Sustainable Global Food Supply

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Abstract

There is no area of human activity more basic to society than a sustainable agricultural, food, and natural resources system. An existing agricultural production system which has provided an abundant, affordable, and safe food supply and many industrial and consumer products face the daunting challenge to meet the needs of a growing world population to approximately 9–10 billion people in 2050 with the need to provide about 60–70 % more food than now

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being produced. However, it is more than just agricultural productivity because the system must function within the space of climate change; minimum (zero) negative impacts on the environment; reduced (zero) greenhouse gas emissions (GHG); reduced water usage; concern for availability and cost of energy; increased application of conservation tillage; worldwide adoption of biotechnology; increased organic food production; major adoption of information technologies at all phases of the agricultural, food, and natural resources system; and significant advancements in machine innovations. Specifically, there is a need to transcend the debate between the vocal constituencies rooted in ideological solutions and rather invoke and encourage a broad recognition that many different approaches are needed to coexist to meet this huge challenge. Thus, there is no system more in need of and more likely to benefit from a comprehensive application of convergence technologies embodied in nanotechnology, biotechnology, information sciences, and cognitive sciences.

Introduction

Can the world's population be fed in 2050 and beyond? Can it be done sustainably? Feeding the world is one of society's biggest issues and is considered to be an increasingly major challenge in light of the projection of a world population reaching between 9 and 10 billion persons by 2050 (United Nations 2014). Not only can enough food be produced to meet this need, but can it be done without destroying our planet? Rhodes (2012) in *Earth: A Tenant's Manual* writes, "For all of our freedom, versatility, and creativity, we have only one Earth, and its carrying capacity is finite. And we may be about to test that capacity to support a growing human population at a subsistence level that we would regard as adequate. This will involve a real time experiment and its outcome may not be benign."

Others have issued stark warnings about an adequate food supply, most notably going back to Thomas Malthus over 200 years ago and reinforced by Paul R. Ehrlich in 1968 in *The Population Bomb* and a following pessimistic assertion about scarcity (Ehrlich 1974) in *The End of Affluence*. The Paddock brothers (1967) suggested a dire triage system in their book, *Famine 1975! America's Decision: Who Will Survive?* because they theorized that an exponential population growth, an insufficient agricultural production, and political ineptness would not meet world food needs, and therefore, they suggested that food aid needed to be categorized according to (1) "can't-be-saved nations, (2) those who would stagger through without aid, and (3) those who could be saved with aid". Fortunately, these old forecasts have not come true, at least not yet.

However, Malthus's assertion is not inherently incorrect because food production is bounded by natural resources of soil, water, and crop productivity underpinned by science, and the carrying capacity of the earth is limited. The earth has an approximate land area of 150 million square kilometers (about 16 times the land area of the USA), and this global land area (Rhodes 2012) can be categorized as:

Arable land area	10 %
Permanent crops	1 %
Forest and woodlands	31 %
Pasture	24 %
Unusable	34 %

In addition, almost all of the land area available for sizable and economically feasible food production is in use which creates the challenge of meeting increasing food production, not by adding new land but by increasing food production from the existing area by creating much higher yields. Making the challenge even more difficult is how and specifically what technologies will be acceptable to accomplish the large increases in yields? How can this be done in the face of the huge challenges from advancing global climate change; scarcity of water in many areas; environmental concerns for pollution due to applications of fertilizers, pesticides, and herbicides; increasing cost of energy; and changing diets with an increased worldwide consumption of meat which has tripled since 1961 with an accompanying use of as much as 34 % of grain production?

Another theme frequently raised is that instead of focusing on agricultural productivity, we should address access to food. Gordon Conway (2012) in his book, *One Billion Hungry: Can We Feed the World?* writes, “If we were to add up all of the world’s production of food and then divide it equally among the world’s population, each man, woman and child would receive a daily average of over 2,800 cal – enough for a healthy lifestyle.” On a positive note, the rate of population growth began to decline in the 1980s and may level off at about nine billion according to the United Nations (2014) as a result of increased prosperity and education, particularly for women and girls. Interestingly, Ausubel et al. (2012) write that

> Rather than rampant exploitation, the global use of cropland to supply a growing population in the last half-century shows restraint and innovation and suggests humanity now passes peak use of land in arable and permanent crops. As affluence rises, people do consume more calories and more animal products. Nevertheless their appetites grow more slowly than their affluence and eventually level off. . . ..Leveling population, saturating tastes, and improving efficiencies promise to spare land from cultivation. By 2060 they might allow to revert to Nature nearly 150 million hectares.

Given the expectation of 9–10 billion people, food security is making headlines around the world and is an issue now! Major media coverage in the USA alone suggests that a “tipping point” may have or soon will be reached. Featured stories in Time Magazine (August 2009); *The Real Cost of Cheap Food*, Time (September 2012); *What to Eat Now*, Scientific American (September 2013); A *Special Food Issue*, The National Geographic (May 2014); *The New Food Revolution* and The National Geographic (monthly issues from June to December 2014) have focused on food and the challenge of feeding the global population in the future.

Food security, food safety, and food production are no longer on the back burner. As with water, air, and energy, it is incumbent on us to meet these challenges in a sustainable way. Webber (2015) articulates that our future rides on our ability to integrate this nexus of food, water, and energy.

Thus, can we produce enough food to support healthy people without destroying our biosphere? Smil (2000) articulates three principles to answer this question: (1) an understanding of the complexities of the realities of the food system, (2) a consideration of fundamentals of crops and animal systems to food production, and (3) a need to concentrate on efficiencies of the food chain from production to consumption. Failure to recognize these realities can lead one to despair or for another, a misplaced optimism.

"Toward" a Sustainable Global Food Supply

While agricultural productivity has been a consistent and important emphasis over the past several decades, there has been a significantly increased emphasis on assessment of impacts of agriculture on the environment; reduced greenhouse gas emissions (GHG); reduced water usage; increased application of conservation tillage; worldwide adoption of biotechnology; major adoption of information technologies at all phases of the agricultural production, transportation, and delivery systems; and significant advancements in machine innovations which have led to automation and precision farming.

Many agricultural practices have unintended consequences relative to water quality, greenhouse gas emissions (GHG), degraded soil quality, biodiversity, and animal welfare. Changes in agricultural production systems and usage of natural resources have raised public concerns about the ecological sustainability of agriculture and well-being of rural communities, farm families, farm laborers, and animals. During the past decade, the concept of sustainability of agriculture has been much discussed and was addressed in the NRC report (2010) wherein four goals are used to define sustainable agriculture:

Satisfy human food, feed, and fiber needs and contribute to biofuel needs
Enhance environmental quality and the resource base
Sustain the economic viability of agriculture
Enhance the quality of life for farmers, farm workers, and society as a whole

However, sustainability is best viewed, not as a particular end point, but rather as a process moving agriculture, food, and natural resources toward greater sustainability on these goals. The authors suggest a working description of sustainable development as a "process of change in which the direction of investment, the orientation of technology, the allocation of resources, the development and functioning of institutions and advancement of human and community well-being meets present needs and aspirations without compromising the ability of future generations to meet their own needs and aspirations" (adapted and modified from Roy

Weston 1992). While this description may not satisfy everyone, it suggests an imperative for action by which the goals for development of sustainable agriculture, food, and natural resources can be measured. Moreover, in addition to implications for resources, it embodies the attributes of environmental, economic, and social recognition and responsibility, now and into the future. Clearly not all societies see or will see sustainability the same way, but this description and the goals for a sustainable agriculture, food, and natural resources provide a sound basis for assessing future approaches to advancing sustainability.

Advances in the Agriculture and Food Systems to 2014

Modern agriculture has had an impressive history of increasing productivity that has led to abundant, safe, and affordable food, fiber, and recently biofuels. Farmers today are meeting both expanded domestic and international markets on the same acreage as a century ago as a result of technological innovations, economies of scale, consolidation of food processing and distribution, and advanced retailing.

It is important to recognize that the broad agriculture and food system is huge. For example, the total amount spent for all food consumed in the USA was $1.4 trillion dollars in 2013. The ERS/USDA (Economic Research Service/US Department of Agriculture) indicates that spending on food away from home was 49.6 % of the $1.18 trillion in total food expenditures in 2013 and spending for food at home was 50.4 %. The result is that US residents spent on average about 9.8 % of their annual consumer expenditures on food in 2013 compared to 21 % in 1950, and this is less than any of the other 83 countries which the USDA tracks (USDA 2014). By contrast, in Pakistan the average person spends about half his/her annual income on food.

During the past decade, US agriculture has continued to become increasingly dependent on large-scale, high input farms that specialize in a few crops and concentrated animal production practices; for example, 2 % of US farms are responsible for 59 % of US farm products (NRC 2010). By contrast, small- and medium-sized farms represent more than 90 % of the total farm numbers and manage about half of US farmland.

At this time, hunger and malnutrition are the number one risk to health worldwide, not disease. Thus, to feed the one billion chronically hungry and to get to a food-secure world by 2050, it is necessary to address the issue of poverty. If one looks at this problem as a pyramid (Clay 2010), those wealthy at the "top" (two billion) will be able to afford anything, those at the "bottom" (two billion) the poorest will be greatly challenged to meet daily needs, while for the five billion falling in the "middle," it is likely to be a matter of where calories come from such as "eating up the food chain," meaning more animal protein, vegetables, fruits, and processed foods. Bittman (2014) offers a unique perspective suggesting that there are no hungry people with money; there is not a shortage of food nor a distribution problem but rather a need to end poverty.

Thus, it is abundantly clear that the agriculture and food system is exceedingly complex and is a perfect case for the implementation of an integrated application of converging technologies – nanotechnology, biotechnology, information science, and cognitive science. However, first, we offer a brief review of key technologies that have driven the modern success of US agriculture and food system into the twenty-first century.

Biotechnology crops in 2014 (ISAAA 2015) are utilized in 28 countries reaching 181.5 million hectares at an annual growth rate of about 3 %. The global hectares in biotech crops have grown from 1.7 million hectares in 1996 with numerous stated benefits of:

- Contributing to food, feed, and fiber security, sustainability, and climate change. Biotech contributes by creating more affordable food and by increasing productivity and economic benefits sustainably at the farm level. Economic gains at the farm level can be generated through major crop improvements reducing production costs, lesser pesticides, less labor, and increased yield. In 2014, a record number of 18 million farmers grew biotech crops, and over 90 % were risk-averse small, poor farmers in developing countries.
- Conserving biodiversity through land-saving technologies. Higher productivity on the current 1.5 billion hectares of arable land can preclude deforestation and protect biodiversity. For example, as much as 13 million hectares of tropical forests are lost annually in developing countries. It is projected that without impact of biotech crops, 123 million hectares would have had to have been used.
- Contributing to alleviation of poverty and hunger. For example, biotech has made significant contribution to incomes of approximately 16.5 million small, resource-poor farmers in developing countries in 2014, primarily in cotton, maize, and rice.
- Reducing agriculture's environmental footprint by reduction in pesticides, saving on fossil fuels, decreasing CO_2 emissions, and increasing efficiency of water usage.

Despite this rapid adoption of genetically modified crops, there exists a large public controversy surrounding GMOs in terms of risks and benefits as well as the impact on the structure of agriculture and specifically concerns about who benefits (large corporations) or who loses (small and poor farmers). A major meta-analysis study of the impacts of GMO crops by Klümper and Qaim (2014) of 147 original studies reports, "On average, GM technology adoption has reduced chemical pesticide use by 37 %, increased crop yields by 27 %, and increased farmer profits by 68 %. Yield gains and pesticide reduction are larger for insect-resistant crops than for herbicide-tolerant crops. Yields and profit gains are higher in developing countries than in developed countries."

Precision agriculture, or precision farming, is a systems approach for site-specific management of crop and animal production systems. The foundation of precision farming rests on geospatial data techniques for improving the management of inputs and documenting production outputs (Reid 2011). As the size of farm implements and machines increased, farmers are able to manage larger land areas. A key technology enabler for precision farming resulted from the public availability of Global Navigation Satellite System (GNSS), a technology that emerged in the mid-1990s. GNSS provided meter, and later decimeter, accuracy for mapping yields and moisture content. A number of information and communications technology (ICT) approaches were enabled by precision agriculture, but generally, its success is attributable to the design of machinery with the capacity for variable-rate applications. Examples include precision planters, sprayers, fertilizer applicators, and tillage instruments. In general, advances in machine system automation have increased productivity, increased convenience, and reduced skilled labor requirements for complex tasks. Moreover, benefits have been achieved in an economical way and increased overall TFP (total productivity factor) – the output per unit of total resources used in production.

Conservation tillage systems can have both environmental and economic benefits. Conservation tillage leaves a minimum of 30 % of crop residue on the soil surface or at least 1,100 kg/ha of small grain residue on the surface during the critical soil erosion period (NRCS 2012). The most significant advantage is significantly less soil erosion due to wind and water. Conservation tillage systems also benefit farmers by reducing fuel consumption and soil compaction. By reducing the number of times the farmer travels over the field, farmers realize significant savings in fuel and labor. The adoption of less intensive tillage operations, if adopted by many farms, can sequester substantial carbon by allowing the soil to retain more organic matter which will contribute to the reduction and control of greenhouse gas emissions. It is estimated that 35.5 % of US cropland (~35 million hectares planted to the eight major crops had no tillage ["no till"]) operations in 2009 according to an ERS report (Horowitz et al. 2010). These crops – corn, barley, cotton, oats, sorghum, soybeans, and wheat – make up 94 % of the total planted US acreage. No-till practices have increased for corn, cotton, soybeans, and rice at a median rate of roughly 1.5 % per year. However, in some systems there has been an increased reliance on herbicides for weed control. Data on yields are somewhat mixed with many studies showing the same yields, others some reduction and others an increase.

Livestock systems – Positive environmental effects have been realized and opportunities developed for considerable gains in livestock systems during the past decade. In the USA, advances in animal nutrition, management systems, and genetics have resulted in a large increase in annual milk yield of dairy cattle. Capper et al. (2009) report a fourfold increase in milk yield in 2007 compared to that of 1944 with 84.3 billion kg in 2007 compared to 53 billion kg in 1944 with 64 % fewer cows. Carbon emissions and total emissions per unit of milk were reduced by 66 % and 41 %, respectively. Similar results for emissions per unit of product have been seen in the beef cattle industry and in poultry production. The Food and Agriculture Organization (FAO) confirms, on a worldwide level, that as livestock production intensity increases, the carbon footprint decreases substantially on the basis of product output per input.

The livestock sector supports almost one billion of the world's poorest persons, and it is likely to continue for quite some time (FAO 2009). Many people rely on livestock for their sustenance and livelihood. Thus, the livestock sector faces the challenges of balancing opportunities against risks and needs of different smallholders, food security, and nutrition. People relying on livestock for their livelihood are facing increasing pressures from global economic forces of growth and competition that are driving structural changes. Adding to these challenges is the human health concerns due to the potential for pandemic outbreaks of zoonotic diseases. Because livestock agriculture is increasingly recognized as important in rural development and poverty reduction, there is a need to balance policies and innovations technically and socially to meet the multiple demands of society.

Biofuels – At a time when the USA imported 52–60 % of its oil consumption (from 2005 to 2009) and transportation use accounted for about 30 % of carbon dioxide (CO_2) emissions, interest in biofuels reached a high point. The USA, as the world's largest consumer of crude oil, faced two significant problems: concern about energy security and high greenhouse emissions. Thus, the US Congress in 2007 enacted the Energy Independence and Security Act (EISA) because biofuels were seen to improve energy security as a renewable resource and to provide life cycle greenhouse benefits. A Renewable Fuel Standard (RFS) within EISA for 2008–2022 was developed as an annual mandate for biofuel consumption for conventional biofuels and advanced biofuels. In general, conventional biofuel is corn ethanol and advanced biofuels are cellulosic-derived biofuels. Controversy surrounded the use of corn for ethanol because of concerns over effects on food/feed prices, distortion of land use and increased cropland prices, as well as uncertainties about whether there were net environmental benefits. Clearly, corn farmers, primarily in the Midwest USA, were initially beneficiaries of a booming market and increased prices for their corn crop. Against this backdrop, the US Congress requested that the National Research Council (NRC) conduct an independent assessment of the economic and environmental effects in meeting the RFS. The NRC (2011) established two findings: (1) the RFS may be an ineffective policy for reducing global greenhouse gas emissions because the effect of biofuels on greenhouse gas emissions depends on how the biofuels are produced and what land-use or land-cover changes occur in the process and (2) key barriers to achieving the RFS are the high cost of producing cellulosic biofuels compared to petroleum-based fuels and uncertainties in future biofuel markets.

Processes using microorganisms, specifically bacteria, have been utilized to convert organic materials into methane and carbon dioxide. Anaerobic digestion using methanogenic bacteria in the absence of oxygen in airtight structures has been utilized for many years ranging from small home-owned digesters in China to large commercial tanks in Europe and the USA. The biogas, primarily methane (~60–70 %) and carbon dioxide (~30–40 %) with small amounts of other gases, can be used to create energy. In China, over ten million systems have been employed in rural villages for managing both animal and human wastes to provide biogas for cooking at the household level. In Europe and the USA, much larger systems have been developed to handle animal manures and food wastes by co-digestion to produce energy options such as combined heat and power (electricity and heat) and methane, after processing and compressing, for gaseous fuels for transportation vehicles. Germany has been particularly adept at creating bioenergy villages that effectively illustrate the potential for distributed energy generation at a local level from organic materials, including manure and plant-based biomaterials.

Vision to 2050

The challenges or threats of further population growth, increasing hunger, increasing water shortages, energy availability, and climate volatility can only be met by seeking an integrated systems approach where there are environmental, economic, and social benefits – sustainable solutions. Having stated the need for a holistic approach, we deviate for the moment to focus on emerging scientific platforms (Conway 2012) of nanotechnology, biotechnology, information science, and cognitive science (referred to as NBIC technologies by the National Science Foundation [NSF]) to meet the challenges of a sustainable global food supply (Fig. 1).

A series of reports have suggested some possible solutions to address food security and environmental challenges (IAASTD 2009; Royal Society 2009; Godfray et al. 2010; Foley et al. 2011; Conway 2012).

- Stop expanding agriculture – This means primarily stopping the clearing of tropical forests for agriculture. Potential loss of agricultural production perceived to be small can be compensated by reducing losses from productive cropland.
- Closing yield gaps – Foley et al. (2011) suggest that closing yield gaps sustainably will significantly increase global food supplies. For the 16 most important

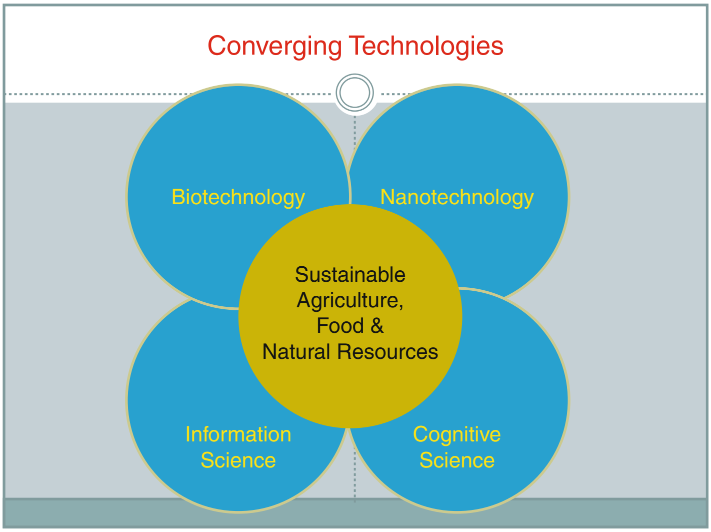

Fig. 1 Converging technologies

crops, if yields were increased to 75 % of genetic potential, global production could be increased by 28 % (by 2.6×10^{15} kcal).

- Increase efficiency – More sustainable pathways can be employed for intensification that will increase productivity while, at the same time, reducing water, nutrient, and chemicals.
- Close diet gaps – The current agricultural system has many economic and social benefits and the existing variety of products is not likely to change completely. However, small changes in diet and not using food crops for biofuels can improve food security and reduce environmental effects.
- Reducing food wastes – A surprising amount of food which is produced is not consumed (FAO 2011). This study suggests that as much as one-half of all food grown is lost. In developing countries, as much as 40 % is lost after harvest, and while industrialized countries sustain lower producer losses, it is estimated that losses as high as 40 % occur at the retail and consumer level.

Nanoscale Science and Engineering for Agriculture and Food Systems

Nanoscale science and engineering has the potential to revolutionize the agriculture and food system, comparable to or exceeding the impact of farm mechanization and the green revolution. It can play an important role in creating a safer and more productive agriculture and food system. The food supply chain can and will be affected by the utilization of nanotechnology at each point in the system along the supply chain from production through domestic consumption (Scott and Chen 2012, 2013).

Food Quality and Safety

- Detection of presence of residues, trace chemicals, viruses, antibiotics, pathogens, toxins
- An integrated, rapid DNA sequencing process to identify genetic variation and GMO's
- Tracking process for integrity of food during production, transportation, and storage
- A delivery approach to reduce calories of food while retaining flavor, lowered fat, reduced salt, less sugar, and improved texture
- A system to enhance bioavailability and delivery of nutraceuticals, nutrigenomics, increased vitamins, and nutrient content of foods
- Introduction of "personalized nutrition" to meet very specific individualized health needs
- Major improvements in food manufacturing processes
- Widespread advances in food packaging and food contact materials for quality assessment and enhanced shelf life (eliminate the need for refrigerated storage), including edible packaging

- Processes to substantially reduce crop and postharvest losses from production to consumer

Animal Health Monitoring and Management

- Applications of developmental biology techniques to detect onset of estrus to enhance and advance breeding
- Detection processes to sense presence of residues, antibiotics, pathogens, toxins, etc.
- Processes for early, predisease detection, rapid diagnosis, and prevention of diseases
- An integrated health monitoring process including therapeutic intervention as necessary
- A process for identity tracking of animals from birth to the consumer's plate
- New techniques such as nutrigenomics that will influence or control genetic expression
- Major nutritional platforms which will alter food products (milk and meat) with healthful human benefits
- Approaches to lessen greenhouse gas emissions (GHG) from livestock
- Application to manure management processes to reduce GHG and create renewable energy for distributed generation of electricity and heat

Plant Systems

- Development of "smart field systems" to detect, locate, report, and direct application of water, only as needed and in necessary quantity
- Development of "smart field systems"(possibly electronic "dust" particles) for early detection and monitoring of diseases for intervention strategies
- Applications of precision and controlled release of fertilizers and pesticides
- Utilization of bioselective surfaces for early detection of pests and pathogens
- Applications of a laboratory-on-a-chip proteomics technology for microbial biocontrol agents
- Development of "new" plant varieties with characteristics of drought resistance, salt tolerance, tolerance to excess moisture, enhanced photosynthesis activity, and capture nitrogen from atmosphere
- Plants (nonfood crops) for bioenergy (e.g., photosystems)
- Use of specialized (nonfood) plants, including trees, for nanocellulose and biofuels

Environmental Management

- Utilization of nanophase soil additives (fertilizers, pesticides, and soil conditioners)
- Nanoparticles to transport and deliver bioavailability of nutrients to plants
- Developed understanding of soils as a complex nanocomposite
- Comprehensive management of land, water, and air pollution (detection and remediation processes) – e.g., magnetic nanoparticles to collect pathogens
- An ability to track hydraulic and nutrient flows in the landscape

- Carbon nanotubes as filters to clean water at point of use and at larger scales
- Nanoparticles for desalination systems

Biotechnology

For most agriculture and food operations, the primary way to improve labor productivity is by increasing yields to better approach genetic potential for both crops and animals. Particularly in plant breeding, conventional breeding has had practical limitations of being largely random plant crosses in an attempt to create desirable characteristics, and it is a slow process. However, there are advanced breeding methods that do not involve genetic modified organisms (GMOs) that are being developed that utilize advanced computer analyses and other high-tech techniques. As stated in a preceding section of this chapter, biotechnology has been implemented in 28 countries over a 20-year period with arguably excellent results. Interestingly, the meta-analysis study (Klümper and Qaim 2014) reports higher yield and profits in developing countries than in developed countries. Nevertheless, a significant minority expresses strong concerns about the health effects on the environment (because of claims on increased use of pesticides and herbicides) and possible human health effects as well as demand for the labeling of products that contain GMOs. To date, there has been a lesser effort in inserting genes for yield increases than genetic modification for the control of weeds and pests. Rather, improvement in yields has been accomplished by conventional breeding applied to lines containing GM genes (Conway 2012).

In the USA, persons have been consuming GM foods for more than 15 years without obvious health effects. Lemaux (2009) has reported, based on an extensive review of potential health hazards, that GMO crops and products are “at least as safe in terms of food safety as those produced by conventional methods.” Thus, if we are to increase yields and create new crop varieties and improved animal breeds, we need to utilize the science of biotechnology as well as organic practices to advance both large commercial operations and smallholder farmers. The great potential for biotechnology to enhance photosynthesis, nitrogen fixation, nutrient management, and water usage and yield improvement should not be ignored and left underutilized.

Information Science

ICT (information and communications technologies) can be broadly viewed as any communication device or application, encompassing radio, television, cellular phones, computers and network hardware and software, satellite systems as well as the various services and applications associated with them, such as videoconferencing and distance learning. Agriculture and food systems have increasingly embraced ICT at all levels from large farmers to poorest farmers in developing countries through a comprehensive integration of sensors, satellites, and cell phones. Farmers are gaining intelligence and experience to operate within the unprecedented challenges of extreme climate, water limitations, energy availability, price volatility, resource availability, natural disasters, and social issues. As one farmer (a family farm, although large through expansion to over 7,000 ha) said, “I’m hooked on a drug of information and productivity. We’ve got sensors on the combine, GPS data from satellites, cellar modems on self-driving tractors and apps for irrigation on iPhones” (NY Times 2014). Although poor farmers in Asia and Africa are not engaged at this level of ICT, they are increasingly utilizing the cell phone to obtain critical information on expenses of agriculture inputs and prices, connect to markets, and participate in newly developing mobile network operators worldwide through digital financing.

In the USA, from the advances in precision agriculture comes real-time data about moisture, yields, net nitrogen, net yields per hectare, and other information stored on electronic tablets which is sent, by wireless modems, to computer servers (cloud computing) for later analysis. Farmers will use the data from the last season’s information to plan for the next season’s cropping system. Thus, can “big data” be worked to help agriculture meet the numerous challenges? Not only have many farmers invested in this new technology, but numerous businesses from Microsoft to Amazon to Nestle to small software startups are joining an increasingly crowded field to help farmers use data sets in innovative ways for dealing with weather data, scheduling planting and harvests, conserve fertilizer, water efficiency, manage irrigation, nitrogen use efficiency, and global information such as crop production and assessments.

Two technical innovations that are likely to gain rapid and widespread adoption in agriculture, food, and natural resources are robotics and drones (unmanned aerial vehicles). Robotic systems encompassing integration of sensors, imaging, and analytics will play an important role in the future of precision agriculture of animals and plants. Some existing and future applications of robotics are:

- Milking systems (both small and large herds)
- Animal feeding systems based on productivity data
- Plant systems for picking fruits and vegetables
- Application of nitrogen more accurately during growth
- Application of water at specifically water stressed plants
- Vehicle to identify and eliminate weeds
- In food processing plants for sorting, sizing, and packaging

While drones (unmanned aerial vehicles) have been used for years in military missions and intelligence gathering, the use of drones in agriculture (commonly referred to as small unmanned aircraft systems, sUAS) is on the verge of exploding. Some estimates suggest it is likely that there will be ten times more sUAS applications in agriculture than in other civilian area and that 80 % of the economic impacts will be in agriculture. Some farmers/managers have or will use sUAS to:

- Map crops to forecast yields
- Identify water stressed areas
- Identify flooded areas
- Locate weeds to implement management
- Identify hail damage
- Spot onset of plant diseases or pests and deliver intervention schemes
- Implement surveys for agriculture (animals and plants) and forestry
- Deliver fertilizer, possibly water at points of high need
- In absence of bees, supplement pollination process
- Monitor crop emergence
- Monitor animals in inaccessible regions in natural environment
- Deliver contraceptives to manage wild horse and burro population

On the positive side, the cost of small sUAS is relatively small in the range of $1,000–2,000 plus auxiliary sensors, cameras, and actuators. On the negative side, the Federal Aviation Administration (FAA) in the USA has failed to pass an act permitting the use of UAV/sUAS in agriculture, although there is an expectation that an act will be passed relatively soon.

It is clear that the impact of information science is a significant development for agriculture and food systems in both the developed and developing world, the difference being only in scope and size.

Cognitive Science

Convergence in knowledge, technology, and society is suggested as a driver for change, and this chapter has sought to demonstrate that convergence of separate disciplines characterized by nanotechnology (atoms), biotechnology (genes), information technology (bits), and cognitive science (neurons) can change the face of agriculture, food, and natural resource systems. Without question, the element least addressed across the concept of converging technologies in the agriculture and food systems is the cognitive sciences. Cognitive science is defined here "as the interdisciplinary scientific study of the mind and its processes. It includes research on intelligence and behavior, especially focusing on how information is represented, processed, and transformed (in faculties such as perception, language, memory, reasoning, and emotion) within nervous systems (human or other animal) and machines (e.g., computers). Cognitive science consists of multiple research disciplines, including psychology, artificial intelligence, philosophy, neuroscience, linguistics, anthropology, sociology, and education."

Critical to the vision for the agriculture, food, and natural resources system is public acceptance of the converging technologies if they are to be adopted for the benefit of human wellness, happiness, and development. However, by and large, the technical transformations created by nanotechnology, biotechnology, and information science have not included empowerment of persons and groups by expansion of human knowledge and cognition. Rather, ethical and social issues have been largely ignored, leading to a uniformed public at best and an anti-technology mindset at the worst. A true convergence requires that the agriculture, food, and natural resource system begin to include cognitive science as an integral element. Persons outside these technologies often have a quite different belief and value system. While both groups share a concern about effects of these technologies on the environment, health, biodiversity, and food safety and quality, they often diverge in their concerns about:

- The need to label foods if they contain GMOs or nanoparticles
- Questions of ownership and control issues
- Who benefits? Are the poor more vulnerable?
- Consolidation of corporate power and marginalization of farmers' rights
- Lack of regulations? Standards?
- Lack of public engagement or if there is an effort it is seen as a "reactive engagement" rather than an inclusive and participatory one

Thus, if convergence is to embrace a societal component and lead to solutions of a growing world population, increased agricultural productivity, reduced greenhouse gas emissions, and reduced water usage and availability of energy, all in the face of climate change and the complexities of a hugely complex global agriculture and food system, it is crucial that the cognitive sciences be included more actively in moving forward.

Some Guesses for 2050 and Going Forward

In concluding this chapter, the authors are compelled to reflect on emerging areas that may well play an important role in the agriculture, food, and natural resources sector during the twenty-first century going forward:

- *Edible insects for animal feed as well as human food* – The potential role of insects for food and feed is reviewed in a comprehensive report by the FAO (2013).
- *Aquaculture* – Given the diminishing source of seafood from the oceans, it is anticipated that aquaculture, both farm raised (cages in a natural environment and recirculating indoor systems), will grow to meet increasing demand.
- *Synthetic foods* – Although in its infancy, synthetic foods (lab-grown meat) are making headlines, if not yet commercially viable as a replacement for meat.
- *3-D printing* – A futuristic R&D effort is underway on 3-D printing of organic products such as food.
- *Food waste reduction* – The recognition that as much 30–50 % of the food produced is wasted between production and the consumer's plate has awakened scientists and engineers to solving a doable problem.

- *Vertical farming* – Although energy consumption for an indoor, vertical farm is a serious limitation, the idea of vertical farming may be a rational option in megacities of the future for fresh and locally available food.
- *Investing in women and girls* – Increasingly, there is recognition that investing in women is the most efficient and effective way to increase food production in the developing world because about 43 % of all farmers are women.
- *Agricultural investment in the developing world* – As foreign aid decreases, a changing model is developing where private sector partnerships with governments are taking shape. A mix of businesses can offer business skills training, financing, and mentoring. Ideally, the partnership provides greater resources for small farmers to carry out a successful farming enterprise and thereby achieve greater profits. However, the potential for displacement of small-scale food producers and exploitation by businesses is a real concern.
- *Autonomous farming systems* – Interesting developments are being researched to create futuristic farming technologies. Some examples are driverless tractors, machine-to-machine communications, self-propelled sprayer, electric-driven tractors, and electric-powered equipment. At first reflection, this high technology may be perceived as only affordable and applicable in "industrialized" agriculture. However, the possibility of developing electric-driven tractors and equipment is conceivable for the developing world because smaller machines can be well adapted to small land holdings. Advancement in battery technology is key together with the adaptation of solar energy.

Concluding Remarks

Returning to the basic questions, can the food system be adapted to feed the world and can it be done sustainably? There are no silver bullets to meet the many challenges to be faced in feeding the 9–10 billion persons by 2050. Specifically, there is a need to transcend the debate between the vocal constituencies rooted in ideological solutions and rather invoke and encourage a broad recognition that many different approaches are needed to coexist to meet this huge challenge. Thus, there is no system, more in need of and more likely to benefit from a comprehensive application of convergence technologies embodied in nanotechnology, biotechnology, information sciences, and cognitive sciences. Holistic thinking must be employed using a lens of sustainability to insure environmental, economic, and social benefits.

References

Ausubel JH, Wernick IK, Waggoner PE (2012) Peak farmland and the prospect for land sparing. Popul Dev Rev 38(Suppl):221–242

Bittman M (2014) How to change the food system. https://www.youtube.com/watch?v=JWKa9DWSlz4. Accessed 26 Feb 2015

Capper JL, Cady RA, Bauman DE (2009) The environmental impact of dairy production: 1944 compared with 2007. J Anim Sci 87:2160–2167
Clay J (2010) Agriculture from 2000 to 2050 – the business as usual scenario. http://www.globalharvestinitiative.org/Documents/Clay%20%20Agriculture%20from%202000%20to%202050.pdf. Accessed 26 Feb 2015
Conway G (2012) One billion hungry: can we feed the world? Cornell University Press, Ithaca
Ehrlich PR (1968) The Population Bomb, Ballantine Books
Ehrlich PR (1974) The End of Affluence, Ballantine Books
Foley JC, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnson M, Mueller ND, O'Oconnell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockstrom J, Sheehan J, Siebert S, Tillman D, Zaks DPM (2011) Solutions for a cultivated planet. Nature 478:327–342
Food and Agriculture Organization (FAO) (2009) The state of food and agriculture 2009. Conclusions: balancing society's objectives for livestock. pp 94–100. http://www.fao.org/docrep/012/i0680e/i0680e.pdf. Accessed 26 Feb 2015
Food and Agriculture Organization (FAO) (2011) Global food losses and food waste – extent, causes and prevention. Rome http://www.fao.org/docrep/014/mb060e/mb060e00.pdf. Accessed 26 Feb 2015
Food and Agriculture Organization (FAO) (2013) Edible insects: future prospects for food and feed. http://www.fao.org/forestry/edibleinsects/74848/en/. Accessed 26 Feb 2015
Godfray HCJ, Beddington JR, Crute IR, Haddad I, Robinson S, Lawrence D, Muir JF, Pretty J, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818
Horowitz J, Ebel R, Ueda K (2010) "No-till" farming is a growing practice. Economic Information Bulletin Number 70, November Economic Research Service, United States Department of Agriculture, Washington DC
International Assessment of Agricultural Knowledge (IAASTD) (2009) Agriculture at a crossroads, global report. Island Press, Washington, DC, Chapters 1, 4
International Service for the Acquisition of Agri-Biotech Applications (ISAAA) (2015) Global status of commercial biotech/GM crops. http://www.isaaa.org/. Accessed 26 Feb 2015
Klümper W, Qaim M (2014) A meta-analysis of the impacts of genetically modified crops. PLoS One 9(11):e111629
Lemaux P (2009) Genetically engineered plants and foods: a scientist's analysis of the issues (part II). Annu Rev Plant Biol 60:511–519
National Research Council (2010) Toward sustainable agricultural systems in the 21st century. The National Academies Press, Washington, DC
National Research Council (2011) Renewable fuel standard: potential standard: potential economic and environmental effects of U.S. biofuel policy. The National Academies Press, Washington, DC
National Resources Conservation Service (2012) Source for information on conservation tillage. http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/home. Accessed 26 Feb 2015
Paddock W, Paddock P (1967) Famine 1975! America's decision: who will survive New York Times (2014). "Working the land and data", Quentin Hardy, November 30. Little, Brown, New York
Reid JF (2011) The impact of mechanization on agriculture the bridge. Natl Acad Eng 41(3):22–29
Rhodes FHT (2012) Earth: a Tenant's manual. Cornell University Press, Ithaca
Scott NR, Chen H (2012) Nanoscale science and engineering for agricultural and food systems, part I. Ind Biotechnol 8(6):340–343, (also guest editors for special research section, 344–364)
Scott NR, Chen H (2013) Overview, nanoscale science and engineering for agricultural and food systems, part 2. Ind Biotechnol 9(1):17–18, (also guest editors for special research section, 19–50)
Smil V (2000) Feeding the world: a challenge for the twenty-first century. MIT Press, Cambridge, MA

The Royal Society (2009) Reaping the benefits: science and the sustainable intensification of global agriculture 1–10, 47–50. http://royalsociety.org/Reapingthebenefits/. Accessed 26 Feb 2009

United Nations (2014) World population prospects: probabilistic population projections based on world population prospects; the 2012 revision. http://esa.un.org/unpd/ppp/Figures-Output/Population/PPP_Total-Population.htm. Accessed 26 Feb 2015

USDA/ERS (2014) Food expenditures. http://www.ers.usda.gov/data-products/food-expenditures.aspx. Last accessed 24 Feb 2015

Webber ME (2015) A puzzle for the planet, Scientific American, 312(2): 63–67

Weston RF (1992) Sustainable development: definition and implementation strategies. Roy Weston, West Chester, PA