alleles to indicate the relationship between chromosome loci and quantitative or continuous traits. These associations have been extensively analyzed on multiple species (rice, maize, and other crops); results can help infer gene-trait relationships in other crops. Another technique that could add efficiency in identifying gene-trait relationships is *functional genomics*, which examines the dynamic aspects of genomics. In plants, manipulating or adding genes and then examining the effects on a trait has the potential of identifying genes that regulate a trait.

Induced Mutation Breeding is a technology that has been used since the 1930s for creating genetic variation of traits for crop improvement. Plant breeding requires genetic variation, but natural variation is limited and genes with a desired trait might not be in the gene pool. To induce genetic variation, mutagenic agents, such as radiation or certain chemicals, are used on seeds from which mutants with desired properties can be selected. Before the tools of molecular biology and plant cell culture became available, the selection of desirable mutants was tedious and took many years of observing multiple generations of field plantings. These new tools have moved much of the work from the field to the laboratory. *Targeting Induced Local Lesions In Genomes* (TILLING) is an approach to accelerate the plant breeding process by inducing mutations in known genes in large populations of plants, which are then screened for mutations with the high-throughput genetic analysis tools of molecular biology.

Crop improvement fundamentally depends on identifying genetic variation in crops. The emerging technology advances resulting from the Human Genome Project that relate human genetic characteristics to healthcare needs are transferable to crop improvement needs. Applying the tools of molecular biology to plant breeding is leading to an extensive understanding of the variations (alleles) in every gene in a plant so that the genetic diversity of equivalent segments (haplotypes) in a crop germplasm would provide the ability to select efficiently and rapidly parent plants and subsequent progeny. Key traits such as drought tolerance and long-lasting resistance to diseases and pests, however, are complex and involve many genes. Gaining that level of understanding requires a *Systems Biology* approach in which the dynamic interaction among proteins, metabolites, biochemical pathways, and signaling pathways are analyzed in an integrated fashion. This requires progress in computer modeling to guide experimental observations. The search for higher productivity in crops, including the understanding of these complex traits and the application of a systems approach, might be one of the ways of gaining the needed breakthroughs by 2040.

Transgenic Crop Technology

To avoid limitation to the natural and induced genetic variations of a crop, scientists have developed transgenic technologies in which traits from other plant species or organisms are inserted into a crop genome. Herbicide resistance and insect resistance are commercialized seed products of transgenic plant technology in common use. A gene from the bacterium *Bacillus thuringiensis* (Bt) that produces a toxin to kill insect pests has been inserted by recombinant DNA technology into the genome of maize, cotton, and potato, resulting in higher yields and requiring fewer chemical pesticide applications. By inserting a gene from Agrobacterium that produces enzymes resistant to glyphosate, a common herbicide, scientists have used recombinant DNA technology to develop herbicide-resistant crops that make weed control more efficient. Herbicide-resistant soybean, maize, canola, sugar beet and cotton are all commercialized and herbicide-resistant wheat and alfalfa are under development.

The transgenic development process requires a plant to go through seven steps before its modified form becomes commercialized:

- DNA extraction from a desired organism.
- Gene cloning by separating the single gene of interest from the extracted DNA and using the *Polymerase Chain Reaction* (PCR) technology to produce many copies of the gene.
- Gene design by modifying the gene to function in the crop plant cells using new promoter and termination sequences and adding a marker gene for antibiotic resistance.
- Gene insertion into the nucleus of cells of a callus tissue of the crop plant by *Agrobacterium*, using a gene gun or microporation technology.
- Propagation of the plant in tissue culture in a medium containing an antibiotic so that only the transformed callus tissue can grow into a plant.
- Maturation of the transgenic plants in a greenhouse and collection of the seeds.
- Backcross breeding to combine the desired traits of the parents with transgenic plant to produce a single line with the offspring crossed back with the parent elite line until a high yielding transgenic line is produced. About 6 to 15 years are needed for the transgenic line to be commercialized.

Hundreds of known transgenes can affect the traits of crop plants, but few have been commercialized. As more fundamental knowledge is developed about plant genomics and the dynamics of plant cells, those transgenes that affect crop productivity will be applied. Researchers are developing technologies that can refine the process for applying transgenes to agronomic problems:

- **Directed Evolution of Genes.** Laboratory techniques have been developed to shuffle domains of genes or to generate random mutations in gene sequences that can alter enzymes or proteins encoded by these genes. This approach has been used to alter Rubisco, an enzyme in plants that converts carbon dioxide to biological molecules, and enhance photosynthesis and plant growth. This approach has also been proposed for altering Bt to provide toxicity in plants to specific pests.
- **Gene Silencing.** The discovery that small RNA molecules are active in plant development and resistant to stress has led to the examination of *RNA Interference* (RNAi) technology. Although at an early stage of research, researchers can design and overexpress (enhance the functionality of) genes encoding RNAs that target pests or pathogens. Likewise, researchers can silence genes that are unique to pests or pathogens and as a result the pests and pathogens cannot survive. This technology has shown some promise in control of bollworm in cotton.
- **Metabolic Pathway Engineering.** As the understanding of metabolic pathways in plants increases, transgenically enabled traits will become more common. An example of this technology currently underway is “Golden Rice,” a rice that contains carotene as a means of producing a fortified food for areas deficient in foodstuffs containing Vitamin A. The technology involves three transgenes—one from bacteria, one from maize, and one from a daffodil. The combination of these genes gives a metabolic pathway that produces beta-carotene (Vitamin A precursor).

- **Site-Specific Gene Insertion.** Current transgenic practice inserts genes into a plant chromosome at random, which leads to large variations in expression of traits and the need to screen hundreds of transgenic plants to determine the optimum insertion. If one allele could be replaced by another at a specific site in a homologous recombination, then the process of plant improvement would be greatly enhanced because it enables the study of functions of specific genes. Homologous recombination requires a double strand break in a chromosome. *Zinc Finger Nuclease* (ZFN) technology enables a method for making precise double-strand breaks in chromosomes for a homologous recombination of an allele. Different zinc finger nucleases can be engineered to specifically make a break at a particular gene. In addition to ZNF technology, other enzymes can be used that are capable of recombining two identical specific sequences. This technology can be used to stack multiple transgenes at a target site to provide several new traits to a plant. Single transgene insertions have been performed in rice, wheat, and corn.

- **Artificial Chromosomes.** Ultimately crop improvement will require stacking the best alleles for important genes into a single plant variety at a single locus so that the transgenes do not segregate in later generations. Although homologous recombination and site-specific gene insertion provide this capability, artificial chromosomes might be a more efficient method. The process consists of synthesizing a mini-chromosome by linking genes of interest and forming a singular loop of DNA. The artificial chromosomes are then inserted into plant cells by particle bombardment. In experiments with maize, the artificial chromosomes were regularly inherited in up to 93 percent of the plant offspring after three generations. The technology has the capability of stacking up to ten genes. Syngenta Biotechnology and Monsanto have both formed partnerships with the inventing company, Chromatin. Because about 20 genes are involved in nitrogen fixation, artificial chromosome technology might be a route to install nitrogen fixation capabilities in non-legume crops like rice, wheat, and maize.

- **Apomixis.** Because hybrid seeds are more expensive than seeds saved from a previous harvest, farmers might chose not to use them, even though they have higher yields and greater resistance to pests and diseases. If the performance of hybrid seeds could be maintained from one harvest to the next, the cost of seed would be considerably reduced. In some wild plant species, a hybrid genotype is preserved through apomixes, which is a process by which progeny seed are produced in a plant without sexual fertilization. Research is underway to see if transgenes can be designed to change the mode of plant seed production from sexual fertilization to apomixes.

- **Signals of Plant Stress.** Research has shown that transgenes can be designed and inserted in a plant that responds to stress and provides an observable signal indicating deficiencies in soil or water or early-stage disease. A signal such as a pigment change produced by the plant at an early stage in its development could give the farmer time to take corrective action to preserve the productivity of the crop.

Biocontrol Technology

Although most farmers use pesticides and herbicides or genetically engineered plants for pest and weed control, biocontrol technology is an alternative that has also been used. Biocontrol consists of releasing a specific natural enemy (parasites, predators, or naturally occurring pathogens) to control invasive weeds and insect pests, nematodes, and plant pathogens. This technology requires extensive research of a particular pest in a particular region and for a particular crop. The United States Department of

Agriculture (USDA) and a number of universities have biocontrol research programs aimed at specific pests. The USDA biocontrol projects include control of Asian citrus plant lice with a parasitoid, control of rangeland grasshoppers with fungal pathogens, and control of the Russian knapweed with a gall midge. The EU Specific Targeted Research Project is studying the enhancement and exploitation of soil biocontrol agents for bio-constraint management in crops. The European and Mediterranean Plant Protection Organization have an extensive list of biological control agents that are widely used in the 50 member countries. Although biocontrol technology has been used for many decades, it might have an increasing impact in the future as concerns about the use of chemical pesticides increases.

Biocontrol is a component of *Integrated Pest Management* (IPM), which is a process for managing a pest problem that combines biological, cultural, physical, and chemical controls that minimize economic, safety, and environmental risks. Farmers currently use some aspects of integrated pest management and will probably include more of its elements as knowledge gained from molecular biology of pests and weeds increases, and the advantages of using less pesticide and herbicides increase.

Application of molecular biology has been proposed by scientists around the world as a means of making biocontrol and biopesticides more effective by improving their success rate, robustness, and reliability. Genetic engineering could enhance the speed of pest kill, reduce the initial amount of biocontrol agent required, and enhance persistence of the agents. This technology is at a very early stage of development. As an example of its potential, scientists at the Shanghai Institute for Biological Sciences and the University of Maryland increased the virulence of an insecticidal fungus by using a transgene from a scorpion that expresses an insect-specific neurotoxin. The genetically engineered fungus had its toxicity to the tobacco hornworm increased 22 fold. Other research has demonstrated genetically engineered hypervirulent viruses and fungi as controls of pests and weeds. However since genetically engineered biocontrol is still in the early stages, it will not likely have a measurable impact on agriculture by 2040.

Annex B

Emerging Technologies for Livestock Breeding and Health

In a process similar to plant breeding and protection, the advances in molecular biology are having an important impact on livestock management. For centuries, livestock breeders have been observing variation of traits in breeding animals and selecting those with genetically superior traits, such as growth rate, quality/quantity of products (milk, meat, eggs), fertility, survival in different environments, and disease resistance. Worldwide in 1993 there were 783 cattle breeds, 863 sheep breeds, 263 pig breeds, and about 1,260 chicken breeds. The selective animal breeding process takes several decades to reach a highly productive livestock pedigree. Through a lengthy process, animal breeding has proved to be successful as exemplified by the three-fold increase in milk yield from dairy cattle over a period of 50 years without any knowledge of the relationship between genes and traits. The emerging use of genomic information, however, will likely increase the efficiency of the breeding process as well as enhance the health of livestock by 2040.

Marker-Assisted Selection Technology in Livestock Breeding

Genome sequencing of economically important livestock has been proceeding rapidly by leveraging the technologies applied in the Human Genome Project. Genome sequences for chickens, cattle, swine, sheep, fish, and horses are now available and provide a basis for understanding the genetic variation related to economically important traits. Similar to results in the Human Genome Project, sequencing of animal genomes has uncovered a large number of genetic polymorphisms that can be used as markers for evaluating the genetic basis of phenotypes. The genomes that have been sequenced can be used as a reference for a particular family of animals.

Using gene mapping, scientists have begun to locate regions of DNA in an animal genome that influence production traits. They use molecular biology and quantitative genetics to find differences in the DNA sequences in these regions. To discover individual animals with superior traits, breeders apply Marker-Assisted Selection (MAS) technology in which Single Nucleotide Polymorphisms (SNPs) analyses are used to locate markers in the genome. Markers are not normally the actual gene sequence, but rather a sequence that is near the gene of interest in the chromosome. Laboratory tests can then genotype individuals to determine which DNA-marker alleles they carry. Some simple traits such as coat color and presence or absence of horns are controlled by one gene whereas economically important traits (e.g. birth weight, reproduction, meat quality, or milk production) are complex traits controlled by protein products of multiple genes and affected by the environment of the animal. This process is an emerging technology that will likely become increasingly more precise through 2040. MAS has the potential of more rapidly discovering superior livestock genetics and enhancing the productivity of livestock farming.

Genetic Engineering of Livestock

MAS has the potential of vastly increasing the efficiency of selective breeding livestock, but it cannot introduce traits that are not part of a particular animal species as can genetic engineering of animals. The technology has been available for almost 30 years, and it has evolved from a very inefficient level at which only 1 to 5 percent of the offspring were transgenic because the pronuclear microinjection into an animal egg immediately after fertilization produced random integration of the transgene in the genome. The introduction of somatic cell nuclear transfer (SCNT) technology greatly advanced the transgenic modification of animals. This technology consists of inserting a transgene in the nucleus of the cell of the animal and then transferring that nucleus into the denucleated egg of the animal, and then transplanting that egg into the womb of a surrogate animal. This technology can also be used to clone livestock as was done with the sheep, "Dolly." It is now the most efficient option for producing transgenic or cloned animals. In recent years, other efficient methods of delivering transgenes have been developed. Transposon-mediated transgenesis technology consists of microinjecting a transposon-containing plasmid DNA into fertilized eggs, which are then transferred to a surrogate female. This technology has produced transgenic animals with an average frequency of 80 percent. Viral-mediated technologies are also being developed for transferring the transgene. Currently a number of livestock species with a variety of transgenes have been successfully produced using these methods. Other areas still require technology improvement, such as when a non-targeted gene insertion can disrupt important genes in the host animal; this decreases the efficiency of producing animals that express the transgene.

Until the present, the only application of transgenics in animals that has been commercialized is a drug, a recombinant antithrombin, produced in transgenic goats' milk. Transgenic animals for food production have not achieved regulatory approval anywhere in the world, and the technology has met with public resistance for food applications. Some potential applications, however, could benefit livestock agriculture by increasing the efficiency of production, improving animal health, and altering the nutritional value of animal products. A genetically engineered Atlantic salmon with a growth hormone transgene is undergoing the FDA approval process. These transgenic salmon reach market weight faster and use feed more efficiently than wild salmon. Another potential application is genetically engineering a pig to synthesize lysine, an essential amino acid. A metabolic pathway for synthesizing lysine is not part of any pig breed; as a consequence, pig feed must be supplemented with lysine. By introducing a transgene for lysine synthesis from a bacterium or yeast into a pig genome, the process of separately adding lysine to pig feed could be eliminated. Transgenics can also be used to protect animal health. Using a transgene from a nonpathogenic species of *Staphylococcus* that produces lysostaphin, scientists genetically engineered cows that produced lysostaphin in their milk to resist the bacteria *Staphylococcus aureus* that causes mastitis. Despite the potential for genetic engineering technology to produce major breakthroughs in livestock production, the technical and regulatory hurdles that transgenic and cloning face make them unlikely to have a major impact on agriculture by 2040.

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Annex C

Emerging Water Management Technologies

Because agriculture uses approximately 70 percent of the global freshwater supply and 40 percent of agriculture uses irrigation, technology that reduces irrigation requirements is critical to the long-term availability of water. Global population increase will put more demand on arable land and water resources. Irrigation as generally practiced is very inefficient. The Food and Agriculture Organization of the United Nations reported that agricultural irrigation wastes on average 60 percent of the water withdrawn from freshwater sources. Losses occur through evaporation, deep infiltration, or weed growth. Increasing the efficiency of irrigation for the global food production dependent on irrigation would have a major impact on water availability.

Although rainfed agriculture, which represents 58 percent of global agriculture production, does not rely on rivers and lakes for its water, technologies do exist that can contribute to increasing the yield of rainfed agriculture and reduce the need for withdrawal from surface water sources. Worldwide 69 percent of all cereal area is rainfed, including 40 percent of rice, 66 percent of wheat, 82 percent of corn and 86 percent of coarse grains. Adopting water management technologies in rainfed agricultural regions can contribute to overall agricultural productivity.

Desalination of seawater and brackish water is widely practiced and has in some cases achieved water cost of production close to that of freshwater acquisition. Even though desalination might be economically feasible for household and industrial water, it is not feasible for large-scale agriculture. Adopting technologies that increase water-use efficiency is the only option farmers have for confronting global water scarcity.

Advanced Irrigation Technology

Subsurface-Drip-Irrigation Systems. Recognizing the low-water efficiency of irrigation, farmers have begun using drip irrigation, which reduces water losses substantially. Drip-irrigation systems consist of plastic tubing with regularly spaced emitters or pores that distribute a controlled flow of water directly onto the ground. To avoid evaporation and apply water at the active root zone of plants, subsurface, drip-irrigation (SDI) systems are becoming the norm. Since the 1960s, Israel has led the application of drip irrigation in the world as the most efficient way of delivering water to plants and has made innovations applicable to large- scale agriculture. In desert climates evaporation causes as much as 45 percent loss of water in conventional surface or spray irrigation. Drip irrigation can reduce evaporative losses by 30 to 70 percent. Generally water-application efficiency (percentage of water delivered to a field that is stored in the crop-root zone) for SDI is 90-95 percent compared to furrow irrigation of 35-60 percent or sprinkler systems of 60-80 percent. Initially farmers used SDI for annual row crops and permanent tree fruits, but design improvements have made the technology suitable for any crop, including those not planted in rows or beds. Advances in drip-irrigation technology are well under way, especially in Israel, and the technology will likely evolve through 2040. The major limitation of SDI is its initial cost, which is about

$1700-$2000/hectare compared to $250-$1400/hectare for conventional irrigation. An additional cost advantage of SDI is its efficient application of fertilizer. SDI applies water directly to roots so less nitrate is leached from the soil and less fertilizer is needed. Other advantages of SDI include:

- Better weed and disease control because the absence of moisture above the soil limits seed germination and disease conditions
- Less concern about wastewater contaminating the crop with disease-causing microorganisms
- Long system life, typically 15 years because it is buried underground and out of the heat and sunlight

Except for Israel, SDI is not widely applied currently, but its high-water efficiency and likely cost reductions with improved designs will likely make it the norm for irrigation by 2040.

Vapor-Transfer Irrigation. To use salt water or other contaminated water for agriculture, vapor-transfer irrigation uses buried tubular pervaporation membranes that allow only vapor to transfer from inside the tube to the external soil. The vapor condenses in the soil where the plants can absorb the water; the salt or other contaminating minerals remain in the tube. This technology is at an early stage with only a few experimental applications completed so far. No cost data or long-term results have been published. As with any desalination technology, the issue of concentrate disposal remains. Although this technique might represent the beginning of a breakthrough in using saltwater for irrigation, we do not know how competitive it will be in 2040 with other desalination technologies to produce water for agriculture.

Variable-Rate Irrigation. Farmers can use precision agriculture to save water in crop irrigation. Precision agriculture uses advanced technologies such as global positioning satellites (GPS), remote sensors, aerial images, and geographic information systems (GIS) to assess agronomic condition-related to in-field variability. A farmer can use the information gathered by these systems to evaluate precisely sowing density, fertilizer requirements, and other conditions, including the timing and quantity of water for optimum plant growth in various sections of the farmer's field. A GPS receiver provides location data in a field to one meter or less. This information, along with remote sensing of soil conditions, leads to a series of GPS maps of a field. These maps show the moisture and fertilizer levels as well as other soil factors affecting crop growth. This process has given birth to an emerging technology: variable-rate irrigation. Because of the variability in a field—resulting from different soil types, topography, or multiple crops—different timing and amounts of water are needed in various areas. The rate of water application is controlled by varying the amount of time water flows in the irrigation system in specific locations in the field. In a study done in south Georgia using center pivot irrigation systems, 5.7 million gallons of water per year were saved on 279 acres, in comparison with uniform application of water on these fields. The tools to apply variable-rate irrigation are well developed and by 2040 their cost will likely come down sufficiently to lead to widespread application.

Yield Advantages with Selected Cultivars and Improved Water Management in Kamataka, India

Yield Improvement (percent)			
Crop	**Local Cultivar with Improved Management**	**High-Yielding Variety with Usual Management**	**High-Yielding Variety with Improved Management**
Finger Millet	74	22-52	103-123
Groundnut	27	13-36	47-83
Soybean	62	0	83
Sunflower	67	54-150	152-230
Maize	–	26	70
Sorghum	–	–	31

Source: CAB International Rainfed Agriculture. (NOTE: source does not explain blank cells)

Water Management Technologies in Rainfed Agriculture. Managing water in a rainfed farm operation can substantially increase crop yield as shown in the table.

The yield improvement with improved water management alone, even using a local cultivar, is evident. When integrated with a high-yielding variety, the yield improvement is remarkably improved. Of the rain falling on a crop in a semi-arid zone, 15-30 percent is used by the plant in transpiration, 30-50 percent is non-productively evaporated from the soil, 10-30 percent percolates through the soil, and 10-25 percent is surface run-off. Water management in rainfed agriculture involves two basic technologies: harvesting and evaporation control. Water is harvested by collecting and storing runoff and drainage for irrigation in dry spells. Secondly minimizing evaporation from the soil and maximizing transpiration by the crop accomplishes a "vapor shift." Water has been stored in tanks and ponds for centuries, but an emerging technology stores water in an underground aquifer through a recharge basin or through a recharge-extraction well. Soil management to reduce evaporation using mulching, zero tillage, intercropping, and windbreaks also results in vapor shift.

Greenhouse Agriculture

Hydroponic Greenhouse Agriculture. By growing crops on a large scale in hydroponic greenhouses, water usage can be reduced by 90 percent by precisely monitoring plants' water needs. Besides saving water, this technology has other advantages: reducing dependency on weather conditions, maintaining consistent crop quality, and avoiding pest control chemicals. Furthermore, greenhouse enclosures that use films to block infrared and ultraviolet light reduce water evaporation and require less cooling. The economics of crop production with greenhouse agriculture currently are not established, but even though greenhouses are currently being used in many parts of the world, their future growth depends on the cost of the greenhouses and the level of automation that can be applied.

Vertical Farms. The use of vertical farms for crop production, a step further than hydroponic greenhouse agriculture, would radically alter current agricultural practice for food production. The technology might be able to produce yields 20 times those of conventional agriculture with 95 percent less water. Envisioned as a means of keeping food production close to urban centers, it would have the advantages of greenhouse agriculture but also eliminate the need for additional farmland, reduce the extent of transportation of food products, and readily recycle the wastewater produced in urban centers. Vertical farming faces some foreboding challenges. It will probably not be energy efficient unless its design includes renewable energy (e.g. wind or solar power), especially since it is not able to rely entirely on sunlight. At this stage, vertical farming is a concept that envisions a radical change in agricultural production that has not been tested, giving its future adoption a high degree of uncertainty. Furthermore, a cost analysis comparing it to conventional farming has yet not been prepared.

Water Saving with Plant Genetic Engineering

Drought-Tolerant Crops. Another approach to save water in agriculture is to design plants that can survive and grow with less water. When a plant takes CO_2 from the atmosphere, it loses 500 to 1000 grams of water for each gram of harvested product. A drought-tolerant plant adapts to dry or drought conditions. Even though scientists have for years been breeding drought-tolerant plants, the genetic traits that contribute to drought tolerance are usually associated with low growth rates and poor yields. Scientists are now using the tools of genetic engineering to breed plants that can survive and grow with less water without a loss of yield. Researchers have discovered genes or molecules that they can alter to produce plants that are drought tolerant. Three approaches exist to engineer drought-tolerant plants: expression of functional proteins, manipulation of transcription factors, and regulation of signaling pathways. Functional proteins (glycine betaine and proline) are osmolytes that increase a plant's water uptake and retention. Transcription factors control the expression of genes involved in drought tolerance. Regulation of signaling pathways involves messenger molecules such as nitric oxide, which prevents loss of cell function and death when low-water conditions stress a plant. Scientists have developed drought tolerance in several large-acreage crops. Monsanto, Pioneer Hi-Bred, and Syngenta are testing genetically modified corn varieties that can tolerate periodic drought conditions without loss of yield stability. Arcadia Biosciences and the University of California, Davis have developed and are field-testing genetically engineered rice that displays drought tolerance. Monsanto and BASF have jointly developed genetically engineered maize that has been subjected to field trials in South Africa and the western United States. Without additional irrigation, the drought-tolerant maize produced yields that were 24 percent higher than conventionally grown maize. Research on developing drought tolerance in crops has been ongoing for many decades. The task is foreboding because over 50 genes are reportedly active in drought tolerance. Performance Plants in Kingston, Ontario is commercializing drought-tolerant corn, soybean, cotton, ornamentals, and turf grass with yields reported to be 15 to 25 percent higher than non-transgenic control crops. Pioneer Hi-Bred began selling drought-tolerant corn in 2011.

Salt-Tolerant Crops. Developing salt-tolerant crops might be a way to reduce the freshwater requirements of agriculture. Wild plants (halophytes) exist that tolerate salt and grow in saline environments. Genetic engineering to make salt-tolerant crops uses three general approaches: sodium exclusion from the plant cells, compartmentation of the sodium, and excretion of sodium. Scientists at the University of California, Davis have engineered tomato and canola plants. These transgenic plants were able to tolerate water with a salt concentration equivalent to 40 percent of the salt in seawater, a level that normally inhibits the growth of all crop plants. The edible portion of these plants showed only marginal increases in sodium. Scientists at the University of Adelaide—in collaboration with scientists at the University of Cambridge—are developing salt-tolerant wheat, rice, and barley. They modified genes involved with the conduction of water in the plant so that salt is removed before transpiration and does not enter the plant shoot. Scientists at Arcadia Biosciences in Davis, California are developing technology that allows plants to have normal yields and quality in saline conditions. They expect the technology to be widely applicable to various crops, including corn, rice, soybeans, wheat, alfalfa, vegetable, and turf. Although this salt-tolerant crop technology would reduce the need for freshwater in some agricultural regions, it currently has been only tested in field trials. It has not been tested in long-term trials to see whether the technology has adverse effects. Furthermore, regulatory approval has not yet been sought for genetically engineered salt-tolerant crops. The technology faces many hurdles before it can be commercialized, which is unlikely by 2040.

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Annex D

Emerging Technologies in Soil Management

Soil productivity depends on how well the soil provides the physical, chemical, moisture, and biological conditions to sustain plant growth. In searching for increased agricultural productivity, scientists are examining technologies that restore and maintain the physical structure of soils, improve the efficiency of water and nutrient use, and enhance the rhizosphere where microbes interact with plant roots. The content and structure of soils varies considerably in different regions, as does the climate, so that localized soil management technologies are necessary. Current agricultural practices include a number of technologies for maintaining soil productivity and improving soil nutrition: mulching, application of manure, crop rotation, contouring, conservation tillage and nontilling, irrigation control, soil nutrient management, biological nitrogen fixation, and controlled use of fertilizers. Soil organic carbon (SOC) correlates strongly with soil productivity, for example, in India when soil management practices increased SOC, yields increased by a factor of 4.7.

Nitrogen Fixation Technology in Non-Legumes

Transgenics. Because nitrogen in soils is the limiting factor on plant growth, chemical fertilizers are used for most crops. Bacteria can convert atmospheric nitrogen to a form that can be used by a plant for nitrogen fixation. In legumes, a symbiotic relationship exists between nitrogen-fixing *Rhizobia* bacteria and mycorrhizal fungi that interact with the roots of a plant to supply nitrogen to the plant. Scientists have for many years worked on ways of transferring the nitrogen-fixing capabilities of legumes to other crops like cereal grains, but have had little success. In 2008, scientists at Recherche pour le Developpement and the University of Munich discovered the genetic element in leguminous plants that gives them nitrogen-fixing capability. This might be a first step in developing a transgenetic technology for installing a nitrogen-fixing capability in cereal crops like rice, corn, and wheat. However, it is only a first step because at least 10 genes would have to be inserted into a non-legume to transform it with the capacity of fixing nitrogen.

Facilitated Evolution. The development of nitrogen fixation in non-legumes by facilitated evolution is another research approach for developing nitrogen-fixing for non-legumes. The method entails a stepwise genetic improvement of both the nitrogen-fixating microbes and the host plant with the aim of eventually finding an effective nitrogen-fixation association. The research requires identification of dozens of genes related to the complex interaction between the bacteria and the host plant. Scientists have worked with the main cereal crops and the bacteria *Rhizobia*, *Frankia*, and cyanobacteria by inserting the bacteria into the roots of a plant or the entire plant. So far, they have gained some initial insights in genetically controlling the ability of nitrogen-fixing bacteria to colonize in plants.

If either transgenics or facilitated evolution were successful in transferring nitrogen-fixing capability to the major grain crops, this breakthrough would be extraordinary in agricultural technology. However, technical hurdles that the transgenic technology faces are especially difficult to overcome: one, the linkage of desired nitrogen-fixing genes to genes providing disease and pest resistance might interfere with a plant's resistance to pests and diseases; two, the insertion of bacterial plasmid sequences along with the desired nitrogen-fixing genes might harm the plant; and three, genes might flow from the transformed plant to non-transgenic plants or wild plants. Because of the difficult technical challenges and the limited ongoing research effort, nitrogen-fixation might not be accomplished in cereal crops by 2040.

Soil Microorganism Modification Technology

Phytostimulation. The rhizosphere consists of root tissue, root surfaces, and the soil influenced by the root. Microbes exist in this environment on plant roots and soil surfaces in thin water biofilms. The rhizosphere is different from the bulk soil biologically and chemically, and the effects of plant pathology and growth promoting microorganisms affect the yield and quality of crops. Research on the rihizosphere has indicated that modifying soil microorganisms might reduce the need for fertilizer and pesticides and stimulate growth. Phytostimulation refers to the technology of stimulating the effect of the rhizosphere on plant health and growth. Farmers use soil inoculants to enhance crop growth and yield, but the relationship between plants and rhizosphere microorganisms is not well understood. Application of molecular biology to the microorganisms of the rhizosphere might lead to increases in crop yield. For example, scientists have shown that the phytohormones of cyanobacteria can improve the growth and yield of wheat plants.

Disease-Suppressive Soils. Scientists have discovered that some groups of soil microorganisms can protect plants and suppress plant pathogens. Because many of these organisms cannot be cultured in a laboratory, metagenomic analysis has been used to study them in their natural environment, identify them, and use them in soil inoculants. Further developments in this area might lead to better control of plant diseases and reduce the need for pesticides.

Phosphorous Uptake. Another key input to plant growth is phosphorous, which must be externally supplied to the plant. Phosphorous uptake in plants is very inefficient because much of it is locked up in the soil and is unavailable to the plant. The plant recovers only 10 to 20 percent of the applied phosphorous. In addition the world supply of phosphorous used in fertilizers is limited with forecasts projecting its total depletion before the end of the century. Bacteria and fungi can also enhance phosphorous uptake, but so far progress has been limited in developing this technology. Research on the relationship between crops and phosphorous uptake organisms might eventually lead to major improvement in phosphorus fertilizer efficiency. However, in view of the limited progress so far, this development is unlikely by 2040.

Nano-Particles. Zeolites are used as soil amendments to improve the efficiency of fertilizer, improve water infiltration and retention, and retain nutrients for plants. Research on zeolites has focused on changing its molecular structure to improve its effectiveness. Some researchers are investigating nanotechnology as a way to improve the performance of zeolites. The atom-by-atom arrangement in nanotechnology enables the ability to control the size, shape, and orientation for reaction with soil or plant tissue. The soil applications of nanotechnology that have been proposed include nanoporous zeolites for slow release of fertilizer and water, nanocapsules for controlled release of herbicide and pesticide delivery, and nanosensors for pest detection. Concern about the health effects of nano-particles is growing, and some organizations have advocated not using them in soils until their safety has been established.

Annex E

Emerging Technologies in Aquaculture

Fish food supplies have grown significantly since 1961, fueled by the rapid increase in aquaculture—the growing of aquatic animals and plants for food. It is increasing at an annual rate of 3.1 percent since 1961, compared to the annual rate of increase for the world's population of 1.7 percent. As an excellent source of affordable, high-quality animal protein, fish accounted for approximately 16 percent of the global population's intake of animal protein in 2010 and approximately 6 percent of all protein consumed. With capture-fish production stagnating, the increase in demand for fish products will have to be met by aquaculture. As the fastest growing animal-food-producing sector, aquaculture's contribution to total food fish consumption has increased from less than 10 percent in 1970 to 46 percent in 2008, and will soon account for more than half of the world's supply of food fish. The Asia-Pacific region dominates aquaculture, which accounts for 89 percent of production in terms of quantity. Per capita supply of food fish from aquaculture increased from 0.7 kg in 1970 to 7.8 kg in 2008, an average annual growth rate of 6.6 percent. In a 2006 World Bank report, all forecast scenarios where stagnating capture-fish production was a key assumption showed the demand for aquaculture would continue to grow to 2040, with growth rates ranging from 1.4 percent to 5.3 percent per year.

Major increases in aquaculture productivity through the entire production and distribution cycle have driven the growth in aquaculture. Key developments have included advances in fish seeds (genetically improved fish), fish nutrition, and disease control; the developments of new forms of aquaculture; the integration with farming and waste disposal systems; and the development of a global supply, distribution, and retain chain. In Asia, many large processors have established large centralized processing plants to improve yields and respond better to evolving quality and safety requirements. Improved processing technologies also contribute to better utilization of fish waste for a wide variety of uses, including water treatment, cosmetics, agrochemicals, biofuels, and pharmaceuticals. As a result of the productivity improvements and significant output increases, prices of many aquaculture products, including large quantity products like carp and tilapia, have fallen steadily over the last 20 years.

Through to 2040, four technologies will fuel the growth in supply of aquaculture and very likely falling prices:

Genetically Improved Fish. Genetic improvement of cultured species will likely continue to improve aquaculture productivity and reduce the impact on the environment. Culture biology advancements and genetic improvements focus on the domestication of new species, development of new rearing methods in hatcheries, and development of new breeding stocks to increase the yield and help reduce disease and requirements for feed, space, and water. In 2000, Gjedrem of the Institute of Aquaculture Research in Norway estimated that only 1 percent of aquaculture production was based on genetically improved fish and shellfish, but expects this percentage to increase by 2040.

Nutrition, Feeds, and Feeding Practices. Feed is typically the largest cost item in commercial aquaculture systems in which animals are fed, accounting for approximately 60 percent of total costs.

Research is continuing on the development of alternative ingredients to fish meal and fish oil, such as chicken-processing waste or plant products like soybean and canola; the development of optimized high-efficiency, low-polluting diet formulations; and more precise, automated feed delivery systems. Salmon farmers, for example, have reduced the food-conversion ratio (ratio of the total weight of feed eaten by a crop of fish from the time they are purchased as juveniles to the time they are harvested to the weight of the fish at harvest) from 2:1 in the 1980s to 1.3:1 in the first decade of the 21st Century, resulting in substantial savings in cost and reduction in wastes discharged. Gains in the future will likely reduce this ratio to below 1:1.

Closed Recirculating Systems. Aquaculture is leveraging advances in biological processes and the complex interactions among nutrients, bacteria, and cultured organisms to engineer closed aquaculture systems that will even allow farming of marine organisms at locations far from the sea. In recirculating systems, some or all of the water in a fish culture facility is reused to control better the rearing environment, minimize water usage, effectively remove waste products from the system, and provide for more efficient heating and cooling of the water. A key advantage of these closed systems is the isolation of the aquaculture systems from the natural ecosystems, minimizing the risk of disease or genetic impacts on the environment. Recirculating systems have been producing eels in Denmark for many years, helping Denmark to be a leading eel producer in Europe. Coinciding with the development of large-scale recirculating technology will be the development of alternative fish feeds that use plant-based proteins to replace fish meal and fish oil.

Open Ocean Systems. With oceans occupying most of the earth's surface, the use of open ocean systems could dramatically change the nature of human food production. Today most ocean aquaculture takes place in protected coastal areas. However, inshore experiences and technology from marine engineering and the offshore oil and gas industry will likely combine to facilitate the use of large cages or containment structures in open seas for rearing and harvesting fish. The key barriers will be the costs of the large offshore installations and the challenge of minimizing the potential for environmental impacts from those facilities when in operation. To withstand the harsh conditions offshore, mechanization of key tasks will be required to minimize human involvement, continuous monitoring of key environmental conditions and fish behavior and health will be needed to ensure productive and efficient operations, and surface containment structures that can survive rough seas or below-the-surface facilities will be required. The engineering knowledge exists to design large-scale open-ocean farms. Since 2001, several early commercial designs have been deployed around the world, including in the United States. A UK water analysis in 2007 concluded a large open ocean farm in UK waters would be economically viable for fast-growing species of marine finfish. A NOAA Technical Memorandum in 2008 also highlighted the current commercial potential of open-ocean systems.

This paper does not represent US Government views.

Annex F

Emerging Precision Agriculture Technologies

Precision agriculture encompasses a range of related technologies and practices that help farmers understand and manage land variations that can affect crop growth. Existing precision agriculture techniques tend to focus on discovering how factors like soil quality, water availability, drainage patterns, and the like vary within a single field, and then adapting planting, harvesting, and management strategies to address those variations. Information about within-field variations can come from a range of sources, including sampling and testing; handheld, equipment-mounted, or field-distributed sensors; or ground-based, aerial, or satellite-based surveys. Management strategies can vary widely in sophistication, aim to increase crop yields, or reduce the consumption of costly inputs like seed, fertilizer, and herbicides.

Precision agriculture's focus on understanding and adapting to within-field variations likely results from various factors that helped fuel precision agriculture's development. Although crop scientists have long been experimenting with methods to leverage information from aerial and satellite photographs and field surveys to inform crop-management practices, precision agriculture techniques did not begin to see widespread adoption until the 1990s, when changes in the US agribusiness landscape began to increasingly favor very large farms and high levels of vertical integration. As farm fields grew, conventional field-management methods that treated each field as a monolithic entity gave way to alternative management techniques that emphasized understanding of intra-field variations and their impacts on crop yield. At the same time, satellite-navigation systems were falling rapidly in price, and the various information-technology resources necessary to generate, update, and leverage customized field maps were becoming accessible to and affordable by commercial farmers.

Because of its development history, precision agriculture is bound up heavily with the large-scale industrial-agriculture practices that predominate in regions like the midwestern United States, southern Brazil, and parts of Canada, Germany, and Australia. Relatively low capital costs, high land availability, and an emphasis on efficiency (including labor-efficiency) help motivate farmers in these regions to purchase larger and more sophisticated farm vehicles that integrate precision agriculture technologies. Although some precision agriculture techniques can be employed on small-scale farms that rely on human labor instead of mechanical labor, the most advanced precision agriculture technologies rely on a very high level of automation—not just in terms of application but also in terms of decisionmaking. The capital recovery costs for US corn (maize), soybeans, and wheat shown in Annex J account for 15 to 24 percent of the production cost. Precision agriculture would likely add considerably to these existing costs, and it may be that by 2040 the yield increases with this added technology cannot compensate for the added costs. For precision agriculture technologies to diffuse on a wide scale in the future and in a manner that will have a substantial impact on global food production and resource consumption, the kinds of automated guidance and application systems that are emerging on large farm vehicles will have to decrease in size—and cost—to also work well in small-scale plots in the developing world, where the greatest potential productivity gains can be made.

This paper does not represent US Government views.

The following overview of precision agriculture technologies illustrates a potential pathway of progression that could see mechanized agriculture undergo a dramatic transformation that would make it suitable for application almost anywhere.

Basic Elements: Mapping and Managing

In many respects, satellite-navigation receivers are a foundational technology for precision agriculture and have the most widespread adoption of all precision agriculture technologies. Such receivers typically use signals from the US Global Positioning System (GPS) satellite constellation, together with correction signals from a fixed ground-based transmitter to provide the kind of extremely accurate location information that is important for precision agriculture applications. One of the most common uses of GPS receivers in precision agriculture is generating geo-referenced soil maps. Farmers use handheld GPS receivers to mark the precise within-field locations of soil samples, and then correlate soil samples and GPS coordinates in a geographic information systems (GIS) database. Various technologies and techniques are available for measuring soil properties, including laboratory testing of samples, probes that can measure soil's electrical conductivity (to determine water content), and handheld pH meters (many of which integrate or connect to GPS receivers to produce geo-referenced data without requiring the farmer to input such data separately). Many sensors can also mount on vehicles to facilitate faster testing in large fields. Remote sensors can also take continuous measurements of soil quality indicators and transmit those measurements for incorporation in a central database.

GPS and GIS are also used to measure and map indicators of crop health and vigor, and as with soil sampling, a wide range of sensors and methods can be used to conduct such geo-referenced measurements. For example, handheld and vehicle-mounted sensors are available that can measure the chlorophyll content in crop leaves by measuring the light energy reflected off the leaves. Low chlorophyll content can indicate nutrient deficiency, plant diseases, or other problems. Similar sensors are available for measuring other health indicators including crop temperature (which can indicate water deficiencies), sugar content (to help determine the ripeness of fruit), and insect infestation.

Farmers can use geo-referenced monitoring data to support site-specific field management practices that vary the application of crop inputs (seed, fertilizer, and pesticide) based on factors like crop vigor and soil fertility. A common technique for site-specific input management is to break down a field into management zones and then calculate the optimal distribution of inputs within each zone. The zone method is popular because it is relatively easy to use with imprecise application systems that disperse uniform amounts of inputs in a broadcast pattern. Calculating required inputs is typically the job of specialized software that often requires expensive licenses. However, inputs can be calculated manually using formulas, assuming the farmer possesses the requisite knowledge. A major ongoing issue with precision agriculture is determining what levels of inputs are appropriate for various field conditions. Current recommended formulas generally are based on many decades' worth of crop science research. However, they are typically used for conventional "whole-field" management on a region-by-region basis, and are not necessarily well suited for the much smaller scale management techniques in use in precision agriculture. Researchers are developing new suites of algorithms that are tailored for precision agriculture applications and can be customized to conditions within individual fields regardless of region. Unlike many precision agriculture technologies, geospatial-referenced input mapping might be relatively straightforward to adapt to work with the kind of small-scale farming operations that are common within the developing world.

Because of their centrality to both mechanized and possible future nonmechanized precision agriculture, mapping and recommendation technologies are likely to become the most critical precision agriculture components.

The First Integrated Systems: Yield Monitors

Yield monitors, the first integrated precision agriculture solutions to emerge, became available on combine harvesters in the 1990s and are currently the most popular type of integrated precision agriculture system. A typical yield monitor uses an impact sensor to measure the flow of processed grain as it enters a harvester's grain tank. A separate sensor measures the grain's moisture level to help correct for moisture-induced variations in grain mass, thereby improving the reliability of the grain-flow measurement. Yield monitors enable farmers to track yields with considerably more accuracy than is possible using legacy methods (such as weighing grain at the time of sale to a downstream processor). Such accurate yield data help farmers manage the business aspects of running a farm, such as negotiating crop leases. Farmers also have used moisture sensor components in yield monitors to gather information about crop conditions that can inform subsequent planting strategies and crop-handling practices.

Yield monitors become a far more powerful tool when combined with satellite-navigation information and mapping software. Combine harvesters equipped with both yield monitors and GPS systems can correlate instantaneous yield measurements with precise locations within a field. Specialized software can then use those correlated data to generate yield maps, which can show farmers which areas of the field generate exceptionally high or low-yield levels. Yield maps can help farmers troubleshoot a wide range of issues with their fields that they would otherwise have had great difficulty in uncovering using other techniques like geo-referenced soil mapping. For example, a low-yield area of a field that also produces grain with unusually high moisture content might have drainage problems. Yield monitoring can also help farmers track the results of experimentation with different planting strategies and management techniques to determine what works best for specific areas of their fields.

Emerging Technologies: Variable-Rate Application and Automated Guidance

One of the most significant developments in integrated precision agriculture systems to occur in the past decade was the introduction of variable-rate application systems for fertilizer, seeds, pesticides, and herbicides. Such systems replace conventional fixed-rate application systems on farm implements or purpose-specific vehicles. Variable-rate systems can allow a farmer to deliver a targeted dose of crop inputs precisely where they are needed. The most basic variable-rate application systems are controller-operated, meaning that a farmer must manually adjust the system's outputs when the vehicle's navigation system indicates that it is entering a new management zone. Increasingly, variable-rate application systems link directly to a vehicle's onboard GPS/GIS systems and modulate input dispersion rates based on mapping data. The most advanced systems use on-the-go sensing and application technology, in which implement- or tractor-mounted sensor arrays measure crop status indicators dynamically and direct spray nozzles or other variable-rate applicators to deliver appropriate inputs to address problems. For example, an herbicide-spraying implement equipped with on-the-go technology can identify weeds using optical sensors and deliver just enough targeted herbicide to kill each weed using articulated spray heads. On-the-go sensing and application systems can also leverage data from mapping databases to improve accuracy and responsiveness, and the sensors' inputs can, in turn, provide valuable information to update those databases to facilitate future decision support.

Farmers frequently pair variable-rate application systems with guidance systems that help keep tractors and implements on course within a field, reducing farmer workload while improving the accuracy of variable-rate application. Even without variable-rate application systems, farmers can find guidance systems helpful in navigating fields and determining crossover points between management zones. The most basic guidance systems supplement a navigation map display with a light bar indicator that assists the farmer to keep the vehicle on a predetermined path as precisely as possible. More advanced systems increasingly incorporate active guidance, including automated tractor steering and a separate guidance and steering system for the implement. Basic automated steering systems keep tractors on a very precise straight-line course through a field, but the farmer still needs to turn the tractor around manually to initiate another field pass. The best current systems can both steer and turn a tractor and can achieve extremely high levels of precision, directing massive farm implements that span dozens of crop rows in repeatable patterns with +/- 1 inch tolerance even over rough or sloping fields.

Future Technologies: Farm Robots and Smart Fields

Future trends in precision agriculture point to increasing automation of farm vehicle and implement control. Several manufacturers have already demonstrated guidance systems that allow tractors to drive themselves, performing limited tasks like following alongside a human-driven combine harvester while pulling a grain-collecting wagon, autonomously driving the wagon to a preset point to drop off the grain, and then returning to the harvester's location to collect more grain. Within the next five to ten years, autonomous tractors will likely begin taking on a full range of roles on large-scale farms. Efficiency gains from widespread use of automated guidance and on-the-go sensing and application technology might help autonomous farming become much more profitable than conventional farming, spurring increased investment in autonomous farming technologies.

More importantly, once the benefits of autonomous farming become well established, experts widely expect that efficiency-driven trends toward ever-bigger farm vehicles will reverse themselves. Many experts expect that efficiency concerns will instead favor deployment of large swarms of small, specialized farm robots that will work on small sections of field at a time, perhaps 24 hours a day. Each vehicle will equip sufficient sensors and software (either through onboard control systems or data links to remote systems) to allow it to manage its field section in an optimal way. Together with distributed sensor networks that monitor soil and crop conditions and the software that integrates data gathering and command-and-control, future "smart fields" could all but farm themselves. Among other things, economies of scale that could result from a proliferation of smart fields in the developed world might help make mechanized precision agriculture more feasible in smallholder- and urban-agriculture contexts, dramatically increasing the amount of land undergoing high-intensity, high-yield cultivation in the future.

The path from autonomous tractors to farm robots might not be a smooth one. Experts have noted that autonomous farm vehicles present novel safety and security concerns. Although autonomous farm machines might operate far more safely than human-driven machines, accidents still might occur. Depending on jurisdiction, a court might have a relatively easy time applying current product liability laws to a future case in which an autonomous farm machine injures or kills a person who happened to stray into its path. But such an incident—or, especially, a rash of such incidents—might have very uncertain consequences public acceptance of the technology. If the public comes—rightly or wrongly—to regard autonomous farm vehicles as a menace, then lawmakers might act to ban or severely restrict application of the technology. Depending on when and under what circumstances such a ban occurs, and the nature of the ban, development of the kinds of farm robots that could help bring precision agriculture to the masses would stall.

A related concern involves malicious actors' taking control of autonomous farm vehicles and using them to wreak havoc. An autonomous tractor the size of a large bulldozer, even without its implement (which can be wider than a four-lane highway) could be a potent terrorist's weapon. Smaller farm robots might be less readily "weaponizable," but still certainly present concern. A number of potential strategies exist for manufacturers to ensure that farm robots are not misused. Whether such strategies will be effective at deterring attacks is unknown. Another unknown is whether lawmakers will impose so many security-related restrictions on farm robots that deploying such robots in areas where they can have the highest impact might become impossible.

Of course, many of the gains possible from precision agriculture do not require farm robot swarms or smart fields; human workers could perform variable-rate application by hand by using handheld sensors and GPS maps. But precision agriculture is much more than sensing and application; it is also extremely challenging knowledge work. Specialized software for data-processing and decision-support can automate much of that knowledge work and help make precision agriculture easier for individuals to practice. However, using such software still generally requires a significant level of knowledge. The same trends that might drive down the size of farm vehicles might also end up helping to move many of the planning and decision making aspects of precision agriculture so that the human farmer is out of the loop. In such a scenario, the self-managing smart fields of the future might be agnostic as to whether humans or robots tend to them. In the case of human-managed fields, software might be able to provide field hands with exact, easy-to-follow instructions on where to go, when and how to apply inputs, which fruit to pick, and so on. In any case, farm labor is extremely difficult and demanding work, and chemicals used on farms can be very harmful to humans. A future of smart farms managed by what are essentially human robots is not necessarily a desirable one, but the high cost of robotic smart field systems might ensure that much of the developed world uses a mix of human- and robot-managed fields.

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Annex G

Emerging Biofuel Technologies

The use of transportation biofuels—primarily ethanol and biodiesel—has grown rapidly worldwide, but according to some experts, today's biofuels have drawbacks: they provide little environmental benefit, consume food crops, and are expensive. US corn-based ethanol production reached 13 billion gallons in 2010, but consumed 30 percent of the US corn crop and billions of dollars in federal government subsidies while supplying only 9 percent of US gasoline demand. Next-generation technologies that convert biomass (rather than food crops) to advanced biofuels and chemicals promise to be more sustainable and lower cost. These emerging technologies are critical to the long-term security of the world's food supplies and help reduce global dependence on petroleum fuels. This section provides an overview of new technologies and market issues that will influence the success of advanced biofuels over the next several decades.

One of the biggest drivers of advanced biofuels is government policies. The United States and the European Union have aggressive biofuel mandates in place that include sustainability standards. The US Renewable Fuel Standard (RFS) requires 36 billion gallons of biofuels by 2022 with increasing amounts of advanced biofuels that significantly reduce greenhouse gas emissions below a 2005 fossil-fuel baseline. A variety of advanced biofuel technologies is in development that might meet the requirements, but costs are still too high and the technologies are not yet proven at commercial scale. Achieving the RFS goals will require years of consistent government support, including Research and Development funding, tax credits, and loan guarantees that support the construction of commercial-scale plants.

The viability of advanced biofuels will also depend on relative prices for competing transportation fuels. Biofuels face significant competition from petroleum-based gasoline and diesel fuels, which are widely available to consumers through a highly developed distribution and retail system in most countries. High crude oil prices improve the cost competitiveness of renewable biofuels. Very high-efficiency vehicles, including hybrid and pure electric vehicles and hydrogen-powered fuel-cell vehicles, help reduce fossil-fuel use and carbon emissions and thus will also compete with advanced biofuels.

Cellulosic Ethanol

Cellulosic ethanol is the nearest-term advanced biofuel. This second-generation biofuel is derived from various types of lignocellulosic biomass feedstocks including agricultural and forest residues (such as corn stover, rice straw, wheat straw, and bagasse), nonfood energy crops (grasses and trees such as switchgrass, poplar, and miscanthus), and municipal solid waste. Lignocellulosic biomass consists of complex cellulose, hemicellulose, and lignin polymers, which are much tougher to break down than corn kernels.

Current Status. The basic biomass conversion technologies—biochemical and thermochemical designs—have been around for decades, and researchers have made significant progress in reducing costs over the past ten years. Biochemical (sugar-based) pathways use acid or enzymatic hydrolysis of lignocellulose to create sugars, such as glucose and xylose, which subsequently ferment to cellulosic ethanol. Thermochemical pathways use gasification to convert feedstocks to syngas, which subsequently ferment or catalytically convert syngas to cellulosic ethanol and other valuable products. A variety of cellulosic ethanol demonstration plants has operated worldwide since 2004, but developers still do not know which approaches and feedstocks will be most successful at a commercial scale. A major R&D focus is improving the efficiency of the multistep processes. For the biochemical pathways, researchers are working to improve the pretreatment process for breaking down hemicellulose into fermentable sugars. Cellulase enzyme complexes that break down plant cell walls are available commercially but still cost about ten times more than enzymes for corn-based ethanol. Researchers are also engineering specialized yeasts that can ferment the difficult-to-metabolize C5 and C6 sugars from cellulosic feedstocks to ethanol. In addition, researchers have identified microbes that that can break down cellulose and ferment sugar in one step—eliminating the costly pretreatment step. Future breakthroughs as a result of these efforts are likely to result from alterations by molecular biologists to the genetic code of microorganisms in order to improve enzymatic activity and other functions.

Plant breeding and biotechnology can also offer major benefits such as improving biomass yield, reducing feedstock quality variations, and increasing the performance of biomass feedstocks in downstream conversion processes. Researchers at Massachusetts-based firm Agrivida and Swiss-based Syngenta International AG have already incorporated cell wall degrading enzymes directly into the genome of plants. The enzymes activate only under biofuel-processing conditions and initiate hydrolysis of the plant polysaccharides from within the modified biomass, greatly reducing the need for costly pretreatment enzymes. California-based Ceres is developing seeds and traits for high-biomass energy crops and has identified hundreds of candidate genes for traits such as biomass yields, plant architecture, tolerance to environmental stress, more efficient use of soil nitrogen, and disease resistance. Researchers at DOE's BioEnergy Science Center discovered the gene that controls ethanol production capacity in a microorganism, which will allow scientists to genetically alter biomass plants to produce more ethanol. DOE's Advanced Research Projects Agency-Energy is funding breakthrough plant technologies through its Plants-Engineered-to-Replace-Oil (PETRO) program. PETRO researchers are developing enhanced crops that scan deliver more energy per acre by improving plant photosynthetic processes and producing high-energy fuel molecules within plant leaves and stems, in addition to seeds.

Outlook. Cellulosic ethanol companies say they are ready to build at least a dozen commercial-scale facilities over the next few years that could supply several hundred million gallons of cellulosic ethanol. Obtaining financing for risky new plants has been a major barrier. The USDA and DOE have awarded loan guarantees to several cellulosic-ethanol projects. Recent recipients include INEOS Bio, part of Swiss-based chemical firm INEOS, and Illinois-based Coskata, Inc., which plan to start up hybrid plants that combine feedstock-flexible gasification processes with biological fermentation in 2012. Midwestern ethanol producers Abengoa Bioenergy and Poet have announced plans to start up biochemical-based cellulosic-ethanol plants in 2013. Government and other studies suggest that initial production costs will be significantly higher than costs to make ethanol from corn—even with corn prices at historic highs. Nonetheless, one or more early developers might be able to produce cellulosic ethanol successfully. The coming wave of commercial plants will provide valuable insights and might lay the groundwork for a viable cellulosic-biofuel industry to begin to develop.

Successful cellulosic-biofuel developers will also need to build up new regional supply chains in which all of the necessary pieces fit together efficiently—collecting biomass from fields or forests; creating, storing, and delivering high quality biomass feedstocks to biorefineries; and converting biomass to bioenergy products. A recent study by the DOE's Oak Ridge National Laboratory indicates that the United States has more than enough lignocellulosic biomass from forest and agricultural sources—one billion tons of dry biomass annually—to displace 30 percent of US petroleum consumption by 2030. Meeting the one-billion-ton benchmark requires adequate biomass market pricing ($60 per dry ton at the roadside or farmgate according to the study) without any major changes in agricultural practices (only 1 percent annual yield growth in corn and energy crops and current trends toward no-till cultivation). A new USDA initiative is funding R&D projects that address advanced biofuel needs across supply chains—from sustainable production of forest and agricultural energy crops to production of high-value biofuels. Projects include planting grasses with legumes to provide nutrients to marginal land while reducing nitrogen runoff into waterways.

Many cellulosic-biofuel developers have partnered with large industrial firms to help speed the commercialization of novel technologies. Oil companies have a natural affinity for the biofuels business, including knowledge of how to manage large-scale commercial projects and produce and market transportation fuels on a massive scale. Royal Dutch Shell is a long-term investor in Iogen Corp., which makes cellulosic ethanol from agricultural residues at a large demonstration plant in Canada. Shell also has an interest in California biocatalyst developer Codexis, focusing on the development of more powerful enzymes for faster conversion of biomass to fuels. BP recently acquired all of the assets of Vercipia Biofuels, a cellulosic-ethanol business that BP created with Massachusetts-based Verenium. Chemical giant DuPont owns DuPont Danisco Cellulosic Ethanol LLC, which operates a demonstration plant in Tennessee and is planning to build a commercial facility within the next few years.

Biomass-Based Biodiesel

Biodiesel has seen rapid growth worldwide, especially in Europe. Most biodiesel currently is derived from food plant oils such as rapeseed, soy, and palm oil, used cooking oils discarded as waste from restaurants, and animal fats. Biodiesel is typically blended with conventional diesel fuel in low concentrations since pure biodiesel has a tendency to solidify or gel at low temperatures. Finland's Neste Oil produces an enhanced product (NExBTL renewable diesel) that can be used in blends in any concentration. Researchers are also developing cellulosic-biodiesel technologies that use biomass feedstocks and do not depend on food crops. Choren Industries GmbH, with collaboration from Shell and other partners, has developed a biomass-to-liquids process involving high-temperature gasification of biomass followed by a catalytic process to make a clean, high quality, synthetic biodiesel. Choren's Carbo-V process converts more than 50 percent of woody biomass material, whereas conventional biodiesel processing converts less than 10 percent of the mass of dried plants. In 2008, Choren commissioned a large biomass-to-liquids pilot plant at Freiberg, Germany, and is studying the feasibility of larger-scale facilities.

Biobutanol

Biobutanol is a new biofuel that is not yet commercially available. Biobutanol gained wide prominence in 2006 when BP and DuPont announced plans to produce it commercially using a fermentation process. Most butanol (for chemical uses) today comes from petrochemical feedstocks. Butanol has several advantages over ethanol, including higher energy density and immiscibility with water, allowing it to blend more easily with gasoline and other fuels. Biobutanol production processes are still at the lab scale or early pilot stage of development. However, published data on butanol-producing organisms indicate low yields relative to ethanol production via fermentation. BP-DuPont Biofuels and several other companies are working to develop and commercialize new biobutanol technologies using proprietary biocatalysts and microbes. Initially, developers will use the same agricultural food crops as ethanol—such as corn, wheat, sugar beet, cassava, and sugarcane. The use of lignocellulosic biomass feedstocks is planned for later and requires further technology development. Colorado-based Gevo, Inc. recently received a USDA research grant to enhance its cellulosic yeast strain and fermentation process to produce biobutanol jet fuel from woody biomass.

Drop-in Biofuels

Since the mid-2000s, many advanced biofuel developers and investors have shifted their focus to third-generation "drop-in" biofuels that have higher energy potential than ethanol or biobutanol and can blend with conventional petroleum fuels at high percentages without changes to existing transportation-fuel infrastructures. By contrast, ethanol cannot be mixed with gasoline at refineries or transported by pipelines. Instead, ethanol is typically transported by rail or truck and blended into gasoline at terminals near the end users, which adds costs and can strain distribution systems. Drop-in technologies include renewable hydrocarbons produced by algae and advanced processes that convert plant sugars to hydrocarbons. These technologies are less mature and costs are still high. Many developers are initially targeting higher-value fuel, chemical, and specialty markets rather than commodity fuel markets.

Algae-Based Biofuels. Algae are potentially rich sources of biofuels and have become a subject of intense research and investor interest. Algae-based technologies offer major benefits including very high production rates; the ability to use otherwise nonproductive, nonarable land and a wide variety of water sources—fresh, saline, and wastewater; and the potential to recycle carbon dioxide and other wastes. More than 50 percent of algae mass might consist of bio-oils that can be used as drop-in replacements for diesel, gasoline, aviation fuels, and specialty products. The DOE was a major force in early algal-biofuels development from 1978 to 1996. That work ended because crude oil prices were far too low for algae-based fuels to compete, but the National Renewable Energy Laboratory's Aquatic Species Program demonstrated impressive productivity, with photosynthetic algae yields in excess of 10 dry tons per acre in an open-pond system.

The DOE's latest algal-biofuels-development roadmap published in 2010 indicates that a dedicated R&D program can bring algal-fuel economics to a competitive level within ten years, although that time frame might be optimistic. Major technical challenges remain—from basic algal biology to cultivation to production and scale up of integrated processes. Synthetic-biology techniques are helping to bring down the costs of algae-based biofuels by changing the way microalgae use light and improving their efficiency in producing fuels. However, growing and harvesting algae is still somewhat of an art. Technology approaches include the cultivation of photosynthetic algae in large open ponds, growing genetically engineered algae in enclosed photobioreactors, and growing genetically engineered algae that consume sugar inside dark fermentation tanks. Each approach has drawbacks. In open ponds, for example, wild algae strains from the environment can crowd out highly productive strains, and high-growth algae in sealed bioreactors can overheat. Algae production is energy intensive—technologies typically produce biofuels indirectly by growing algal biomass; then harvesting, dewatering, and extracting oil; and then processing the oil into a biodiesel or other fuel product. Researchers also need to better understand and manage high water-related costs. Algae can grow in wastewater, but potential pathogens can kill the algae—and water-treatment technologies are expensive. For the open-pond option, large amounts of freshwater are necessary to replenish evaporated water to avoid concentrating contaminants.

Some investors have begun to question whether algae-based biofuels will ever be economically viable. California-based algal-biotechnology developer Solazyme, Inc. has had success in lowering production costs significantly by growing algae in fermentation tanks without sunlight by feeding them sugar—a concentrated source of energy that allows the algae to grow rapidly. Solazyme received an order from the US Navy in late 2010 to provide 150,000 gallons of its algae-based biofuel. Solazyme's recent S-1 filing with the Securities and Exchange Commission indicates that its lead algae strain for fuels and chemicals could make a crude oil for less than $1,000 per metric ton (about $120 per barrel) at a commercial scale using sugarcane feedstock.

Renewable Hydrocarbons. Wisconsin-based Virent Energy Systems has developed new technology—the BioForming process—to make renewable hydrocarbons from bio-based feedstocks. This process converts plant sugars into "biogasoline" using a chemical-reforming catalyst. Virent claims that the biogasoline's performance is similar to that of petroleum gasoline. The company began operating a demonstration plant in 2010 using conventional biofuel feedstocks such as sugar beets. Virent has also shown that it can convert cellulosic biomass including corn stover and pine tree residuals to biogasoline. Virent's technology is one of six different process strategies in the DOE's grant program with the National Advanced Biofuels Consortium. Virent is collaborating with Royal Dutch Shell and Cargill to help commercialize its technology.

Researchers are also developing highly engineered "designer" microorganisms using synthetic-biology-platform technologies to produce renewable hydrocarbon drop-in biofuels. These technologies are still at the laboratory stage. Massachusetts-based Joule Biotechnologies is developing an algal technology that it claims is fundamentally different from other algae-based systems. First, Joule is using a different type of engineered microorganisms (*prokaryotic* rather than *eukaryotic* microorganisms that fit the scientific definition of algae). Joule's engineered microorganisms directly produce and secrete liquid hydrocarbons in a continuous, single-step process. Other custom-designed biofuels developers include two California start-ups—LS9, Inc. and Amyris, Inc. Both companies are focusing on high-value fuel products such as high-quality diesel and jet-fuel formulations as well as specialty biochemicals from plant sugar sources. A fundamental challenge will be scaling up the processes and using more sustainable feedstock sources.

Artificial Photosynthesis

Researchers are in the early stages of developing fundamentally new technology to make liquid fuels directly from sunlight, water, and carbon dioxide—similar to photosynthesis in plants. Although still in its infancy, the technology has long-term potential to replace the use of biomass-based fuels and thus free up agricultural land for the production of food. A 2008 report by the DOE's Basic Energy Sciences

Advisory Committee identified fuels-from-sunlight technology as a key strategic goal to help transform US dependence on imported oil and limit rising emissions of carbon dioxide. The ultimate aim for artificial photosynthesis is to produce large amounts of fuels that are as easy to store, ship, and use as current petroleum-based transportation fuels. In 2010, the DOE began funding the Joint Center for Artificial Photosynthesis (JCAP), led by the California Institute of Technology, to lay the groundwork for creating a direct-solar-fuels industry within five years. JCAP's mission is to demonstrate a scalable, robust, and cost-effective, solar-fuels generator to produce fuel derived from solar energy ten times more efficiently than can current crops—including corn, sugarcane, and switchgrass. Developing practical and economically viable solar-fuel-generation systems requires deeper scientific understanding than exists today as well as the development of new materials and processes for the transfer of energy among light, electricity, and chemical fuels at the atomic and molecular level. Many researchers are initially working on producing hydrogen in solar-fuel devices with later efforts to produce natural gas, methanol, gasoline, or diesel fuels. Daniel Nocera and his research team at MIT have demonstrated artificial-leaf systems made from inexpensive components—nickel and cobalt catalysts—incorporated into a silicon photovoltaic cell and electronics.

This paper does not represent US Government views.

Annex H

Emerging Post-Harvest Technologies

The productivity of the agricultural industry depends to some extent on what happens to a food product after it is harvested. Postharvest losses for grain products are 10 to 20 percent and for fresh fruits and vegetables 5 to 25 percent in developed countries and 20 to 50 percent in developing countries. Causes of these losses include microbiological deterioration, mechanical damage of processing equipment, insect infestation, and over-ripening. Post-harvest technology (PHT) consists of three elements:

- Primary processing: Removes foreign matter and immature and damaged product; stabilizes the product by drying, refrigeration or fumigation; segregates the product into different grades

- Secondary processing: Converts the raw material from primary processing to a product suitable for consumer preparation

- Tertiary processing: Converts the product of secondary processing into a ready-to-eat product.

Most of the post-harvest losses occur in primary processing; the secondary and tertiary processing focus more on the nutrition and safety of food products. All of PHT research receives only about 5 percent of the total research funding directed at the agricultural industry, whereas agriculture production receives the remaining 95 percent. The research effort aimed at reducing losses in primary processing is limited, takes place mostly in developing countries, and relates mostly to fruit and vegetable crops. PHT is not likely to produce any breakthrough technologies by 2040; however technologies applied in the developed countries will increasingly diffuse to developing countries.

Primary Processing Technologies

Controlled Atmosphere Storage. The horticultural industry in developed countries has used controlled atmosphere (CA) storage for decades. It consists of controlling the oxygen, nitrogen, and carbon dioxide atmosphere as well as the temperature and humidity for the storage of fruits or vegetables. CA provides stability during long-term storage and preserves quality by slowing down the respiration rate of the fruits or vegetables. Each fruit or vegetable requires a different atmospheric composition, but typical concentrations are 2-3 percent oxygen, 3-10 percent carbon dioxide, and the remainder nitrogen. Storage warehouses keep the temperature near 0 degrees Celsius and vary storage from one to six months. Most of the CA research on fruits and vegetables has been aimed at finding the optimum conditions for storage of particular species of fruits and vegetables. CA has been quite successful at reducing losses of fruits and vegetables by extending the time of availability as well as extending the geographic market availability. There is no evidence that any breakthrough in this technology will occur before 2040. R&D is likely to continue to refine the conditions of storage for various fruits and vegetables and extend the technology to more developing countries.

Modified Atmosphere Packaging

By extending the shelf life of perishable food products, modified atmosphere packaging (MAP) has contributed to reducing losses of agricultural products in the distribution chain. The MAP process changes the composition of the internal atmosphere of packaged meat products, seafood, or fruits and vegetables. In the case of meat products and seafood, the composition is mostly carbon dioxide and nitrogen, which inhibits the growth of bacteria. Some oxygen (2-3 percent) needs to remain in packages of fruits and vegetable to avoid anaerobic respiration. The polymer packaging films are the key to this technology. Meat products and seafood use barrier films that prevent exchange of gases, whereas respiring fruits and vegetables require exchange of gases and use permeable films. The development of films that allow selective permeation of gases has been an advance in MAP technology in the last 15 years that allows further extension of shelf life.

Disinfestation Technologies. The USDA has an ongoing research program seeking alternatives to widely used methyl bromide, which is being phased out because of EPA regulations. CA has been proposed as a substitute for fumigation by methyl bromide, which is highly toxic, potentially a mutagen and carcinogen, and depletes ozone. Grains can be disinfested by adding pure carbon dioxide or combustion gas and oxygen or by using hermetic storage where the natural respiration of grains will subside. Scientists at USDA are testing chemical and non-chemical means of disinfestations of both durable commodities (dried fruits and nuts) and perishable commodities (fresh fruit and vegetables).

Irradiation Technology. Applying electron beam, gamma rays or x-rays to harvested products inactivates microorganisms (*Salmonella*, *E. coli*, *Campylbacter*, and *Listeria*) that cause foodborne illnesses, reduces post-harvest losses due to insects and spoilage, and extends the shelf life of perishable foods. The technology has been tested for almost a century without showing any risks to human health. Commercialization has been limited, however, because of public concerns about radiation effects on food products. The large number of scientific studies showing no ill effects has led to domestic and international standards for irradiated foods. In the United States, the FDA regulates irradiation as a food additive so that its safety must be verified before any commercial application. According to FAO and IAEA, more than 60 countries have regulations allowing the use of irradiation for at least one product. Most of the applications are related to the control of insect pests especially for internationally traded products. Given the current level of commercialization and regulatory control, irradiation will probably replace other methods of disinfestation by 2040 and find wider use in extending shelf life of some perishable products.

Postharvest Biocontrol. Applying microorganisms that interfere with other spoilage microorganisms to perishable food products is a post-harvest biocontrol that is being proposed as a substitute for chemical fungicides. Although post-harvest biocontrol research has been ongoing for over 20 years, it has had only limited commercialization. *Pseudomonas syringae* has been developed to control spoilage of potatoes and sweet potatoes and *Metschnikowia fructicola* for sweet potato and carrots. The complex mechanisms of the biocontrol microorganisms include nutrient and space competition, parasitism, induction of resistance in the food product, and volatile metabolites. Because the understanding of the complex interactions among the food product, biocontrol microorganism, and the pathogenic microorganism is incomplete, the technology is not likely to have an impact by 2040.

This paper does not represent US Government views.

Annex I
Global Agricultural Research

Research Organizations

The Agricultural Research Service (ARS) of the USDA has a broad research agenda that addresses most of technological issues facing agricultural development; over its many decades of existence, it has been the source of innovative technologies. Its research includes over 1000 research projects organized into four research programs (see below). The ARS complements the research of the land-grant universities in the United States, all of which have research programs devoted to the agricultural products of their state. Past research by ARS and land-grant universities has produced hybrid crop and animal strains, labor-saving equipment, improved cultural practices, animal disease control, and availability of chemicals to promote growth and protect plants from pests. The innovations arising from decades of this agricultural research has resulted in an increase in output of US agriculture of 2.7 fold from 1948 to 2004 with an annual growth rate of 1.8 percent.

International research organizations are another source of innovative agricultural technology. The most widely know are the 15 international agricultural research centers, supported by the Consultative Group on International Agricultural Research (CGIAR), which carry out research on various agricultural commodities, livestock, fish, water, forests, and policy and management:

Africa Rice Center (Cotonou, Benin)
Bioversity International (Rome, Italy)
CIAT—Centro Internacional de Agricultura Tropical (Cali, Colombia)
CIFOR—Center for International Forestry Research (Bogor, Indonesia)
CIMMYT—Centro Internacional de Mejoramiento de Maiz y Trigo (Mexico City, Mexico)
CIP—Centro Internacional de la Papa (Lima, Peru)
ICARDA—International Center for Agricultural Research in the Dry Areas (Aleppo, Syrian Arab Republic)
ICRIAST—International Crops Research Institute for the Semi-Arid Tropics (Patancheru, India)
IFPRI—International Food Policy Research Institute (Washington, DC)
IITA—International Institute of Tropical Agriculture (Ibadan, Nigeria)
ILRI—International Livestock Research Institute (Nairobi, Kenya)
IRRI—International Rice Research Institute (Los Banos, Philippines)
IWMI—International Water Management Institute (Colombo, Sri Lanka)
World Agroforestry Centre (Nairobi, Kenya)
World Fish Center (Penang, Malaysia)

In 2004 the US National Academy of Sciences (NAS) issued a report on emerging technologies in agriculture aimed at benefiting farmers in Sub-Saharan Africa and South Asia. A committee of 11 agricultural scientists examined about 60 technologies that could increase agricultural productivity; they selected 18 of these technologies as having the greatest potential to impact agricultural production in Sub-Saharan Africa and South Asia as follows:

- Soil management techniques
- Integrated water management
- Climate and weather prediction
- Annotated crop genomes
- Genome-based animal breeding
- Plant-mediated gene silencing
- Biocontrol and biopesticides
- Disease suppressive soils
- Animal vaccines
- Soil-related nanomaterials
- Manipulation of the rhizosphere
- Remote sensing of plant physiology
- Site-specific gene integration
- Spermatagonial stem cell transplantation
- Microbial genomics of the rumen
- Solar energy technologies
- Energy storage technology
- Photosynthetic microbe-based biofuels

These selected technologies were grouped into the four major components of agricultural production: management of the natural resource base supporting agriculture (soil, water, climate), application of genetic diversity to improve the production characteristics of crops and animals (crop and animal genomes), reduction or elimination of biotic constraints (disease, pest, and weeds), and availability of affordable, renewable energy for farmers.

USDA National Programs

The Agricultural Research Service of the USDA is organized into National Programs. The programs coordinate 1000 research projects. The following lists these programs.

Nutrition, Food Safety, and Quality

- The Human Nutrition program conducts research that leads to improved dietary recommendations and a healthier population.

- The Food Safety (animal and plant products) program conducts research that seeks ways to assess, control, or eliminate potentially harmful food contaminants.

- The Quality and Utilization of Agricultural Products program develops cost effective and functional products for industrial and consumer use.

Animal Production and Protection

- The Food Animal Production program focuses on researching animal genetic resources, enhancing animal adaptation and production efficiency, and measuring and enhancing product quality.

- The Animal Health program develops solutions to prevent and control animal diseases.

- The Veterinary, Medical, and Urban Entomology program develops means to prevent or suppress insects, ticks, and mites that affect animals and humans.
- The Aquaculture program develops improved genetic stock and management practices to ensure a high quality and safe supply of seafood and aquatic products.

Natural Resources and Sustainable Agricultural Systems

- The Water Availability and Watershed Management program conducts research on processes that control water availability and quality and develop new technologies for managing agricultural water resources.
- The Climate Change, Soils, and Emissions program conducts research to improve the quality of the atmosphere affected by and affecting agriculture and develops means for agriculture to adapt to climate change.
- The Bioenergy program conducts research on new varieties and hybrids of bioenergy feedstocks, develops practices and systems for maximizing sustainable yields of bioenergy feedstocks, and develops biorefining technologies.
- The Agricultural and Industrial Byproducts program manages and enhances utilization of manure and other agricultural and industrial byproducts.
- The Pasture, Forage, and Rangeland Systems program conducts research to enhance conservation and restoration of agroecosystems; manages fire, invasive weeds, and grazing; develops improved grazing-based livestock systems; develops improved grass and forage legume germplasm for livestock; and develops decision support systems.
- The Agricultural System Competitiveness and Sustainability program focuses on systems that integrate information and technologies to develop new practice and dynamic systems that enhance productivity, profitability, energy efficiency, and natural resource stewardship.

Crop Production and Protection

- The Plant Genetic Resources, Genomics, and Genetic Improvement program furnishes plant and microbial genetic management, provides crop informatics, genomic and genetic analyses, and develops genetic improvement of crops.
- The Plant Biological and Molecular Processes program translates fundamental plant genomics into crop improvement, studies biological processes that improve crop productivity and quality, and assesses plant biotechnology risk.
- The Plant Diseases program detects, identifies, and characterizes plant pathogens, studies the spread of plant pathogens and their relationship with hosts and vectors, studies plant disease resistance, and develops strategies for sustainable disease management.
- The Crop Protection and Quarantine program provides technology to manage pest populations by the integration of environmentally compatible strategies based on the biology and ecology of insects, mites, and weed pests.

- The Crop Production program conducts research to increase crop efficiency, productivity, quality, marketability, and protection of annual, perennial, greenhouse, and nursery crops by expanding, maintaining, and protecting the genetic resource base, and increasing knowledge of genes, genomes, and biological processes.

- The Methyl Bromide Alternatives program develops environmentally compatible and economically feasible alternatives to methyl bromide as a soil and post-harvest fumigant.

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Annex J

Cost of Production for US Farms in 2010

Cost Item	Corn		Soybeans		Wheat	
	$/Acre	Percent of Total	$/Acre	Percent of Total	$/Acre	Percent of Total
Seed	83.23	15.5	59.20	14.7	11.76	4.3
Fertilizer	100.30	18.7	17.87	4.5	41.23	15.0
Chemicals	27.39	5.1	17.04	4.2	10.37	3.8
Services	12.15	2.3	6.52	1.6	7.92	2.9
Fuel lube electricity	35.73	6.7	16.75	4.2	21.57	7.8
Repairs	16.03	3.0	13.46	3.4	14.06	5.1
Irrigation water	0.15	0.0	0.14	0.0	0.40	0.1
Interest	0.27	0.0	1.31	0.3	0.11	0.0
Labor	28.36	5.3	19.44	4.8	27.00	9.8
Capital recovery	83.46	15.5	77.51	19.3	64.63	23.4
Land cost	127.33	23.7	148.34	37.0	58.59	21.2
Taxes insurance	8.23	1.5	9.41	2.3	8.83	3.2
Overhead	14.71	2.7	14.86	3.7	9.43	3.4
TOTAL COST	537.34	100.0	401.85	100.0	275.90	100.0

Source: USDA

US corn production costs and returns per planted acre, excluding Government payments, 2005-2010.

US soybean production costs and returns per planted acre, excluding Government payments, 2005-2010.

US wheat production costs and returns per planted acre, excluding Government payments, 2004-2010.

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