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Technology, complexity and change in agricultural production systems

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Abstract

Technological advances have contributed to impressive yield gains and have greatly altered US agriculture. Selective breeding and directed molecular techniques address biological shortcomings of plants and animals and overcome environmental limitations. Improvements in mechanization, particularly of power sources and harvest equipment, reduce labor requirements and increase productivity and worker safety. Conservation systems, often designed to overcome problems introduced from other technologies, reduce negative impacts on soil and water and improve the environmental sustainability of production systems. Advances in information systems, largely developed in other disciplines and adapted to agriculture, are only beginning to impact US production practices. This paper is the fourth in the series of manuscripts exploring drivers of US agricultural systems. While development of technology is still largely driven by a need to address a problem, adoption is closely linked with other drivers of agricultural systems, most notably social, political and economic. Here, we explore the processes of innovation and adoption of technologies and how they have shaped agriculture. Technologies have increased yield and net output, and have also resulted in decreased control by producers, increased intensification, specialization and complexity of production, greater dependence on non-renewable resources, increased production inputs and hence decreased return, and an enhanced reliance on future technology. Future technologies will need to address emerging issues in land use, decline in work force and societal support of farming, global competition, changing social values in both taste and convenience of food, and increasing concerns for food safety and the environment. The challenge for farmers and researchers is to address these issues and develop technologies that balance the needs of producers with the expectations of society and create economically and environmentally sustainable production systems.

Key words: technology, sustainability, technological drivers, genetic improvements, mechanization, conservation systems, information systems

Introduction

The 20th century's unprecedented advances in the application of biological science and engineering to agriculture have revolutionized farming. Technologies are implicitly functional, benefiting society by solving a problem or circumventing a functional constraint. Agricultural technologies include both engineering and biological inventions and discoveries, such as modifications to machinery, the physical environment or biological components of a system. Knowledge systems, such as decision support tools and management systems, are examples of cultural technologies.

The intensification of agriculture over the past 50 years has resulted in impressive yield improvements[1]. In the US, yields have risen steadily, with corn yields roughly tripling and wheat and soybean yields approximately doubling over the past half-century (Fig. 1a)[2]. Similar gains in animal production have increased egg production in chickens by 18% in the past 16 years, milk production

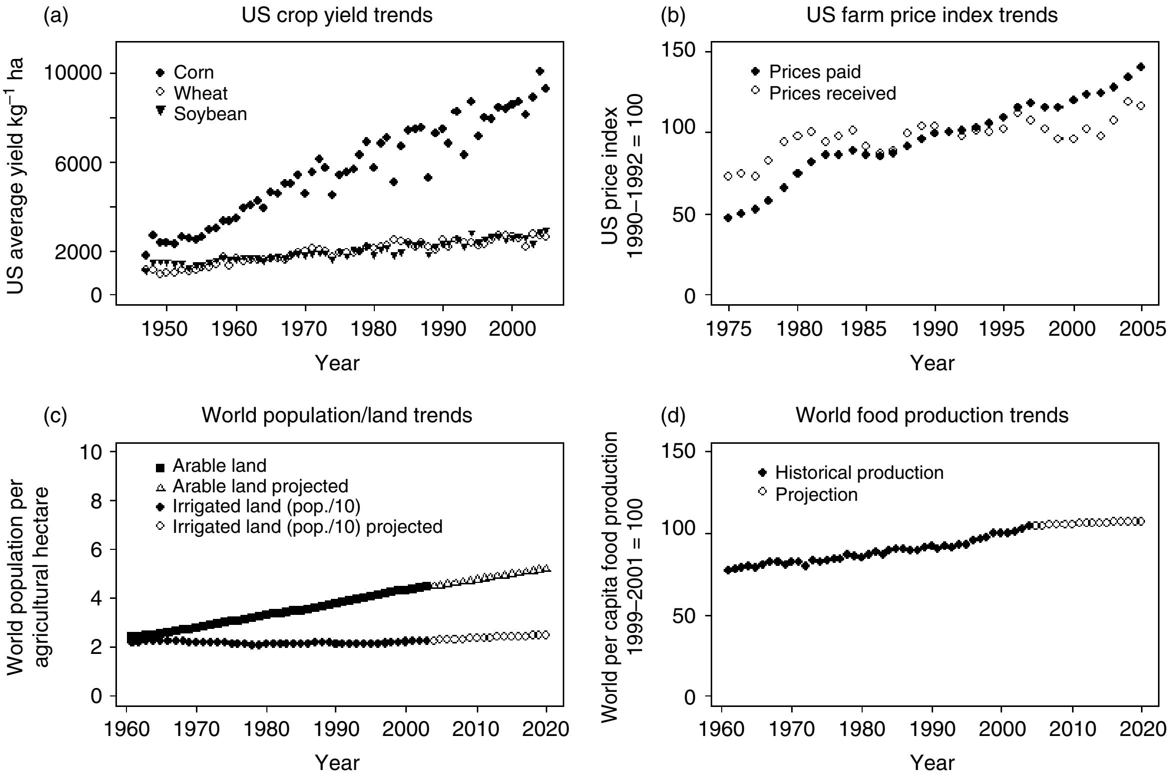

Figure 1. Historical and projected trends in agriculture.

in cows by 28% in the past 10 years, and average live broiler chicken weight by 155% in the past 80 years[3].

While addressing concerns of a growing world-wide population, these impressive yield gains have come at a cost to natural resources[4] and the farming community[5]. Capital intensive technologies required to realize these gains can favor agribusiness over family farms[5]. The continued development of new technologies, at times needed to address issues introduced from adoption of previous technologies, puts farmers on a technology treadmill[6] that limits their flexibility in making management decisions. Globalization has increased competition and generated new problems and opportunities. Current technologies have opened a proverbial Pandora's Box of opportunities, risks and hope for future developments.

In this manuscript, we explore how the technological revolution has altered American agriculture and how it is likely to contribute to changes in future production practices. We examine the traditional development and adoption cycle, and explore new models of innovation delivery that are changing the process of technological advancement. Our premise is that as the world population and agricultural productivity move towards sustainability, agricultural problems will become more difficult to solve with strategies focused solely on increasing yield potential. Agricultural productivity will need to shift from a simplistic focus on yield per hectare to incorporate a broader, interdependent set of constraints including all inputs to the production cycle: natural resources, financial and human resources[4]. We explore five fundamental ways that technology has impacted farming: (1) increased intensification of production, (2) increased reliance on natural resources, particularly soil and water, and non-renewable resources, primarily fossil fuels, (3) increased production inputs and dependence on future technology, leading to a technology treadmill that limits choices, (4) increased complexity of the farming system, and (5) decreased control by producers. These trends in agriculture have led to declining support for agricultural production as fewer people are directly involved with farming; increased degradation of natural resources through contamination of soil, water and atmosphere; depletion of natural resources, particularly water and fossil fuels; and decreasing profit margins. To address the interconnected constraints facing American agriculture and ensure future advances in agricultural productivity, multidisciplinary problem solving approaches will become increasingly important.

Processes of innovation and adoption

The problems and needs of the production community drive the interdependent processes of development and adoption to bring an innovation into use. Rather than a linear event, these two processes occur in a continuous spiral, with continued adaptation and modification of a technology furthering the advancement and continuing the cycle[7].

The traditional processes of technology development and adoption have been described as a linear or 'Push' system[8,9] in which the problem is identified and technology developed for delivery to the end user. This method works well during crisis conditions, such as invasive pests or diseases (e.g. Karnal–Bundt and avian flu), or for problems requiring a high input of technical expertise or capital, such as development of genetic modification techniques.

Emerging models of development and adoption rely on closer interaction between technical developers and non-technical end-users. In a 'learning selection' model, developers interact closely with a self-selected group of interested end-users, and use their knowledge base to refine the initial design concept to the needs of the user group[8]. As the development–adoption process continues, the initial user group becomes invested in the technology and plays a key role in the dissemination of the information and adoption of the technology by a larger user group. This model works well in the development and delivery of mechanized agricultural technology, such as harvesting equipment[8]. In the 'Pull' model[9], a platform for information exchange is established that expands the base of knowledge available to the developers and end-users by bringing together large groups of diverse individuals to solve or influence a problem. Complexity and chaos are seen as opportunities for expansion of ideas rather than as negative factors that need to be controlled. This emerging model is operating in media, global process networks and education. The 'Pull' model holds particular promise for the large, complex problems, ranging from social to technical, that face today's agriculture. Expansion of the knowledge base, through increased participation of people from a diversity of disciplines, has the potential to enhance the creativity applied to solve emerging agricultural production issues.

The process of adoption is driven by interactions between a broad range of external and internal factors, such as political readiness, social and political pressure and monetary constraints[10]. Farmers have a desire for increased profitability and greater lifestyle security[5,11]. Competition from global markets has also facilitated adoption of new technologies as farmers recognize the need to remain competitive[12]. Innovations that reduce production risk and are relatively simple to use are most successfully adopted[13]. In addition, farmers who have ready access to an expert are much more likely to implement new technologies[14].

Problems driving innovation

Fundamental limitations to agricultural production arise from edaphic, abiotic and biotic constraints of the natural environment. Water has a particular global significance[15], and limits production in many areas due to quantity and quality constraints, as well as pumping costs. The biological capacity of crops and animals also limits yield. Natural resource limitations are critical to current and future production, and future impacts of global warming and climate change are of increasing concern to farmers. Additionally, the availability and expense of fossil fuels has become a concern as they are needed both as fuel for tractors and for fertilizer production.

Social and political pressures alter the expectations from agriculture[5]. Changes in the social conscience moved society towards the industrial model of success based on production output. Simultaneously, growing awareness of inequities in food availability encouraged aggressive production goals to increase the worldwide per capita caloric uptake[16]. To increase production levels with a declining pool of laborers for farm work, farmers needed to do more work with fewer people[17]. Legislation impacts major decisions through set-aside programs or price supports and the adoption of specific technologies directly, such as the 1996 Food Quality Protection Act[18]. The current discussion of environmental credits versus commodity payments will further impact farmers' decisions as to which production systems to implement[5,19]. Human resource limitations in management expertise and time further hinder productive capacity, requiring improved marketing and management skills to remain competitive.

Technological Advances

Genetic improvements

Advances in our understanding of reproductive biology and the mechanisms of inheritance enhanced our ability to make directed changes in crop and animal traits, improve yield, address environmental limitations, and overcome a host of production constraints. Genetic manipulation by selective breeding or direct molecular techniques is an established method for improving productive capacity and the regional usefulness of crops. Other technologies, such as weed and insect control and resistance to or control of diseases, increase productivity by preventing indirect competitive losses.

Hybrid maize was one of the 20th century's major scientific innovations contributing to yield improvements, and is widely cited as one of the most rapidly adopted agricultural technologies in the 20th century[20,21]. In addition to the yield advantages with hybrid crops, the greater crop uniformity increased the ease of management. Prior to the introduction of hybrids, a field of maize contained a mixture of unique genotypes varying in economically important traits such as ear height, maturity and grain characteristics. This variation made mechanization of production difficult, especially harvest. Mechanized harvesting of corn coincided with the adoption of hybrids[22]. Both improvements in yield and management hastened the adoption of hybrid technologies.

Though greater uniformity in the timing of plant developmental events may be desirable for timing of agricultural inputs and harvest, this uniformity renders the crops more susceptible to catastrophic losses from insects and pathogens. By compromising the seeds' natural defensive abilities by selecting for more desirable traits, producers must increasingly rely on chemical control methods and increased management for some of the functionality that the crop once provided for itself. Extensive implementation of monoculture production has increased reliance on technologies such as chemical control methods and reduced crop diversity.

Hybrids have also instrumented a substantial paradigm shift in how society views genomic property rights, and played a role in the evolution of the seed industry. With hybrid technology, farmers must buy the seed each year rather than saving seed from the previous harvest. Competitors cannot sell a company's hybrids unless they obtain the rights. Development of hybrids and subsequent genetic modifications have removed natural genetic material from public ownership and placed it in the hands of a few companies[23]. As development and adoption of genetically altered materials increases, the production system becomes more complex. Moreover, producers increasingly lose control of their production decisions, as the management technology is genetically hard-wired in the seed[23].

The social response to genetic technologies is most apparent in the current debate over genetically modified organisms (GMOs)[24,25]. While opponents of the technology accuse agribusiness of profiteering at the expense of risks to public health, the purported harms of GMOs are often ascribed to political posturing and anti-science[26] by supporters of the technology. Regardless of one's support[25] or contempt[27] for the technology, it is obvious that it has had, and will continue to have, substantial social impacts[28].

As with plants, the natural genetic variations in animals have been used to selectively improve animal stocks. Until the mid-20th century, the formation of most modern breeds of livestock was defined by the breeders themselves and selection was strongly influenced by livestock competitions. Development of artificial insemination (AI) dramatically increased productivity, especially of dairy cows[29]. Combined academic and industrial research addressed a major constraint on genetic improvement through development of semen extenders, a method of freezing semen, and a convenient method of safely transporting frozen semen. Improved quantitation of genetic lineage has allowed managers and advisors to evaluate and benchmark their specific management strategies. Widespread dissemination of extended and frozen semen has resulted in international commerce of tens of millions of semen doses[30].

Formation of farmer-owned AI cooperatives and long- and short-term experiments conducted on cooperator farms were keys to the successful adoption of AI[29]. While these initial cooperatives were formed between producers, advances in AI technologies led to the consolidation of AI organizations and increased investment by privately held companies[31].

Modern gene manipulation tools have expanded our capacity for improvements and are used in animal and aquaculture systems to identify superior traits, enhance breeding programs, facilitate disease resistance and establish, meet and verify standards. Molecular genetics can be used to improve the population through identification of genes and genetic markers associated with a desired trait, such as disease resistance, improved growth rate or meat quality. Biotechnology in animal systems can be used to do the same things currently done through traditional breeding, but more quickly, more accurately, and (or) with a different price structure, thereby changing competitive advantages among individuals, companies and countries.

In the dairy industry, improved genetic evaluations for milk production led to rapid increases in milk production and a subsequent decline in the number of cows needed to sustain production levels. Mechanization and other improvements in dairy production intensified the consolidation of dairy farms. The reduction in nationwide herd size and consolidation of dairy farms has led to a reduced genetic diversity and increased inbreeding, which may be contributing to the recently observed reduction in fertility[31]. While genetic improvements of animals have increased performance and yield, as with crops, they have been associated with (a) a loss of farms through consolidation, (b) a decline in farmer control of the production process, and (c) an increased complexity of the farming system.

Mechanization

In the US, social pressures have driven the evolution of agriculture to deliver abundant, inexpensive, readily available foods year round. The changing social conscience introduced with industrialization shifted the social expectations away from farming as a way of life towards efficiency and production output[32]. Technological advances developed during and immediately after World War II increased mechanization and introduced chemicals to manage soil fertility and pests. Changes in commodity supports[10] and increased social pressure to feed the world further directed production towards large-scale monoculture agriculture[16]. While advances in biological and engineering technologies made large-scale monoculture production possible, changes in the social conscience made it desirable.

To address the social demands for food and expand production and improve yields, farmers needed easier, faster, less labor-intensive and more efficient means of managing crops. Mechanization of US agriculture during the 19th and 20th centuries began with the introduction of the tractor which removed much of the backbreaking toil, increased the speed, efficiency and amount of work that could be accomplished and improved worker safety[33]. Throughout the industrial revolution, innovations in farm machinery have dramatically decreased labor demands and improved the efficiency and effectiveness of field operations. The fraction of the population involved in agricultural production continues to decrease. Improved harvest, storage and transportation technologies have all contributed to greater efficiency and allowed feeding a growing population without substantial increases in land devoted to production agriculture.

A major benefit of mechanization is greater efficiency during the harvest operation which minimizes yield and quality loss due to extended exposure to bad weather. Cotton (*Gossypium* sps., L.) has played a significant role in clothing humanity for centuries. Its technological advancement is often a leading sector indicating the level of industrialization of a country. Development of mechanical cotton harvesters substantially impacted the social and economic development of the cotton-growing regions of the US[34]. Cotton harvest technology continues to play a key role in modernization efforts in other societies[35].

While technical limitations hampered the development of mechanical cotton harvesters, social pressures of small farms and the sharecropping system stifled its adoption[36]. Many were fearful of the earliest mechanical pickers, envisioning the destruction of the South's sharecropping system and the loss of work for millions of people[37]. The major migration of 5 million people from the South for higher-paying jobs in the North between 1940 and 1960 led to a severe labor shortage[17]. While the initial adoption of the cotton picker was limited by concern for the prevailing socio-economic conditions at the time, a sharp decrease in available labor during and immediately after World War II became a major impetus for its acceptance[34].

The introduction of mechanization, particularly of harvest, increased the consolidation of fields and farms. The increased size and use of machinery introduced soil problems, such as compaction, and required greater management skill. The mechanization of cotton production increased the cost of machinery and farm operating overhead. Farm size increased to justify this outlay for machinery and to support the general farm overhead. The average cotton farm in the 1940s was about 320 ha, but by the 1970s the average size had increased to 600–800 ha, a trend that continues[17,38]. The harvesting operation had long been the decisive factor in land area one farm could manage, in cotton as well as other crops[39,40].

Additional improvements in mechanization have been realized through a host of highly effective technologies, such as fertilization, irrigation and tillage. These improvements modified the crop environment, minimizing the natural limitations of the crop and its environment. However, this increased reliance on mechanization also contributed to a greater dependence on fossil fuels, for both fuel and fertilizer, increased consolidation of farms, increased production inputs, overuse of natural resources and greater complexity of the farming system.

Lifestyle changes in the US have led to the increased consumption of convenience foods, impacting the food supply and altering agricultural production[41]. This led to the development of vertically integrated production systems, particularly of animals[10], and hastened the development of technologies supporting confinement animal production.

New barriers to production have been introduced through the intensification of animal production in confinement buildings and feedlots. Accurate identification and tracking of animals is needed to determine previous history and potential performance, and especially recognition of potential disease exposure such as bovine spongiform encephalopathy (BSE). As with monoculture crops, intensive animal production exposes animals to increased risks of some diseases, requiring changes in disease management including the increased use of antibiotics with uncertain impacts on consumers. Intensive animal production facilities also concentrate wastes which impair soil and water resources and require additional technologies to handle disposal. Moreover, the vertical integration of animal production, with its rigid top-down management and dependence on expensive animal production technologies, has left many producers frustrated from excess debt and a lack of control on their own farms[14].

Conservation technologies

While technologies addressing genetic improvements and mechanization are driven fundamentally by a desire to improve yield, the development of conservation production systems is driven by concerns for the environment, often resulting from problems introduced from previous technologies. Conservation practices help conserve limited soil and water resources and address production problems on areas too steep or dry for conventional tillage. Reduced tillage operations and use of cover crops protect the soil surface from erosion and ultimately increase organic matter and aggregate stability to improve the soil's water holding properties[42].

In addition to the environmental benefits, conservation technologies often approach agricultural production as a system. By considering the entire agro-ecosystem, the impact of production practices on the supporting natural resource base are recognized. As the knowledge of interactions within the agricultural production system grows, appreciation for the importance of conserving the natural resource base increases. Ancillary benefits to producers include savings in time and fuel from conservation tillage systems, as well as lower capital investment in powerful tractors and tillage equipment[43].

Conversely, conservation tillage has a number of potentially significant disadvantages. Tillage is an effective mechanical form of weed control that prepares the seed bed and reduces pathogens. Without mechanical weed control, herbicide use and costs will generally increase, especially during the early transition years. The introduction of herbicide-resistant crops hastened the adoption of conservation systems, as farmers had a reliable chemical method of weed control. However, this rapid and extensive adoption has increased the development of herbicide-resistant weeds[44]. Farmers are now on a treadmill of needing new herbicide-resistant varieties to compensate for failures in the previous technology.

Increased complexity of management results from the implementation of conservation systems, as timing of operations becomes more critical. Management of cover crop residue is also a concern. Increased residue from cover crops keeps the soil wetter and cooler after planting than tilled soil, shortening the growing season. Increased residue from conservation tillage may also require changes in nitrogen management, as high levels of residue can immobilize nitrogen, limiting its availability near the seedling roots. Yield depression related to inadequate early season nitrogen may have been one of the causes for a dip in no-till use in the late 1990s[42].

Conservation technologies showed a combination of linear delivery and learning selection, with the public and private sectors providing the general outlines of the technology and farmers customizing and adapting the technology to their particular situations. Conservation tillage is adopted more rapidly by farmers with more education, larger operations, and higher incomes, and on farms with higher soil quality[45,46]. Risk-averse farmers adopt conservation tillage more slowly than risk neutral farmers to avoid higher initial costs while learning the new system[47]. Land tenure also influences adoption rates of conservation practices as cash-renters are less likely than owner-operators to adopt practices with medium term payoffs[14,48]. This may be a key finding for the future of American agriculture, as over 40% of US farmland is leased.

Perhaps the biggest boost for adoption of conservation tillage came from government programs, starting with the Conservation Compliance provisions of the 1985 Farm Bill, and continuing through subsequent farm bills. These provisions required farmers on Highly Erodible Land (HEL) to reduce erosion significantly by using an approved conservation system to maintain benefit and program eligibility. For many farmers on HEL, conservation tillage was the only feasible management system to maintain eligibility.

With continued pressure from environmental interests, social and political concerns and increasing fiscal demands, farmers will continue to explore methods to reduce costs by eliminating field operations, provided that options exist that maintain yields and profitability. With steadily improving implements, agrichemicals, and seeds adapted to higher residue levels, increased local experience, and declining social pressures against conservation tillage, conservation tillage should continue to expand, particularly where erosion is a problem, for larger, owner-operated farms and for farmers who are not strongly risk-averse. Improved methods of weed control, particularly if they are simple, would facilitate expanded use of conservation tillage for those crops and regions that have not seen much adoption to date. Modifications to future farm bills away from commodity payments towards conservation payments will likely further hasten the adoption of conservation systems.

Conservation systems have the potential to move agricultural production systems towards environmental sustainability. Environmental concerns will continue to influence governmental programs that promote conservation tillage. Baylis et al.[49] reported that even a moderate increase in adoption of conservation tillage would improve water quality enough to increase downstream recreation benefits nationally by $175 million. A large increase in the use of conservation tillage may contribute $243 million nationally for recreation alone.

Information systems

Information systems are examples of technologies that were largely developed in areas other than agriculture, and have been adapted to farming. Software development and information management systems have improved the ability of the farmer to manage complex agricultural production systems, especially for record keeping and marketing of crops.

The increasing complexity in agricultural systems requires more attention to management and greater finesse in the decision making process. Increased globalization has expanded competition, requiring producers to improve their marketing skills to get the best prices for their products. While some production systems have become more vertically integrated[41], other producers have found ways to recapture income through diversification of farm enterprises in which the producer maintains control, or an economic interest in, value-added products beyond the farm gate[14]. Additionally, increased social and political pressures to minimize environmental impact have increased record keeping requirements and confounded production choices.

Information systems can help manage much larger amounts of information and encompass a variety of technologies. Some information technologies include automated detection systems, such as remote sensing, soil sampling systems, and yield monitors, that allow producers to gather physical information about their production system. These rely on global positioning systems to spatially record physical attributes. Other information systems are designed as management tools for record-keeping, and may incorporate a geographic information system for spatially recording physical and economic information about the system and help make management decisions. More complex information systems, such as crop models, rely on data about the system and make management decisions based on predictive estimates of system function. These tools can be simple, requiring a minimal amount of data collection and computer technology, or complex, requiring extensive data collection and computer expertise. Sophisticated technologies that offer the potential to improve crop management such as precision agriculture[50] are often facilitated by information technologies. As the technology has advanced, potential cost benefits from implementing precision agriculture have improved[51].

The early stages of the development of information technologies fit a linear transfer of technology model, as technology was borrowed from other disciplines such as computer engineering and adapted to agriculture. Increased intensification of farms and improvements in computer and engineering technologies led to the development of precision technologies for agriculture[50]. As the technology progresses, it is evolving into a learning selection model as more end-users are becoming involved in developing or modifying existing tools to suit their needs. However, the complexity of the systems and perceived limited or negative return on investment have hampered wide-spread adoption[52]. The learning curve for adopting information technologies can often be prohibitively steep, though as farmers' education levels increase, their use of computer technologies increases[52,53]. Simplicity of a technology and its potential to decrease risk have been identified as prime factors in the adoption of new technology[13]. The perceived absence of both of these factors is apparently limiting the rapid adoption of information systems in agricultural production. Adoption of technology is also age-related, as older farmers are less likely to adopt computers on-farm[53].

The most common information systems used by farmers are computers for financial and production record keeping and information gathering from the Internet[53]. More complicated technologies, such as crop models and decision support tools, have slower acceptance rates. As information technologies become more user-friendly and the user base becomes more knowledgeable about the potential utility of these technologies, development and adoption of information systems into agriculture are likely to increase.

In addition to their greater complexity, decision support tools rely on the knowledge of complex issues. Many of the factors impacting complex systems will not be observed through traditional reductionist research. Rather, the emergent properties of the system will only be observed in a systems research program. Future advances in the application of information technologies to agriculture may require a greater emphasis on systems research[54,55].

Information systems expand knowledge exchange through technologies such as the Internet and enhance the breadth of expertise available for identifying problems and developing solutions. Farmers now have access to more information more quickly and from a much broader range of sources than ever before. This allows them to make more rapid decisions, such as when to buy and sell products. Information technologies offer methods of integrating the disparate pieces of the production puzzle for information gathering and decision support. As the agricultural system becomes more complex, this information will be increasingly important in guiding farmers.

Implications for Future Agronomic Technologies

Social, political and economic pressures worked in concert to shape the evolution of the current agricultural production systems in the US[10]. Technological advances, often designed to address social concerns or overcome environmental limitations, further refined agriculture. While the current US agricultural systems are unquestionably highly productive, this abundance is based on an unsustainable use of natural resources and fossil fuels. Future challenges will exacerbate an already complex system and introduce new and greater problems[56]. Emerging technologies will be needed to address issues of economic and environmental sustainability, shifts in global population and consumption patterns and competition for land use.

Since technology is developed at the leading edge of our understanding, it is difficult to anticipate the impacts of that technology on the agricultural system. Since the 1930s, increases in production efficiency from technological innovations have occurred in conjunction with substantial structural changes in farming communities as fewer people are involved in agriculture[57]. In light of changing constraints to agricultural production, questions arise as to future advances in agricultural productivity, not from the standpoint of abundance, but of sustainability[4]. How, then, do we transition the current US production system to economically and environmentally sustainable production? While it may seem appealing, it is most likely neither possible nor desirable to discontinue technological advances.

A change in philosophical approach to address sustainability may be more important than simply changing practices[54]. Innovators in agriculture, including farmers, educators, researchers, businessmen, lawmakers, and so on, need to focus on more inherently multidisciplinary approaches to solve agricultural production problems. Moreover, there must be a broader focus on problem identification and resolution, incorporating societal, political and global goals of environment and nutrition together with producers' financial goals. In developing an economically and environmentally sustainable agricultural agenda, society must be willing to compromise its expectations, since current consumption levels of agricultural products, and the natural resources they require, are not sustainable[58]. New approaches to technology development and delivery have the potential to accommodate these needs by establishing a broad network of individuals with a diverse range of expertise, and working closely with the end users to identify goals, delineate problems and develop solutions[9].

Although the US has succeeded in developing an inexpensive, efficient food production and delivery system, over-consumption and lowered nutritional value have negative impacts on soil and water resources and human health[59]. Globalization makes a variety of foods available year round, but increases hidden costs due to transportation and compromises flavor and nutrition[60]. Food in the US is readily available and inexpensive in part because we have ignored the costs of natural resource depletion and non-renewable fossil fuel use in calculating the costs of production. While the caloric content of available food has increased worldwide, increased globalization and concentration of the food system has reduced local production of crops and limited distribution, access and future food options[61]. Exploring the linkages between food, health, agriculture and the environment requires a different philosophical approach to agricultural production than a simple focus on yield[16], and is becoming an increasingly important component of the social environment influencing farming[5].

The current production system is not economically sustainable for farmers. Prices paid to US farmers have not kept pace with the cost of agricultural inputs (Fig. 1b)[2]. The unfavorable price shifts force increases in farm size, limit investment in agriculture and lead to political pressure for substantial farm programs to support agriculture and rural communities[5].

The world's growing population and increasing income imply increased demand for agricultural goods. Contrary to Malthusian expectations[62], however, to date supply has increased faster than demand. Currently, more than four people are fed per hectare of cultivated land, with just over 20 people being supported per irrigated hectare (Fig. 1c)[63]. Estimates of future population growth and rates of cultivated land use indicate a slow increase in population per unit of irrigated land[63,64], limiting the demand for agricultural products worldwide[65].

The integrated worldwide outcome of all factors affecting agriculture shows a rising historical trend in food production per capita (Fig. 1d)[2], which is projected to continue[63]. Rosegrant et al.[63]analyzed a number of future scenarios and found that, across a range of assumptions, agricultural supply is likely to keep pace with demand, resulting in similar or lower prices for agricultural goods out to the year 2020. While technology has helped realize this abundance, future advances will require a different mindset to better balance environmental and production goals and keep agricultural production economically viable.

Previous biological advances have come about largely from increases in the genetic potential of crops. Advances in biotechnology have expanded our ability to modify crop behavior beyond the range of conventional breeding techniques, improved quality and quantity of agricultural products, and incorporated unique value-added traits in newly-released cultivars. Future genetic advances will most likely come from value-added traits, such as neutraceutical and pharmaceuticals; addressing environmental constraints arising from agricultural intensification (soil erosion, water logging and salinity, coevolution of pests and pathogens, global climate change, loss of biological diversity, and limited water supply), and political, financial and human resource issues[4,66]. Additional benefits from advances in genetic technologies will allow improved identification and incorporation of superior traits and increased food safety through improved testing methods.

Improvements in mechanization have increased production output with fewer people, and improved the safety of farm workers. Future advances in mechanization will have to address power requirements of agriculture and the current reliance on fossil fuels. Additional engineering advances have the potential to conserve natural resources through more accurate application, and by better matching inputs with potential output. Improvements in harvest, processing and storing can retain nutritional value and enhance societal access to products.

Conservation systems address environmental, social and political concerns, and, where implemented, have made significant gains towards remediation of environmental damage. Conservation practices will continue to evolve and redefine environmental sustainability and impacts while maintaining production capacity. Future advances in environmental sustainability will come from greater implementation of conservation technologies, increasing the scope of conservation tools and practices to reduce reliance on non-renewable resources and chemical controls, and greater use and reuse of waste products from both agriculture and society.

Information technologies have the potential to address increasingly complex management issues by providing decision support tools for farmers. Additional information technologies will allow tracking products from start to finish and remote monitoring of crops and animals. The enhanced tracking of production will also allow better knowledge of chemical use and application, and prediction of potential environmental impacts. Marketing tools and internet access will assist producers in the global marketing of products.

On a larger scale, our definition of agriculture may change. Agriculture can be defined as the process of using natural resources (sunlight, air, water and soil) to produce a consumable product (e.g. food, fuel and fiber), while maintaining sufficient resources for the next generation. This definition could include alternative production systems such as wind turbine farms[67], which do not involve cultivation of the soil but do tie up a valuable natural resource (land) in the production of a consumable item (power). Similarly, ecosystem services, such as the buying and selling of carbon credits, are potential agricultural products[68]. As energy constraints and ecosystem services continue to escalate in importance, the management of the land for these purposes may surpass our current limited view of agricultural products.

Future production systems will need to be flexible to respond to rapid changes in climate and uncertainties in global markets from shifts in politics, production and population. In addition to addressing growing environmental concerns, sustainable farming systems will need to address energy concerns required for both agricultural production and as potential agricultural products.

An agricultural production system has been suggested that allows for dynamic responses to external pressures[57]. This dynamic management philosophy coupled with multiple cropping enterprises allows farmers to incorporate changes in their production system in response to changing needs. A dynamic system would be able to accommodate the increasingly complex factors influencing farmers today and reduce risks of production. Integrated farming systems allow producers to optimize an array of factors, including environmental and financial, rather than simply focusing on yield alone. By carefully examining current production systems and the influences that have shaped them, we can develop future technologies that will address sustainability with the needs of farmers, society and the environment in mind.

References

1 Food and Agriculture Organization (FAO). 2006. The FAOSTAT Database. Available at Web site http://faostat.fao.org/default.aspx (verified 5 September 2007).

2 NASS. 2006. Prices received by Farmers, Indexes. Available at Web site http://www.nass.usda.gov/index.asp (verified 5 September 2007).

3 Strauss, S. 2002. Best in breed ..... has nothing to do with biotech. The Globe and Mail. Toronto, Ontario. 26 January 2002. Available at Web site http://www.mindfully.org/GE/GE4/No-Biotech-Best.htm (verified 5 September 2007).

4 Naylor, R.L. 1996. Energy and resource constraints on intensive agricultural production. Annual Review of Energy and the Environment 21:99–123.

5 Archer, D.W., Dawson, J., Kreuter, U.P., Hendrickson, M., and Halloran, J.M. 2008. Social and political influences on agricultural systems. Renewable Agriculture and Food Systems 23(4):272–284.

6 Cochrane, W.W. 1958. Farm Prices: Myth and Reality. University of Minnesota Press, Minneapolis.

7 Petroski, H. 1992. The Evolution of Useful Things: How Everyday Artifacts—From Forks and Pins to Paperclips and Zippers—Came to be as they are. Alfred A. Knopf, Inc., New York.

8 Douthwaite, B., Keatinge, J.D.H., and Park, J.R. 2002. Learning selection: an evolutionary model for understanding, implementing and evaluating participatory technology development. Agricultural Systems 72:109–131.

9 Hagel, J. and Brown, J.S. 2005. From push to pull—emerging models for mobilizing resources. Working Paper, October, 2005. Available at Web site http://www.johnseelybrown.com/pushmepullyou4.72.pdf (verified 5 September 2007).

10 Hendrickson, J., Sassenrath, G.F., Archer, D., Hanson, J., and Halloran, J. 2008. Interactions in integrated agricultural systems: the past, present and future. Renewable Agriculture and Food Systems 23(4):314–324.

11 Sumberg, J. and Reece, D. 2004. Agricultural research through a 'New Product Development' lens. Experimental Agriculture 40:295–314.

12 Flora, C.B. 2004. Agricultural change and rural development. Rural Development News 27(3):1–3. Available at Web site http://www.ag.iastate.edu/centers/rdev/newsletter/Vol27No3-2004/agchange.htm (verified 5 September 2007).

13 Batz, F.-J., Peters, K.J., and Janssen, W. 1999. The influence of technology characteristics on the rate and speed of adoption. Agricultural Economics 21:121–130.

14 Sassenrath, G.F., Hanson, J., Hendrickson, J., and Archer, D. 2007. Principles of dynamic integrated agricultural systems: lessons learned from an examination of Southeast production systems. In P. Bohlen (ed.). Agro-ecosystem Management for Ecological, Social, and Economic Sustainability. Taylor and Francis/CRC Press, UK, in press.

15 Watson, R.T., Zinyowera, M.C., and Moss, R.H. 2006. IPCC Special Report on The Regional Impacts of Climate Change. An Assessment of Vulnerability. Intergovernmental Panel on Climate Change. Available at Web site http://www.grida.no/climate/ipcc/regional/index.htm (verified 5 September 2007).

16 Welch, R.M. and Graham, R.D. 1999. A new paradigm for world agriculture: meeting human needs. Productive, sustainable, nutritious. Field Crops Research 60:1–10.

17 United States Bureau of the Census. 1975. Historical statistics of the United States: colonial times to 1970. Government Printing Office, Series C 55–62, p. 93–95.

18 Executive Summary of the EPA's Organophosphate Pesticides: Revised Cumulative Risk Assessment. 2002. Available at Web site http://www.epa.gov/pesticides/cumulative/rra-op/Executive_Summary-pdf.pdf (verified 5 September 2007).

19 Halloran, J.H. and Archer, D. 2008. External economic drivers and integrated agricultural systems. Renewable Agriculture and Food Systems 23(4):296–303.

20 Brown, W.L. 1984. Hybrid vim and vigor. Science 845(9): 77–78.

21 Tracy, W.F., Goldman, I.L., Tiefenthaler, A.E., and Schaber, M.A. 2004. Trends in productivity of US crops and long-term selection. Plant Breeding Reviews 24(2):89–108.

22 Myers, K.H. 1933. Methods and costs of husking corn in the field. Farmers' Bulletin 1715. USDA, Washington, DC.

23 Kneen, B. 1999. Restructuring food for corporate profit: the corporate genetics of Cargill and Monsanto. Agriculture and Human Values 16:161–167.

24 Benbrook, C. 2003. Principles governing the long-run risks, benefits, and costs of agricultural biotechnology. Conference on Biodiversity, Biotechnology, and the Protection of Traditional Knowledge held on 5 April 2003. Available at Web site http://www.biotech-info.net/biod_biotech.pdf (verified 5 September 2007).

25 Chassy, B.M., Parrott, W.A., and Roush, R. 2005. Crop biotechnology and the future of food: a scientific assessment. CAST Commentary. QTA 2005-2 October 2005. Available at Web site http://www.biotech.ucdavis.edu/PDFs/CAST%20Report%20-%20Crop%20Biotechnology%20and%20the%20Future%20of%20Food%2011-05.pdf (verified 5 September 2007).

26 DeGregori, T.R. 2004. Origins of the Organic Agriculture Debate. Iowa State Press, Ames, Iowa. p. 211.

27 Stabinsky, D. and Cotter, J. 2004. Rice: genetically engineered rice—not sustainable agriculture. Greenpeace International, The Netherlands. Available at Web site http://www.greenpeace.org/raw/content/international/press/reports/genetically-engineered-rice-n.pdf (verified 5 September 2007).

28 Pardo, R. and Calvo, F. 2006. Are Europeans really antagonistic to biotech? Nature Biotechnology 24:393–395.

29 Foote, R.H. 2002. The history of artificial insemination: selected notes and notables. American Society of Animal Science 1–10. Available at Web site http://bio.cc/Biohistory/artificial_insemination_of_livestock_1950.pdf (verified 5 September 2007).

30 Thibier, M. and Wagner, H.-G. 2002. World statistics for artificial insemination in cattle. Livestock Production Science 74:203–212.

31 Funk, D.A. 2006. Major advances in globalization and consolidation of the artificial insemination industry. Journal of Dairy Science 89:1362–1368.

32 Mariola, M.J. 2005. Losing ground: farmland preservation, economic utilitarianism, and the erosion of the agrarian ideal. Agriculture and Human Values 22:209–223.

33 White, W.J. 2001. Economic history of tractors in the US. In R. Whaples (ed.). EH Net Encyclopedia. 15 August 2001. Available at Web site http://eh.net/encyclopedia/article/white.tractors.history.us (verified 5 September 2007).

34 Holley, D. 2000. The Second Great Emancipation: The Mechanical Cotton Picker, Black Migration, and How They Shaped the Modern South. University of Arkansas Press, Fayetteville.

35 McClintic, D. 2003. China's big dilemma. Available at Web site http://www.deere.com/en_US/ag/pdf/furrow/2003-summer-article.pdf (verified 6 June, 2007).

36 Lemann, N. 1992. The Promised Land: The Great Black Migration and How it Changed America. Vintage Books. p. 408.

37 Holley, D. 2003. Mechanical cotton picker. In R. Whaples (ed.). EH Net Encyclopedia. 17 June 2003. Available at Web site http://eh.net/encyclopedia/article/holley.cottonpicker (verified 5 September 2007).

38 United States Department of Agriculture, Economic Research Service. 1974. Statistics on Cotton and Related Data, 1920–1973. Statistical Bulletin No. 535. Government Printing Office.

39 Grimes, W.E., Kifer, R.S., and Hodges, J.A. 1928. The effect of the combined harvester-thresher on farm organization in southwestern Kansas and northwestern Oklahoma. Kansas Agricultural Experiment Station. Contribution No. 45. Available at Web site http://www.oznet.ksu.edu/historicpublications/pubs SC142.pdf. (verified 5 September 2007).

40 Martin, S. and Cooke, F. Jr. 2002. Mississippi Delta cotton farm structure 2002. Delta Ag Econ News. Summer. 2002. Available at Web site http://www.msstate.edu/dept/drec/archive/delta_ag_econ_news/agnews8.htm (verified 5 September 2007).

41 Martinez, S. and Stewart, H. 2003. From supply push to demand pull: agribusiness strategies for today's consumers. Amber Waves. Available at Web site http://www.ers.usda.gov/Amberwaves/November03/pdf/supplypush.pdf (verified 5 September 2007).

42 Martens, D.A. 2001. Nitrogen cycling under different soil management systems. Advances in Agronomy 70:143–192.

43 Martin, S.W., Robinson, J.R.C., Cooke, F.T. Jr, and Parvin, D. 2005. Managing tillage, crop rotations, and environmental concerns in a whole-farm environment. Crop Management. Online at http://www.plantmanagementnetwork.org/cm/

44 Osteen, C. and Livingston, M. 2006. Pest management practices. In Agricultural Resources and Environmental Indicators, 2006 Edition/EIB-16. p. 107–115. Economic Research Service, US Department of Agriculture, Washington, DC.

45 Fuglie, K.O. and Kascak, C.A. 2001. Adoption and diffusion of natural resource conserving technology. Review of Agricultural Economics 23:386–403.

46 Napier, T.L., Tucker, M., and McCarter, S. 2000. Adoption of conservation production systems in three Midwest watersheds. Journal of Soil and Water Conservation 55:123–134.

47 Bosch, D.J. and Pease, J.W. 2000. Economic Risk and Water Quality Protection in Agriculture. Review of Agricultural Economics 22:438–463.

48 Soule, M.J., Tegene, A., and Wiebe, K.D. 2000. Land tenure and the adoption of conservation practice. American Journal of Agricultural Economics 82:993–1005.

49 Baylis, K., Feather, P., Padgitt, M., and Sandretto, C. 2002. Water-based recreational benefits of conservation programs: the case of conservation tillage on US cropland. Review of Agricultural Economics 24:384–393.

50 Stafford, J.V. 2000. Implementing precision agriculture in the 21st century. Journal of Agricultural Engineering Research 76:267–275.

51 Martin, S.W., Hanks, J., Harris, A., Wills, G., and Banerjee, S. 2005. Estimating total costs and possible returns from precision farming practices. Crop Management. Online at http://www.plantmanagementnetwork.org/cm/

52 Adrian, A.M., Norwood, S.H., and Mask, P.L. 2005. Producers' perceptions and attitudes toward precision agriculture technologies. Computer and Electronics in Agriculture 48:256–271.

53 Batte, M.T. 2005. Changing computer use in agriculture: evidence from Ohio. Computers and Electronics in Agriculture 47:1–13.

54 Ikerd, J.E. 1993. The need for a systems approach to sustainable agriculture. Agriculture, Ecosystems and Environment 46:147–160.

55 Aldy, J.E., Hrubovcak, J., and Vasavada, U. 1998. The role of technology in sustaining agriculture and the environment. Ecological Economics 26:81–96.

56 Hanson, J.D., Hendrickson, J., and Archer, D. 2008. Challenges for maintaining sustainable agricultural systems. Renewable Agriculture and Food Systems. 23(4):325–334.

57 Hendrickson, J.R., Hanson, J., Tanaka, D.L., and Sassenrath, G. 2008. Principles of integrated agricultural systems: introduction to processes and definition. Renewable Agriculture and Food Systems. 23(4):265–271.

58 Mayo, E., Knight, A., Clifton, R., Jackson, T., Johnstone, J., Furey, S., Lee, A., and Pomfret, C. 2006. I Will if You Will. Towards Sustainable Consumption. Sustainable Development Commission. Available at Web site http://www.sd-commission.org.uk/publications.php?id=367 (verified 5 September 2007).

59 Blair, D. and Sobal, J. 2006. Luxus consumption: wasting food resources through overeating. Agriculture and Human Values 23:63–74.

60 Wilkins, J.L. 2005. Eating right here: moving from consumer to food citizen. Agriculture and Human Values 22:269–273.

61 Koc, M. and Dahlberg, K.A. 1999. The restructuring of food systems: trends, research, and policy issues. Agriculture and Human Values 16:109–116.

62 Ehrlich, P.R. 1971. The Population Bomb. Ballantine Books, New York.

63 Rosegrant, M.W., Paisner, M.S., Meijer, S., and Witcover, J. 2001. Global Food Projections to 2020: Emerging Trends and Alternative Futures. International Food Policy Research Institute, Washington, DC.

64 Rosegrant, M.W., Cai, X., and Cline, S.A. 2002. World Water and Food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington, DC.

65 Johnson, D.G. 1999. The growth of demand will limit output growth for food over the next quarter century. Proceedings of the National Academy of Sciences, USA 96:5915–5920.

66 Trewavas, A.J. 2001. The population/biodiversity paradox. Agricultural efficiency to save wilderness. Plant Physiology 125:174–179.

67 Donavan, L. 2005. Permit sought for wind farm. Bismarck Tribune, Bismarck, North Dakota, 26 October 2005. Available at Web site http://www.bismarcktribune.com/articles/2005/10/26/news/local/104446.txt (verified 5 September 2007).

68 Bricklemyer, R.S., Miller, P.R., Turk, P.J., Paustian, K., Keck, T., and Nielsen, G.A. 2007. Sensitivity of the Century model to scale-related soil texture variability. Soil Science Society of America Journal 71:784–792. Available at Web site http://soil.scijournals.org/cgi/reprint/71/3/784 (Verified 5 September 2007).