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After 10,000 Years of Agriculture, Whither Agronomy?

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ABSTRACT

The evolution of agriculture within the last 11,000 yr marked the first major inflection point in food yield and changed forever the character of the human condition. The application of technology to agriculture early in the 20th Century induced the next major crop yield inflexion point. Identifying the technological wellspring from which increased rates of productivity will be obtained in the decades ahead is far less obvious than during the last century. The agronomic challenge for the decades to come is to increase productivity per unit of land enough to preclude appropriation of other ecosystems for cropland expansions while simultaneously increasing the efficiency of production inputs, reducing their leakage to the environment, and sustaining the integrity of those ecological processes that undergird these intense biological production systems. Such a goal will require different metrics to measure agricultural sustainability and garner public support, new funding sources, and more holistic institutional arrangements. Agronomists, while playing a major role in meeting this challenge, will not necessarily dominate the agenda.

THE NUMBERS ARE STAGGERING. Global population increased fourfold during the 20th Century, coupled with a 4.5-fold increase in economic activity per person (Sachs, 2004). The world's population is expected to increase 50% over the next four to five decades, requiring a doubling of food output to accommodate this human expansion plus those moving up the food chain. The planet's environment will continue to be stressed as worldwide economic activity is forecast to increase 500%, coincident with 300% increases in both energy consumption and manufacturing activity (World Resources Institute, 2000).

As if the challenge for agronomists to double global food output within the next four-plus decades were not weighty enough, demand for nonfood biomass is accelerating. The task ahead centers not only on the necessity to produce humanity's food and biomass requirements, but whether agronomists and their allied partners can deliver this productivity in an ecologically sustainable manner through socially accepted production systems. Given this daunting task, it is fitting at the centennial mark of the American Society of Agronomy (ASA) to reflect on agriculture's history and to ponder its future.

CONTEXT

Well into the 19th Century, the future of agriculture was seen rather accurately through the prism of the past. As Paarlberg and Paarlberg (2000) noted, a farmer from Old Testament times arriving on the American scene in 1900 would have recognized many of agriculture's tools, practices, draft power, crop species, and common irrigation techniques. Crop yields would have seemed unremarkable to this visitor.

As the 20th Century progressed, however, the rate of social and scientific change accelerated while simultaneously reducing the certitude of prophecy. Never in more than 10,000 yr of agricultural history have such dramatic changes occurred in agriculture as during ASA's lifetime. Despite the future's obscurity, various trends have begun to exit the shadows to at least discern some elements of what lies ahead.

Before pondering the future, a brief review of agriculture's evolutionary origins will serve to remind us of its vestiges that remain with us. Then, fast-forwarding to the 19th and 20th centuries, America's agricultural development will be reviewed, especially during the time of ASA's 100 yr of existence, in the interest of providing context and perspective as to what agricultural characteristics will be carried into the 21st Century. And lastly, various issues, forces, and factors will be considered that will likely forge agriculture's and agronomy's future.

AGRICULTURE'S ORIGINS

Predisposition to Agriculture

Agriculture is a manifestation of evolution. Human dietary requirements for specific nutrients evolved through the human lineage during the past 5 to 6 million years (Kay, 1977; Milton, 2000). These requirements are of much higher quality (energy- and nutrient-wise) than would be predicted by body size, due in large part to human's energy-demanding brain (Beardsworth and Keil, 2003). Thus, our foraging ancestors were predisposed to extracting relatively high quality foods from ecosystems.

An emerging consensus among archeologists suggests that plant domestication and agriculture are outgrowths of progressive foraging behavior (Kennett and Winterhalder, 2006;

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Pearsall, 2006). As selective foraging progressed, coupled with increasing human numbers, natural plant propagation cycles were altered which changed the biological character of foraged ecosystems. With time, such passive ecosystem alterations led to morphological changes in plants that characterize domestication (Harlan, 1992; Pearsall, 2006).

Transition to Agriculture

The process of domesticating some plant species and then transitioning to deliberate plant selection and cultivation was underway long before humans embraced full-scale farming. Evidence of clustered populations during early domestication also precludes the conventional wisdom that village life had its genesis as a result of sedentary farming (Pringle, 1998; Tudge, 1998; Kareiva et al., 2007).

Within the last 11,000 yr, cultivation of grains began in earnest for the 10 to 15 million humans estimated to have populated the planet at that time (Eaton et al., 2002; Bellwood, 2005). This transition was driven by the convergence of such factors as climate change, declining rewards from big game hunting and foraging, cumulative experience in manipulating ecosystems, increasing capacity to domesticate plants and animals, accumulated experience in storing and preserving food, and increasing human numbers (Hillman and Colledge, 1998; Diamond, 2002; Bellwood, 2005).

The earliest evidence of sedentary agriculture is dated to about 10,500 yr ago in the uplands of the Fertile Crescent (Cowan and Watson, 1992; Smartt and Simmonds, 1995; Diamond, 2002). From this and other sites, the development of agriculture set humanity on a new course where the foundations of the modern world were cast and where nothing that came afterward—classical Greece, the Enlightenment and Industrial Revolution, the Atomic Age, the Internet—has yet matched the significance of this profound event (Mithen, 2004).

TREK TO THE 20TH CENTURY

Agriculture and Humanity's Well-Being

Although the transition to agriculture resulted in more food energy per unit of land, the nutritional spectrum of farmed food narrowed compared with the broader nutritional band of foraged diets. Furthermore, the amount of labor to produce a unit of cultivated food vs. foraged food apparently increased. The fallout from these changes subsequently impacted human health and physiology in the form of reduced stature and increased markers for infection and nutrient stress as evidenced by escalated skeletal deformities, greater tooth decay, and a rise in bone lesions (Armelagos et al., 1991; Tudge, 1996; Diamond, 1997; Larsen, 2000; Eaton et al., 2002; Manning, 2004).

The transition to agriculture also triggered dramatic changes in humanity's cultural ethos. Hunter-gatherer societies were by and large egalitarian. Converting to agriculture overturned this early cultural climate, eventually giving rise to social hierarchies. Repercussions from these class distinctions ultimately led to social aberrations such as ruling echelons, slavery, racism, gender discrimination, colonization, and other social inequities (Dawkins, 1976; Diamond, 1997; Tudge, 1996, 1998; Manning, 2004; Bellwood, 2005). Still, the evolution of agriculture was a giant step in humanity's trajectory toward more complex social orders and changed forever the character and complexion of the human condition.

Fast-Forward to the Industrial Revolution

The transition to agriculture represented humanity's first major food yield inflection point. Although early advances were made in the delivery of water to cropland, agriculture plodded unremarkably through centuries unencumbered by sweeping technological breakthroughs or revolutionary improvements in its practices.

By 1700, global human numbers had increased roughly 50-fold (∼600 million) since humanity's transition to agriculture (Bellwood, 2005; Cohen, 2006). Societies remained mostly agrarian. Even as late as 1800, only about 2% of the world's population lived in cities (Cohen, 2006). As the Industrial Revolution spread out of Great Britain in the late 1700s, it triggered huge social repercussions as farm and other laborers were lured to cities by the prospect of employment in the manufacturing sector. The proportion of the world's population living in urban centers grew six-fold during the 19th Century (Cohen, 2006; Eaton et al., 2002).

The Industrial Revolution came later to America. The young nation was predominantly agrarian in 1800 with rural residents accounting for over 90% of the nation's population. America's farm labor force in 1810 was 30 times larger than that of manufacturing. As the Industrial Revolution gained momentum, this ratio dropped to 7:1 by 1840 (Peskin, 2007). The lure of industrial employment drove expansion of the nation's cities as had occurred earlier in Great Britain. In 1860, America counted eight cities with populations exceeding 100,000. By 1900, this number had grown to 38 (U.S. Department of Commerce, Bureau of Census, 2006).

Industry had been quick to harvest the technological fruits of the Industrial Revolution since the manufacturing sector was well adapted to stationary power and fixed machinery. Technology was a latecomer to agriculture, however, since mobile draft power and machinery took more time for development and adoption. Thus, the 20th Century began with a wide disparity between the technological sophistication of these two sectors.

AMERICA'S 20TH CENTURY AGRICULTURE

The First Decade

While most industrial sectors employed coal-based steam power, America's agriculture still relied on draft animals that provided 85% of the nation's farm power. These draft animals siphoned off huge amounts of cropland for feed. At the peak of draft horse numbers in 1915 (21 million plus ∼5 million mules), nearly 38 million ha (27%) of the nation's cropland were devoted to *biofueling* this draft power (U.S. Department of Commerce, Bureau of Census, 1975; Gardner, 2002).

America's cultural landscape in 1900 still reflected its agrarian roots. More than 60% of the nation's 76 million people lived in rural areas. Agriculture was still relatively

Table 1. Structural changes in U.S. agriculture, 1900 to 2000.†

Category	1900	1930	1945	1970	2000
No. of farms (× 10^6)	5.7	6.3	5.9	2.9	2.1
Farm size, ha	59	61	79	152	179
Commodities per farm	5.1	4.5	4.6	2.7	1.3
Farm share of population, %	39	25	17	5	<1
Rural share of population, %	60	44	36	26	21
Work force in agriculture, %	41	22	16	4	1.9
Agriculture's share of GDP, %	na‡	7.7	6.8	2.3	0.7
Farmers working off-farm, %	na	na	27	54	93

† Source: Modified from Dimitri and Effland, 2005.

‡ na, not available.

labor intensive, enlisting nearly two-fifths of the U.S. workforce while accounting for only 10% of the U.S. economy (U.S. Department of Commerce, Bureau of Census, 1975; Gardner, 2002). But the seeds of change sown through the Industrial Revolution had begun to change America's demographic and cultural character (Fig. 1; Table 1).

As science came to bear on agriculture, various agriculturally related disciplines organized themselves in the interest of sharing information and providing publication outlets for research. Forty-five days after President Theodore Roosevelt signed off to admit Oklahoma to the union as the 46th state, 43 soil and crop scientists met on the last day of 1907 in the Department of Botany at the University of Chicago during the annual meeting of the American Association for the Advancement of Science and founded ASA.

Agriculture During ASA's First 50 Years

It was during the 1930s that America's agriculture began to fully capture the benefits of the Industrial Revolution and the contributions of science. Mechanization and development of hybrid corn (*Zea mays* L.) became primary drivers of increased production. Hybrid corn adoption began in earnest in the 1930s, illustrated by Iowa that went from a negligible amount of hybrid corn planted in 1930 to 90% of the state's corn land planted to hybrids by 1940. The nation's Corn Belt had converted almost entirely to hybrid corn by mid-century (Gardner, 2002).

Another crop transformation was catalyzed by WWII. China's internal revolution coupled with the war devastated its soybean [*Glycine max* (L.) Merr.] oil industry. With China's soybean oil supply and tropical vegetable oil sources cut off by war, America launched a campaign to increase soybean production. The U.S. cropland devoted to soybean totaled 3.6 million ha in 1942, half of which was used for hay. By war's end, soybean accounted for 5.8 million ha, with more than 75% of this land area harvested for seed (Boerma and Specht, 2004).

By the mid-1930s, the infusion of technology through crop improvements, nutrient applications, mechanization, and other innovations precipitated the greatest crop yield inflection point (Fig. 2) in the history of agriculture (U.S. Department of Commerce, Bureau of Census, 1975; USDA-NASS, 2006a). Before this time, crop yields had hovered around an unchanging mean. From this inflexion point, yields began trending upward at an annual rate of more than 2% (Gardner, 2002).

U.S. Agriculture at Mid-Century

ASA celebrated its 50th anniversary at its annual meeting in Atlanta, GA, 18–22 Nov. 1957. Atlanta was still highly segregated. African Americans were not welcome in meeting hotels and were barred from their restaurants (personal witness). The roots of this racial discrimination can be traced back more than 10,000 yr to the formation of social hierarchies after humanity's transition to agriculture.

From the perspective of ASA's 50th Anniversary in 1957, it was not difficult to identify how yield increases would be derived over the next several decades. Potential yield increases from production investments still retained considerable momentum. Irrigated land continued to be developed and improved crop varieties were introduced that were more responsive to still higher rates of nutrient applications and more tolerant to crop protection chemistry (Ruttan, 1992).

The Latter Half of the 20th Century

Remarkably, the rate of crop yield increases begun in the mid-1930s held nearly steady throughout the remainder of the 20th Century (Gardner, 2002; Heinz Center, 2002), sustained in part by favorable climate across the Corn Belt during 1982 to 1998 (Lobell and Asner, 2003). Soybean yields nearly doubled during the latter half of the century. Wheat (*Triticum* spp.) and cotton (*Gossypium* spp.) yields more than doubled, while corn yields increased about four-fold since mid-century

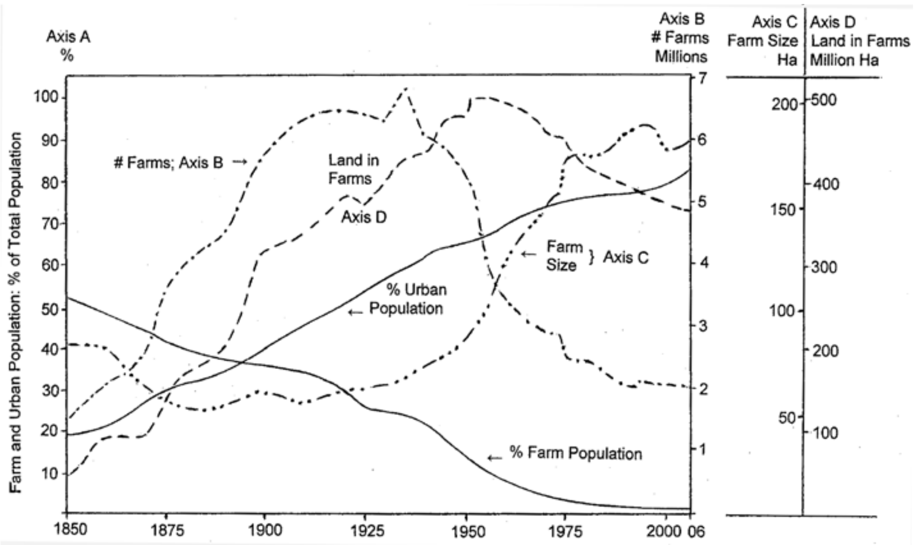


Fig. 1. Trends in U.S. demographics, farm numbers, farm size, and land in farms, 1850–2006. Source: U.S. Department of Commerce, Bureau of Census, 1975; Hoppe, 2001; USDA-NASS, 2006a, 2006b; USDA-ERS, 2007b. Note: Changes in census definition of farms and methodology account for some graph irregularities, e.g., 1974–1975 and 1994–2000. Farm number anomaly in 1935 reflects people returning to farming due to the Great Depression followed by the impact of WWII.

(Fig. 2). America's agriculture had become such a production juggernaut that various government programs were designed to partially quench its output.

Technology and energy increasingly substituted for agriculture's two most expensive production resources, namely, labor and land. The dramatic impact of technology on agricultural labor input is illustrated by the fact that corn required less than 2% of the labor to produce a unit of corn grain at century's end compared with 1900. Over the latter half of the 20th Century, agricultural labor productivity grew seven-fold compared with the 2.5-fold increase for nonfarm labor (Gardner, 2002; Heinz Center, 2002).

Technology also had a dramatic impact on the nation's cropland requirements. Harvested cropland held steady throughout most of the 20th Century. Crop yield increases, coupled with the conversion of cropland previously devoted to fueling draft animals (equivalent to one quarter of U.S. cropland) to other crops (Fig. 3), precluded America from having to increase its cropland base even though the nation's population increased 3.7-fold and agricultural exports increased roughly eight-fold over the course of the century (Dimitri et al., 2005).

The investment of science and technology that brought about America's agricultural cornucopia also visited profound changes on the character and structure of the nation's agriculture. Nor were these investments without social and environmental repercussions, the fallout from which was dramatically portrayed early in the second half of the 20th Century by authors such as Carson (1962) and the widely read polemic by Hightower (1973). These matters continue to be prominent among the issues America's agriculture faces as it enters the 21st Century.

ISSUES ON ENTERING THE 21ST CENTURY

America's Stratified Agriculture

The number of farms at century's end was less than one-third of its zenith in 1935. Farm size tripled over the course of the century. Farm population in 2000 was about one-tenth its peak of 32 million in 1910, although the percentage of the nation's farm population had been in decline since the early 1800s (Fig. 1; Table 1). But, these aggregate figures betray the true character of the nation's agriculture and the complex changes it had undergone.

At the threshold of the 21st Century, commercial farms (defined as generating $100,000 of farm product sales and where most income is generated from the farm) made up only 18% (360,000) of the nation's farms, but accounted for about 85% of the market value of products sold. Thus, more than four-fifths of America's farms in 2000 accounted for only 15% of the nation's agricultural market value. At least 75% of these noncommercial farms have been characterized as rural lifestyles where nearly all income was derived off-farm (Hoppe, 2001).

This farm stratification unveils the dichotomous character of America's agriculture. Increasingly, this segregation of farm types, coupled with differing agricultural philosophies, has resulted in antipathy among the nation's agriculturalists. This estrangement has become contentious with its genesis born out of one of the central themes in the history of American agriculture, namely, the tension between agrarian traditions and the inexorable drive toward modernization and industrialization (Meyer, 1993). Technology-driven agronomic production systems have unwittingly exacerbated this tension.

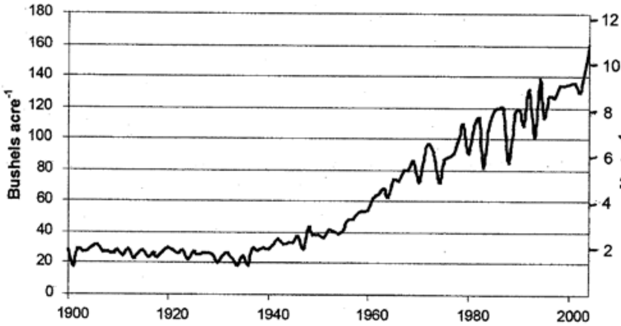


Fig. 2. Average U.S. corn yields: 1900–2002. Source: USDA-NASS, 2006a.

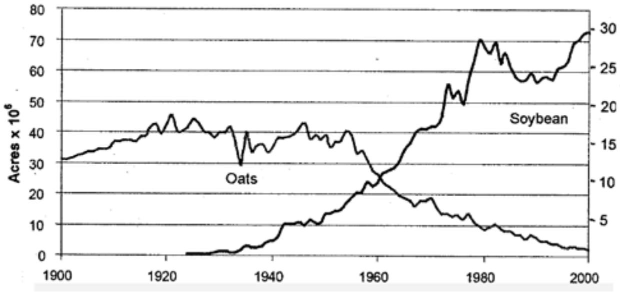


Fig. 3. U.S. harvested area of oats and soybean, 1900–2000. Source: USDA-NASS, 2006a.

Contentiousness in the Countryside

Agriculture is practiced in a cultural as well as an economic and environmental context. The agrarian nature of early America, where farming was viewed as compatible with the nation's rural landscapes, carried well into the 20th Century. This canon plays to the popular image of the countryside as a visual metaphor for human harmony with nature that has enormous public appeal (Nassauer, 1997).

As the 20th Century unfolded, the enterprise of commercial agriculture diverged sharply from the lifestyle of traditional farming. The persistent drive toward increased production per unit of capital catalyzed by economic forces that reward efficiency and economies of scale have yielded commercial agricultural enterprises, the character of which is a marvel to some, unknown to many, and found wanting by others.

Unlike rural America in 1900, where 65% of rural residents lived on farms, only about 5% of the rural population (~50 million) lived on farms in 2000. Furthermore, much of today's rural population is culturally far different than the more agrarian rural population at the beginning of the 20th Century. As Gardner (2002) noted, this difference bears on one of the most contentious issues in rural America, namely, how increasingly large and industrialized farms can coexist peacefully with growing numbers of nonfarm residents.

Fractionated Agri-'cultures'

This coexistence issue, coupled with long-running tensions between those persuaded by agrarian traditions and others pursuing agricultural modernization, imposes pressures on commercial agriculture that most business enterprises do not have to endure. Those allied with more holistic and family-operated agriculture perceive technologically intensive agricultural enterprises as ecologically dysfunctional and morphing into industrialized enterprises accompanied by increasing concentration of the human food chain in the hands of multinational corporations (Berry, 1996; Cox, 2001; Duff, 2002; Manning, 2004; Kirschenmann, 2007).

Those pursuing modern, commercial agriculture see it as a business enterprise, incorporating science and technology in the interest of efficient production, utilizing economies of scale to be globally competitive, and trending toward a product manufacturing-industrial model. Like the U.S. manufacturing sector that is shifting away from mass production to mass customization (Wulf, 2007), modern commercial agriculture is transitioning from the production of bulk commodities to provision of standardized products and specific-attribute raw materials for differentiated markets (Boehlje, 2006).

The Environmental Issue

Among the core issues contributing to tensions between these factions is which system can best protect agriculture's natural resource base and sustain nature's ecological processes. Unlike most industries, agriculture's vulnerability to weather has repercussions on productivity as well as the environment. While soil erosion and the Dust Bowl were the poster children of agricultural mismanagement in the 20th Century's first half, post-WWII agriculture has accumulated its share of vexatious icons in the form of eutrophic and polluted water, declining biodiversity, loss of wildlife habitats, soil carbon loss, salinization, animal waste spills, and other ignominious images (Wood et al., 2000). Clearly, society expects a better track record from agriculture (Heinz Center, 2002; Pew Research Center, 2005).

Agronomy's Holy Grail

These issues, coupled with unrelenting pressure to increase crop yields for both food and nonfood uses, comprise the broad framework within which agronomists find themselves at ASA's centennial mark. Unlike the situation at the time of ASA's 50th anniversary, identifying the wellspring from which increased productivity will be forthcoming in the decades ahead is less obvious. Thus, the holy grail of agronomic challenges for the decades to come is the goal of increasing productivity per unit of land enough to preclude large cropland expansions while simultaneously increasing the efficiency of production inputs, reducing their leakage to the environment, sustaining the integrity of those ecological processes that undergird these intense biological production systems, and, hopefully, garnering society's support.

These formidable challenges require establishing an agricultural vision; developing different metrics, including operational definitions for such concepts as sustainability and ecological integrity; pursuing new research partners; and restructuring institutional arrangements.

A VISION, NEW METRICS, AND A MARRIAGE

An Agricultural Vision

Although conservation and environmental ideologies have punctuated America's history, the nation has never had a socially compelling environmental ethos that has generated sustained public support (Andrews, 1999). Kirschenmann (2005) offers that America's agriculture has had a series of visions formulated from the cultural milieu of the times, ranging from the Puritan ethic of taming the wilderness as part of fulfilling divine destiny to the Jeffersonian vision during the 18th and 19th centuries, whereby agriculture was seen as a civilizing force in creating a democratic republic of small farm landholders. Agriculture's vision in the 20th Century was part and parcel of the industrial dream.

Agriculture's vision for the 21st Century stands ready for marketing. As the most extensive users and managers of America's terrestrial ecosystems (Ausubel, 1996), agriculture, forestry, and other renewable natural resource-based industries currently serve as de facto stewards of the nation's natural resources. No other industry or institution comes close to the comparative advantage these enterprises hold for this vital responsibility while simultaneously providing food, fiber, and other biology-based products.

Agriculture's stewardship role goes largely unseen by and unknown to the public, except when it falls short. But if properly programmed, including new metrics, this stewardship mantle would engender a socially compelling vision (Nassauer, 1997). Otherwise, the nation's agricultural enterprise will acquiesce to the forces of economics, technology, and government policies resulting in a future fashioned more by default than by design. Traditional measures used to characterize agriculture, such as productivity, economic output, and demographics, do not kindle much resonance with society.

Productivity

Agriculture's prodigious productivity is an impressive metric. But society has become numbed to it as agriculture's copious output is largely taken for granted, if noticed at all. Even occasional media references to agriculture have become more odious, given the negative connotations of subsidies, concentrated animal operations, genetically modified organisms, and the trend toward industrialization.

Economic Output

Agriculture's economic output, while large, barely shows up on the nation's economic charts. During the 5-yr period from 2000 to 2004, agriculture's share of the U.S. GDP ranged between 0.7 and 1.0%. Including agriculturally related industries raises agriculture's share to only about 5% of the nation's GDP (USDA-ERS, 2007a). Thus, agriculture's economic metrics do not elicit much attention when buried under America's more than 13 trillion dollar GDP.

Demographics

Another metric that is promoted by agriculturalists with a sense of pride is the small segment of the U.S. population that feeds the rest. Declining numbers of farmers now account for <1% of the nation's population. Even this figure is highly inflated, given that commercial farms make up <20% of all farms. Advocating this small demographic metric serves to rebut agriculture's legislative clout along with Congress' hefty largesse toward agriculture.

Need for New Metrics

The nature of agriculture as an extensive user and manipulator of terrestrial ecosystems requires indicators that portray agriculture's efficiency in using these ecosystems and express their ecological condition. Such indicators would have obvious value to agricultural managers and would seem an easy sell to society. Likewise, economic indicators must eventually include the value of nonmarketed goods and services provided by nature.

Agriculture's Land Use Efficiency

One environmentally related metric has grown out of agriculture's intensification. Although the intensity of modern agriculture has its critics, increased yields have spared large areas of land from being usurped for cultivation. As a case in point, the land area needed for a unit of corn production decreased nearly five-fold during the 20th Century (Kucharick and Ramankutty, 2005). This metric of spared land makes a persuasive case for high output agriculture. It is ironic that those calling for a pull back on agricultural intensification often come from the same camp as those calling for preservation of more wilderness areas as well as a sustainable agriculture.

Metrics for Quality and Sustainability?

Partridge (2000) notes that in the canon of environmental ethics, Leopold (1949) wrote the fundamental credo: "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community; it is wrong when it tends otherwise." While such an aphorism is conceptually understandable, it harbors normative or stipulatory connotations and is laced with subjectivity, ideology, and a dose of dogma. Pursuit of such conceptual creeds is more the domain of philosophy than science.

Relatively recent additions to the lexicon of the natural sciences have raised similar concerns, including such words and concepts as sustainability, ecological integrity, and environmental health or quality. The concept of sustainability is an enigma, burdened with baggage (Kennedy, 2007). Still, these descriptors have become the new banners for nature despite ill-defined boundaries (Holland, 2000). Notions of health, quality, integrity, and maintenance (as a proxy for sustainability) are familiar concepts deeply rooted in American culture, albeit without definitional precision. However, for most scientists, these words and concepts are too abstract, subjective, and normative to be used in meaningful scientific contexts since, it is argued, they are not quantifiable, operational, and predictive (e.g., Peters, 1991; Soule, 1995; Sagoff, 1997, 2000; Letey et al., 2003).

Dismissing these common descriptors out of hand bodes ill for science and society. Society cannot be weaned from this well-entrenched vocabulary. As Karr (2000) notes, it is an effortless intuitive step from "my health" to "ecological health." If such quality-related descriptive concepts could be made operational, they would enhance the potential for engaging public interest in and support for environmental policies. The natural science community would be better served to embrace this lexicon by establishing well-defined boundaries, quantifiable parameters, and, where possible, indices rooted in rigorous science that would render these concepts operational. Such a step is not novel.

Human experience in manipulating biological ecosystems, seeing their responses to management and perturbations, and even developing productivity metrics and taxonomies go back thousands of years. The use of productivity land classes for taxation dates to at least 4000 yr ago (Ahrens et al., 2002). Neither are foresters, fishery scientists, agronomists, soil scientists, farmers, and other ecosystem managers inexperienced at assessing the potential of ecosystems to produce biologically. Measures such as forest site index, fish catch, land capability classes, and yield potential are commonly used proxies for assessing ecosystem functionality or health.

A number of attempts are well underway to develop quantitative ecosystem indices. Environmental ethicists such as Partridge (2000) and ecologists such as Karr (1991, 2000), Costanza (1992), Jorgensen (1997), Svirezhev and Svirejeva-Hopkins (1998), Ulanowicz (1997, 2000), Loucks (2000), Westra et al. (2000), Jorgensen et al. (2005), and others make cogent cases for empirically measurable attributes of ecological integrity that are integrated into ecological indicators. Karr's (1991, 2000) Index of Biological Integrity, Ulanowicz's (1997, 2000) Ecosystem Ascendency concept, Loucks' (2000) Mean Functional Integrity values, and others consist of science-based metrics that are indicative of biological conditions and ecosystem functions.

Among the questions that Loucks (2000) and others raise are how much integrity, quality, health, or sustainability is needed and how are thresholds established to determine when ecosystems fall below these standards? Is a perturbed ecosystem considered to have retained its ecological integrity, even though its measured attributes deviate from a given datum, as long as the resilience of the system is capable of restoring full ecological function? And at what thresholds do ecosystems loose their capacity for resilience? Fig. 4 illustrates a hypothetical representation of ecosystem indices modified from Karr (2000) and Loucks (2000).

As a major manipulator and perturbative agent of terrestrial ecosystems, agriculture is a logical enterprise to develop operative metrics that indicate the ecological integrity and health of the ecosystems on which it operates. The science community is calling for such ecological indicators to assess and manage the nation's ecosystems (e.g., National Research Council, 2000; Heinz Center, 2002; Jorgensen et al., 2005; World Resources Institute, 2005).

Market-Driven Sustainability

If agriculture fails to embrace some form of measuring and monitoring the quality of its ecosystems, the consuming public may yet hold the cards necessary to coax it and the country toward environmental standards and sustainability through the marketplace. Agriculture and the food-processing industry as well as other merchandisers

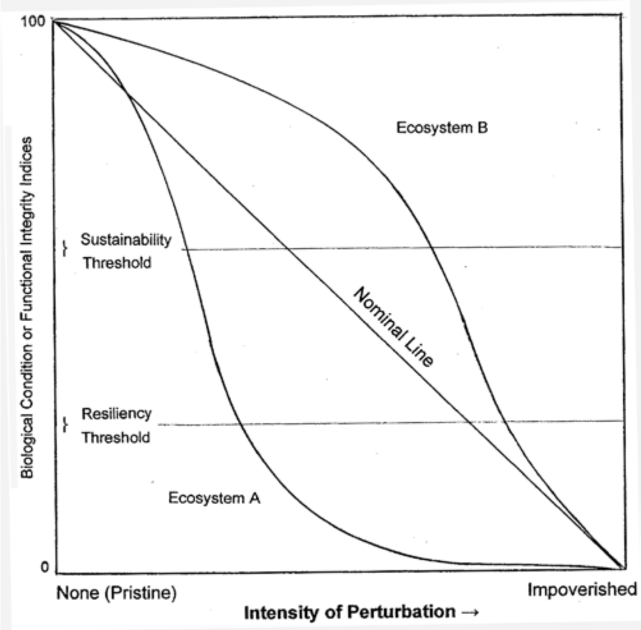


Fig. 4. Conceptual illustration of Biological Condition or Functional Integrity for two ecosystems (A & B) with differing vulnerabilities to perturbation. Source: Modified from Karr (2000) and Loucks (2000). Note: Sustainability and Resiliency thresholds indicate approximate indices below which continued ecosystem perturbation under specific uses is not sustainable and the capacity for resiliency is severely compromised.

are transitioning from production-oriented models to consumer-driven systems. Consumer buying power, especially that which is exercised through large retail outlets, generates enough clout to force suppliers to comply with sustainability standards. Certification programs and product standards related to the environment have been operational in many industries for some time, ranging from bird-friendly coffee and dolphin-safe tuna to animal compassionate labeling and sustainably managed forest products (e.g., GreenSeal, SmartWood).

The International Standards Organization (ISO) reflects the global reach of environmental standards into the marketplace through its ISO14000 series (Edwards, 2004). Such programs are making their way into regulatory and legal domains (Meidinger, 2001). Can mandatory environmental standards for agriculture, such as through USDA's voluntary Environmental Quality Incentives Program (EQIP), be far behind?

New Economic Metrics

Economics drives most commodity and resource management decisions. Traditional economic indicators, such as GNP, GDP, GDP per capita, DOW, and NASDAQ, serve as surrogates of nations' economic health and human well-being. However, under current pricing systems, nature's ecological service assets never show up in national accounts. Nor is degradation of these assets taken into account since there is no minus key on the nation's GDP calculator (Quinn and Quinn, 2000). Only when these assets are lost do they become apparent (Daily and Ellison, 2002).

Attempts to promote an ecology-based and sustainable agriculture in the absence of more comprehensive economic indicators will be sacrificed at the alters of traditional economics and pragmatism. Farmers understand very well that high production correlates with low prices and that having a compelling vision and a steadfast environmental ethic do not translate as collateral for bankers.

Table 2. Hypothetical annual farm income sources under current and future scenarios.†

Income source	Current scenario	Future scenario
	% Share	
Corn	47	27
Soybean	40	25
Wheat	10	5
Periodic woodlot harvest	3	2
Watershed protection: water quality	–	8
Soil conservation: erosion, sediment prevention	–	4
Carbon sequestration: cover crop, woodlot	–	4
Hybrid poplar: biofuel feedstock	–	5
Development rights sold: prorated over 30 yr	–	8
Biodiversity: wildlife, pollination, riparian protection	–	5
Land rental: wind turbine	–	4
Aesthetics: ecotourism, social value	–	3
Total	100	100

† Source: Modified from Daily et al., 2000.

If sustainability, however defined, is to serve as a cornerstone of agriculture's vision, it is imperative that there be a metric derived from the marriage of economics and ecology. Pricing ecological services would dramatically change the calculus of conservation and sustainable natural resource management (Quinn and Quinn, 2000; National Research Council, 2004). Environmental improvement and ecological service markets have been operating in Europe for some time and have been introduced in the USA (Cobb et al., 1995; Heal, 2000; Daily and Ellison, 2002). Table 2 illustrates how ecological service markets would allow farmers to capture the value of ecological services and their stewardship.

An Agronomy–Ecology Marriage

Apart from reproduction, the most natural of all human activities may be the domestication of nature (Kareiva et al., 2007). As these authors have posited, we live in a largely domesticated world. If nature is viewed as a bundle of ecological services, these researchers offer that, instead of recounting doom-and-gloom statistics of nature's alteration, it would be more fruitful to consider the selection of desirable ecosystem attributes, such as increased food production, with consequent alteration of other ecosystem attributes. The challenge of such an approach is to understand and manage the trade-offs among ecosystem services that result from the inescapable domestication of nature (Kareiva et al., 2007).

This approach to managing ecosystems would also bring agronomy and ecology closer together. In the past, agronomy and ecology were viewed as dichotomous disciplines having incompatible missions, namely, agricultural production vs. environmental protection (Hess et al., 2000). Both disciplines have moved toward each other as agronomy has come to recognize its linkages to the environment and its vital ecological processes while ecology has progressed toward the study of domesticated ecosystems (e.g., agroecology).

The ecological basis of sustainability is well established and provides a firm foundation for the pursuit of an ecologically sustainable agriculture that will require still greater integration of both disciplines (Gliessman, 1998).

ISSUES AND CHALLENGES

Green Revolution Redux

The prospect of doubling global food production by 2050 without significant cropland expansion gives the most optimistic agronomist pause. While there is still some momentum available from existing production technologies, their limits seem foreseeable (Cassman, 1999). Yield increases for major crops have become more difficult and expensive to achieve, both in terms of real costs as well as number of scientist-years (Ruttan, 1999). Crop improvement will likely continue to exert the most force in extracting higher yields as biotechnology is brought to bear on traits governing yield. Igniting another Green Revolution, however, will require the concerted thrust of the broader science community in league with agronomic disciplines.

Agronomy's Institutions: Back to the Future

A century ago, agronomy and other agricultural specialties sought their own disciplinary identity and formed colleges, agencies, and institutions apart from the disciplinary and institutional environs in which they were nurtured. Ironically, a century later, agronomy, soil science, and other agriculturally related disciplines are anxious to rejoin the larger science community, driven by broadened disciplinary focus, the trend toward more competitive and nontraditional funding sources, and teaming with other disciplines to address complex questions (Wilding and Lin, 2006).

In the academy, agronomy departments are morphing into broader faculty assemblages as evidenced by department-discipline realignments, new names, hiring nontraditional and more basic science staff, and promoting cross-discipline appointments and interdisciplinary cooperation. Among the repercussions of these trends is the increasing abdication by universities of the agricultural production component of their original land-grant mission to the private sector. Another consequence of these more comprehensive units is that there is no unifying allegiance to any particular professional–scientific society. These larger faculties have memberships in many societies and publish across a wide range of journals, thereby diluting the strength of traditional societies and impacting their journal market share. The character of science authorship has also been impacted.

From the likes of Newton and Einstein to the Nobel Prize, it has been the esteemed tradition in science to emphasize the role of individual genius in scientific discovery (Bowler and Morus, 2005; Wuchty et al., 2007). Increasingly, however, research is done through multidisciplinary teams that result in multiple author papers. Over 45 years (1965–2000), Wuchty et al. (2007) found that multiple authored papers surpassed single authorship publications across most science fields. Teams also produced more highly cited work compared with solo authorship, even when self-citation is removed. The mean authorship for 78,550 agronomy papers over this period increased from 1.96 to 3.34, while the relative team impact factor (ratio of mean number of team-authored citations divided by mean number of single-authored citations) increased 63% (Wuchty et al., 2007).

Funding Agricultural Research

Society served as America's agricultural research patrons throughout most of the 20th Century. But after the 1960s, public funding began to falter and was surpassed by private funding in 1980 with a disparity that continues to widen (Caswell and Day-Rubenstein, 2006). Agricultural and food research funding has traditionally lagged far behind other publicly funded science fields. The National Institutes of Health, for example, spends nearly 15 times as much for research as does USDA, and about 120 times the amount as USDA's peer-reviewed research allocation (Danforth, 2006).

To address this situation, new funding paradigms such as the National Institute of Food and Agriculture (NIFA) modeled after NSF have been proposed (Danforth, 2006). Whatever the outcome of this and other initiatives, the future of public agricultural research funding has and will continue to shift toward more competitive, merit-based allocation of resources open to the entire science community. It is possible, perhaps likely, that this trend will result in agronomists and their allied agricultural scientists no longer serving as the predominant drivers of agricultural research.

Adding to Agriculture's Crop Portfolio

Of the planet's estimated 300,000 described higher plant species, about 30,000 are known to be edible with roughly 7000 species having been used for food. Yet only 150 have ever reached the status of important crops. And now, after more than 10,000 yr of agricultural experience, a mere 20 species carry most of the load with just three crops [corn, wheat, and rice (*Oryza sativa* L.)] accounting for more than 50% of the calories consumed by the world's population (Smil, 2002; Wilson, 2002).

There is great momentum behind the narrow spectrum of crops commonly grown under modern agriculture, including research investments, service and supply industry support, established markets, and a sophisticated infrastructure in the form of transportation, storage, and processing facilities. These entrenched production systems are provided additional impetus through government programs, subsidies, and long-established dietary tastes and traditions.

These embedded cropping systems are difficult to breach with new crops. While it is prudent to maintain crop introduction centers in the interest of providing future crop options as well as providing food and bioproduct security, future additions to agriculture's crop portfolio will most likely occur through researching new crops for unique nonfood attributes and products. As markets develop for these products, they will provide incentives for farmers to produce crops from which these unique products are derived rather than trying to compete with established crops for the same customers.

Dewatering Agriculture

America's irrigated land constitutes one sixth of the nation's harvested cropland but accounts for one third of

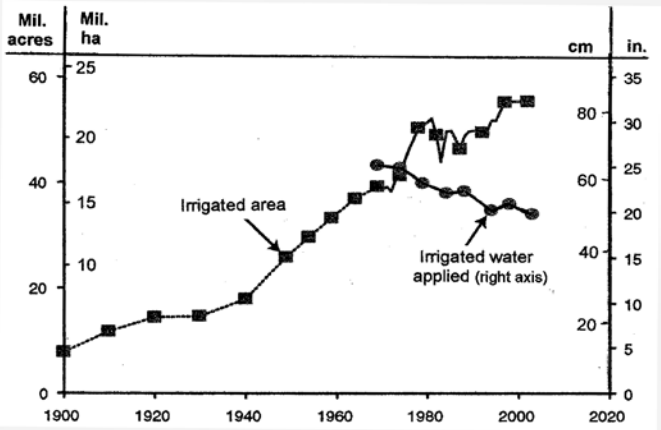


Fig. 5. Trends in U.S. irrigated agriculture, 1900–2002. Source: USDA-NASS, 2006a.

the country's agricultural productivity and about half of the value of all crops. But this irrigated land accounts for about 40% of America's fresh water withdrawals and more than 80% of the nation's consumptive fresh water use. In 2000, the nation's irrigated agriculture withdrew 59% of its water needs from surface water sources. Groundwater supplied the remaining 41%, a percentage that has been increasing (Gollehon and Quinby, 2006).

Irrigated agriculture must increase its water use efficiency as competition and costs increase (Gleick, 2003). While much progress has been made in reducing water application rates (Fig. 5), about 44% of the nation's irrigated land still relied on gravity water application systems in 2003 (down from 63% in 1979) while only 7% of the nation's irrigated land used low flow technology (Schaible and Aillery, 2006). Competition for water will challenge researchers to come up with better water management options, including crops genetically engineered to better withstand water and salt stress, yet are responsive to precisely metered water applications.

Agriculture and Bioterrorism

While agents such as anthrax and smallpox receive the bulk of attention regarding risk assessment of bioterrorism, a deliberate insect or pathogen release on agriculture could have devastating consequences. A lesson in the scale of potential damage was provided in the UK in 2001 when an unintentional infection of foot-and-mouth disease resulted in four million cattle being culled, costing the British economy nearly 50 billion dollars (Gewin, 2003).

According to the American Phytopathological Society, plant pathogens cost the nation between 20 billion to 33 billion dollars (U.S.) annually (Tucker, 2006). Given today's worldwide trading capability and instant communications, the impact of even local infections of crops and animals can be immediate and global. A 2001 outbreak of karnal bunt wheat fungus in northern Texas resulted in more than 25 countries banning wheat imports from the locally infected area within 24 h (Gewin, 2003). It is ironic that the threat of terrorism will fund and accelerate part of agriculture's research agenda for the future, including biomass substitutes for petroleum.

Déjà Vu for Bioresources

Renewable bioresource utilization has come full circle over the last 10,000 yr. Wood and other biomass were primary energy sources before coal. Even at the threshold of the 20th Century, agriculture's draft power was plant-based and many industrial materials such as dyes, solvents, and synthetic fibers were processed from trees and agricultural crops. Petroleum derivatives eventually displaced many of these biological feedstocks.

The increasing cost of petroleum has raised interest in biomass feedstocks to supply part of the future's energy mix. For biofuels in particular, better energy conversion efficiencies and different feedstocks will be necessary. A large portion of this biomass must come from cellulose derived from plants engineered for these uses (Koonin, 2006). A recent study (Perlack et al., 2005) indicated that by 2030 America could displace about one-third of its petroleum consumption with biofuels derived from 1.3 billion dry tons per year of biomass feedstocks. The study concluded that about three-quarters of this biomass would come from agriculture without jeopardizing the nation's food, feed, and export demands. Yet biomass feedstocks are not without their own environmental impacts, including the need to decarbonize future fuel sources. The costs of these impacts may be the most important considerations in society's choices about how much energy should be supplied and from what sources (Fisher, 1998).

In addition to energy feedstocks, there are a host of potential uses for biomass and various crop compounds that, either on their own or as substitutes for petroleum derivatives, will eventually find markets. Thus, agronomists face an unprecedented challenge in that future crop demands may be driven more by the need for trait-specific industrial feedstocks than by food requirements.

FROM THE SHADOWS COMES THE FUTURE

Feeling Our Way

Goodwin (2002) asserts that, given the unexpectedness of so many past surprises, it seems futile to suggest what might lie ahead. There is a way, Goodwin contends, to prepare for the unexpected so that an appropriate transition is facilitated even though it cannot be foreseen. Instead of focusing on the future, we should concentrate on the present and immediate past, particularly those aspects that are just beginning to exit the shadows. It may then be possible to feel our way into a creatively emergent future, even without knowing its trajectory (Goodwin, 2002).

Changes, Breakthroughs, and Needs

Following is a sampling of institutional changes, technological breakthroughs, and future needs that could or might occur in agriculture during the 21st Century.

Feeding Humanity

Food production will be adequate for feeding the world. Access to food by the poor will remain problematic, although progress will be made in addressing this issue. It remains to be seen if this food production can be generated in an ecologically sustainable manner.

Institutional Changes

Agriculture will lose its uniqueness as farm production becomes more integrated with the supply and processing chain as well as the financing, merchandising, and marketing segments. Farm ownership will become more separated from farm management. The USDA may give way to a Ministry of Food as has already occurred in a number of countries (Paarlberg and Paarlberg, 2000; Boehlje, 2006). Agronomy's identity will continue to erode as it integrates with other disciplines, although agronomic disciplines will remain crucial to agriculture's future.

Land Competition and Fragmentation

The combination of increasing rural population in many areas and the need for large, contiguous land tracts for commercial farm efficiency will be jeopardized by increasingly fragmented agricultural landscapes populated by more people unsympathetic to modern agriculture.

Measuring, Monitoring Ecosystems

The case has been made for developing indicators of ecosystem quality and ecological integrity in the interest of creating and monitoring sustainable and restorative management protocols. However, the relationships between ecosystem integrity and ecological services as related to the ill-defined concept of human well-being are poorly understood (Holland, 2000; Carpenter et al., 2006). Developing these relationships would further enhance public support of agriculture's ecosystem stewardship role.

Modeling and Microchips

The increasing power of computers and sophistication of software will revolutionize the simulation of the most complex systems, that is, if enough parameters can be obtained. Advances in the use of microchips that today defy the imagination may yield the necessary data to take advantage of ever-increasing computing power (Paarlberg and Paarlberg, 2000). The next generation of precision agriculture will yield the ultimate in production efficiency.

Weather Forecasting

Improved long-range weather prediction technology, including the capability to characterize phenomena such as El Niño and La Niña, will be necessary to take advantage of precision crop operations and resource applications. Such technology will contribute to a better understanding of global warming and its drivers (Paarlberg and Paarlberg, 2000). Furthermore, the specter of climate change will require enhanced weather predictability in the face of increased weather extremes that are anticipated.

Microbial Services in Soils

There is consensus on the crucial roles microbes play in biogeochemical cycling and sustaining various ecological processes. Among these roles, recent evidence shows the diverse mechanisms soil microbes exercise in imparting resistance to both naturally occurring and synthetic antibiotics, raising the potential for characterizing the kinds of resistance that could eventually emerge clinically (Levy, 2006). In another case, a bacterial species (*Geobacter*) has been found to have the ability to transfer electrons, raising the prospect of building fuel cells from pure cultures of this organism (Lovley, 2006).

Nutrigenomics and Nutrition Profiling

While far off, personal genomic information may be used to customize food products. So far, most studies on measuring genome-wide responses to nutrients have been confined to mice (Check, 2003). Such concepts reinforce the notion that agriculture's future will be oriented to producing commodities with specific market-demanded attributes.

Avant-Garde Agrochemistry

Some molecules are so intricate and elaborate that they can be synthesized only by living organisms. Organic chemists will farm these organisms for their unique products. Agrochemistry will take on a new meaning (Atkins, 2002).

Food Quality

Increased food production will be met with demands for improved nutritional value and quality. Increasing protein content of grains and other crops is an early call on biotechnology. Advances in food technology could allow the provision of meat analogs to those millions who cannot afford palatable and nutritious meat, milk, and eggs (Paarlberg and Paarlberg, 2000).

Genomics' Future

Genetic alteration of crops and animals is responsible for roughly half of modern agriculture's production increases over the last century. And it will be counted on once again as the primary driver of future yield increases. Although biotechnology has been used to impart various traits into crops and animals, it has yet to blossom as a yield enhancing technology. But as Phillips stated, "we can dream of the day when we will know the genomic regions controlling important traits up and down every single chromosome" (CSSA, 2006). Genomics will be required to generate nonfood attributes and products, aid in carbon sequestration, and to render biofuel feedstocks at least carbon neutral.

A Caution: Technology as a Talisman

Agriculture and humanity's future will continue to be molded greatly by science. But caution must be exercised so that science is not used to evade fundamental reforms to sustain nature. Technology has allowed many agronomic and ecological fundamentals to be overridden such as through monocultures, reduced genetic heterogeneity, and diminished biodiversity. As Kennedy (1993) has noted, will the development of crops that thrive in salty soil or in hot dry climates result in farmers and agricultural interests ignoring the cause of environmental damage and count on subsequent fixes for changing conditions?

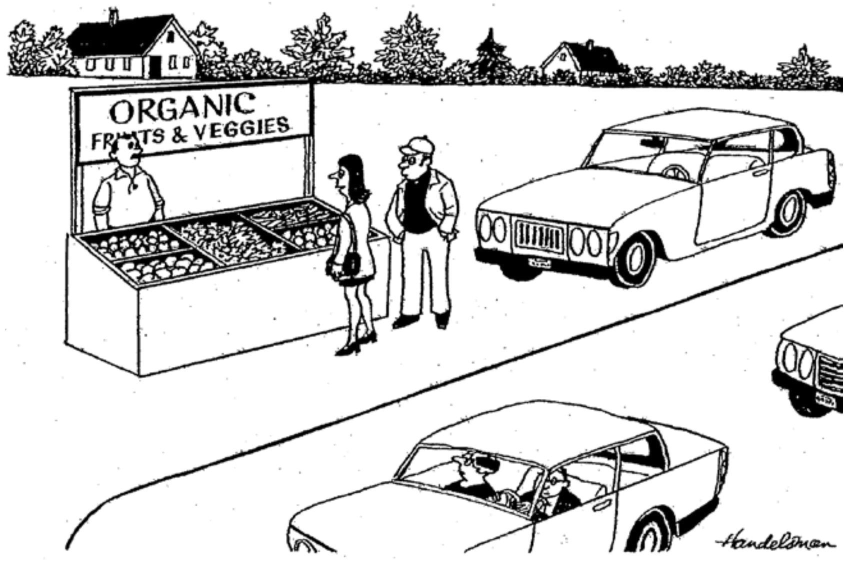
A POST-AGRICULTURAL SOCIETY?

Pills, Patches, and Food Synthesizers

No pondering of agriculture's future would be complete without considering whether photosynthesis-based agriculture will eventually become obsolete. Some trends and thinking bear on this question.

The U.S. military is researching the sequel to the infamous MREs (Meals Ready to Eat), consisting of a transdermal nutrient delivery system. Metabolic microsensors and a microprocessor attached to a soldier's body would transmit micronutrients, caffeine, and nutraceuticals either through skin pores via a "food patch" or directly into blood capillaries (Garamone, 2000). While not intended to replace solid foods, its purpose is to extend a soldier's physical stamina and mental alertness and to reduce field pack weight and bulk.

Transitioning to synthetic foods has been proposed by James Lovelock in his latest *Gaia* sequel (Lovelock, 2006), in which he proposes that humanity must, among other things, reduce the area of cultivated land in the interest of sustaining earth's ecological regulatory systems. Lovelock offers that humanity should start manufacturing food from raw feedstocks or industrial by-products, with the eventual aim of abandoning agriculture altogether.



"Organic is nice, but haven't you got anything digital?"

Fig. 6. A food future without agriculture? The New Yorker Collection, 2005. J.B. Handelsman from cartoonbank.com. All Rights Reserved. Copied with permission.

Lovelock's envisioned future may rest on nanotechnology that, by some estimates, promises to far exceed the impact of the Industrial Revolution (Nel et al., 2006). Just as foods are compounded by natural metabolic molecular machinery from elemental atoms and simple molecules, nanotechnology could possibly build molecular machinery to mimic nature's food fabrication systems. A countertop food synthesizer might replace current food foraging via trips to the supermarket. And what about taste? This too could be synthesized by injecting signals into our sensory system making that Thanksgiving dinner the ultimate repast via virtual reality (Hall, 2005). Perhaps Fig. 6 is not as far-fetched as it might seem.

EPILOGUE

Not withstanding the specter of synthesized food and despite the technological sophistication achieved at this period of our evolutionary odyssey, the essence of agriculture has remained unchanged from its onset more than 10,000 yr ago. Heterotrophic humans continue to rely on the capture of radiated solar energy via plant photosynthesis, manipulation of nutrient stocks, and mediation of plant stress for its sustenance. This inextricable nexus with nature will endure as a preeminent component of humanity's future well-being. It is imperative, therefore, that the ecological foundation of this human–nature–agriculture interconnectedness be sustained.

As the future exits the shadows, irony raises its head. Among the factors that contributed to humanity's transition to agriculture more than 10 millennia ago was climate change that triggered the recession of the last Ice Age. Climate change is once again on the agenda of challenges that agronomists and their allied agriculturalists must address in the design and management of future production systems.

Notwithstanding its problems, agriculture's achievements during the 20th Century were remarkable. Surely the Old Testament farmer introduced at the outset would be amazed at today's agriculture compared with his nonplussed take on agriculture at the time of ASA's founding. And should this farmer return for ASA's bicentennial anniversary in 2107, he most likely will be awed once again.

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