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Agricultural Productivity Strategies for the Future: Addressing U.S. and Global Challenges

West view of the U.S. Capitol Building in Washington, D.C. (Photo courtesy of the Architect of the Capitol.)

DEDICATION

This Issue Paper is dedicated to Dr. Norman E. Borlaug who wrote the paper's preface before his death September 12, 2009, and to his myriad accomplishments. Dr. Borlaug—credited by *The Economist* with saving hundreds of millions of lives, more than any other person who has ever lived—was recipient of the 1970 Nobel Peace Prize, the Presidential Medal of Freedom, and the Congressional Gold Medal. Often called the "Father of the Green Revolution" for his pioneering work developing high-yielding wheats for areas with limited cultivated land and increasing population, Dr. Borlaug was a supporter and promoter of CAST since its inception.

PREFACE

By Dr. Norman E. Borlaug

Agricultural policy has played a key role in my career and will always be near and dear to my heart. I was pleased to be a featured speaker at a CAST–Industry meeting in 1973, and I was honored when CAST distributed those remarks as its first publication (CAST Paper No. 1, *Agricultural Science and the Public*, 1973). As I said in 1973: "CAST has both a tremendous responsibility and opportunity to present unbiased, scientific data so that wise policy and legislation will be enacted. I have faith that the correct decisions will be made if the facts are made known to the general public and to national and state legislative leaders" (Borlaug 2009).

Although modes of communication have changed in the 37 years since CAST was organized, agricultural policy still plays the key role in determining outcomes. Unfortunately, agricultural science—like many other areas of human endeavor—is subject to changing

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fashions and fads, generated from both within the scientific community and imposed on it by external forces, especially the politically induced ones and activist organizations. Increasingly, I fear, too much of international and national research budgets is being directed toward “development bandwagons” that will not solve Third World food production problems, which scientists are ill-equipped to solve.

I have worked with dozens of governments in different parts of world trying to serve as the link between scientists and their own policymakers. You have to be able to communicate. Research information must be applied in order to meet human needs.

We made great strides in the first Green Revolution by bringing improved agricultural techniques, seeds, and technology to poor underdeveloped and developing countries. But in the next 50 years we are going to have to produce more food than we have in the last 10,000 years, and that is a daunting task. I therefore have called for a “Second Green Revolution” (Borlaug 2002).

Now, more than ever, it is important for the general public to know the facts underlying the many agricultural issues influencing daily life. It also is critical that accurate science be communicated and distributed to policymakers and legislators for their continuing debate and eventual decisions on agricultural issues that impact the nation and the world. CAST is uniquely qualified to provide this information now and into the future. I am pleased that CAST has prepared this update on agricultural science and the public.

ABSTRACT

This Issue Paper—dedicated to Dr. Norman E. Borlaug for his countless contributions to agricultural science, commitment to feeding the world, and support of CAST—has been prepared as an update of *Agricultural Science and the Public*, CAST Paper No. 1 written by Dr. Borlaug in 1973. The current paper is a forthright appraisal of contemporary and future challenges facing U.S. and world agriculture.

The authors address several key issues: Correcting pathologies in the broader U.S. economy that will allow American agriculture to become less dependent on domestic markets and take greater advantage of global markets; meeting developed countries’ increased demands on agriculture for fuel and ecosystem services; further increasing production per unit of land, water, and nutrient resources; dealing with global population growth; and serving the increased food demands in developing countries. The convergence of so many challenges at one time is unprecedented.

Increasing the productivity of resources available to agriculture is critical. Enhanced efficiency can be achieved only through research focused on sustainable agricultural productivity. Agriculture can provide the food we eat, the feed for our livestock and companion animals, fiber for our clothes and homes, “flowers” for the environment, and the fuel we need—if countries develop the needed information, knowledge, and technology. The public will have to actively support political action, particularly on such broad issues as global climate change, regulations on the welfare of animals in agriculture, natural resources, and investments in agricultural research and education.

The authors are most concerned about the apparent lack of commitment by the United States and other countries to make the research and education expenditures needed to address the problems affecting our survival on this planet. Complacency is unwarranted given the many warning signs of tighter future agricultural supply–demand balance, rising real food prices, and the increasing role of agricultural commodities in meeting energy needs.

The interrelations between U.S. and global agriculture are large, and the authors discuss four places in the world that are particularly relevant to agricultural productivity considerations for the twenty-first century: China, India, Brazil, and sub-Saharan Africa. Future agricultural policy for all nations must include a strong commitment to science if nations are to meet the coming challenges successfully. The paper concludes with an Appendix of promising scientific approaches that could improve agricultural productivity and help to bring about the “Next Green Revolution.”

INTRODUCTION

American agriculture has long provided adequate quantities of low-cost, healthful food for domestic consumption and substantial quantities for export. Agriculture's ability to continue meeting those needs is challenged by emerging domestic constraints on land use, water availability, and the environment, driven by broad concerns of U.S. society. Recent increases in petroleum prices have encouraged policies that make the conversion of crops into fuel profitable for the ethanol industry. Globally, agriculture faces unprecedented challenges such as increases in the demand for livestock-based foods in Asia, climate change that threatens to decrease production capacity in many places around the world, and increasing demand due to continuing rapid population growth in some poor countries.

This report addresses U.S. agricultural science and technology policy, and also recognizes that actions of one nation cannot be viewed in isolation—given environmental spillovers and improved transportation and communication. The report does not explicitly address important issues of food safety and nutrient balance, international trade barriers, farm price and income supports, the obesity epidemic, water management, rural development, and the like, but instead stresses the more basic need for knowledge to make sound decisions regarding such issues.

The interrelations between U.S. and global agriculture are large; however, given several existing comprehensive analyses of global agriculture and related matters,[1] the authors do not address international policy, with two exceptions. To the extent that actions in other countries have major impact on global food availability, the paper briefly reviews those impacts, and where U.S. policy actions have a dominant impact on the capacity of poor developing nations to meet their own food needs, the paper addresses those actions as well.

Correcting pathologies in the broader U.S. economy can reinforce the ability of agriculture to increase its productivity and exports. Dominant challenges include the need to end the three-decade-long pattern of living beyond our means: importing more than we export, borrowing more than we lend, spending more than we earn, and consuming more than we produce. Correcting this imbalance will require the value of the dollar to fall in relation to other currencies, interest rates to rise, and consumers to save more of what they earn. If we can make those changes, American agriculture will become less dependent on domestic markets and take greater advantage of global markets where food demand will nearly double by mid-century. The limited scope for global land and water resources to meet those demands at current food prices generates an opportunity for the United States. If U.S. agriculture can achieve substantial productivity gains while maintaining the quality of land, water, and biological resources, then it will profitably contribute to meeting the food and agricultural needs of global consumers in the twenty-first century. Improved productivity gains without sharply rising food prices, however, will require increased, sustained support for agricultural research in the United States, as well as assistance to developing countries abroad (Bertini and Glickman 2009).

In addition to traditional expectations, agriculture today also is being called on to contribute to the energy needs of the planet and to help mitigate global climate change. The demand for bioproducts and biofuels is virtually unlimited at expected future energy prices, but resources for production will constrain supply. In addition to supplying feedstocks for biofuels, some agricultural cropland resources will be shifted to trees, which sequester more carbon more sustainably and hence earn more carbon credits than cropland.

Meanwhile, there are huge unfulfilled demands for output of agriculture among the approximately 1 billion people in some developing countries who rarely get enough to eat for a productive life (FAO 2006). And billions of people in growing economies such as China and India will demand more meat, milk, and eggs in their diets as their incomes grow and they increase their expectation for a better life.

Given the finite nature of natural resources and the constraints on their further exploitation, if the United States is to meet a substantial fraction of the global agricultural output needs without a sharp increase in food prices it will have to further increase production per unit of land, water, and nutrient resources. Those increases can be achieved only through enhanced efficiency supported by research focused on sustainable agricultural productivity.

FUTURE DEMANDS FACING AGRICULTURE

American consumers demand food that is safe, convenient, nutritious, and affordable, and U.S. agriculture continues to meet those demands. But the widening scope and depth of future demands on the industry from nontraditional sources is especially daunting. Ever-accelerating globalization characterized by improvements in transportation and communication, falling trade barriers, and ever-growing demand for exports to pay for oil and other imports means that global demand and U.S. demand are virtually indistinguishable to U.S. agriculture. Given the direct relationship between the output of ethanol and the input of corn, when domestic oil and gasoline prices rise sharply, the demand for ethanol and corn in the United States also rises sharply (Eidman 2006). But the opposite holds as well, as illustrated by the ethanol plants that shut down in 2009 after oil prices fell. Hence, when oil prices are high, the competition between bioenergy and food increases. The end result is that the potential demand for farm output is nearly unlimited.

Meanwhile, crop and livestock pests and diseases continue to emerge in varied forms to challenge agricultural productivity, not because past eradication efforts have failed but because pests continue to evolve to thwart earlier controls. Climate change and unstable eco-

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[1] The United Nation's Millennium Ecosystem Assessment (2005) examines the consequences of ecosystem change for human well-being. The United Nation's Intergovernmental Panel on Climate Change (2009) was created to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences. The World Bank-initiated International Assessment of Agricultural Knowledge, Science, and Technology for Development (2007) focuses on how the world can reduce hunger and poverty, improve rural livelihoods, and facilitate equitable, environmentally, socially, and economically sustainable development through the generation of, access to, and use of agricultural knowledge, science, and technology. The International Water Management Institute's Comprehensive Assessment (2007) places water management in agriculture in a social, ecological, and political context and assesses the dominant drivers of change.

nomic conditions arising from nature and human activities also continue to confound the food system's best efforts to serve consumers. In short, the task of serving the myriad demands for agricultural output at home and abroad has never been greater.

The principal drivers of global demand for farm output are growing world population, higher expectations for standard of living, increases in disposable income, and greater energy needs. Global population will continue to grow for at least another 30 to 40 years. Rising income will add to food demand, especially in developing countries where a sizable share of income is spent on food. In addition to biofuels, bioproducts for pharmaceuticals and biodegradable plastics also are potentially huge emerging sources of farm output demand.

The overall global growth rate in per capita food and fiber demand from income has been quite stable at 0.27 % per year during the past 60 years.[2] This stability comes from the slowing increase in per capita food demand from wealthy countries offset by growing food demand in developing countries where food use is more responsive to income.

Table 1 shows past and projected annual growth rates in farm output demand from 1961 to 2050 from population only and from all sources, based on a study by Tweeten and Thompson (2009). (The initial year, 1961, was chosen because several data series began with that year.)

Table 1. Rate of increase and global total demand for farm output due to population only and from all sources in selected years from 1961 to 2050 (Tweeten and Thompson 2009)

	Year					
	Actual				Projected	
Item	1961	1975	2000	Variant	2025	2050
	%/year					
Population only	1.89	1.85	1.31	low	0.48	–0.17
				medium	0.82	0.36
				high	1.13	0.88
Total agricultural demand	—	—	—	low	0.83	0.18
				medium	1.17	0.71
				high	1.48	1.23
Agricultural output, accumulated demand	Year 2000 = 100					
Population only	50	67	100	low	124	127
				medium	131	150
				high	138	176
Total agricultural demand	—	—	—	low	135	152
				medium	143	179
				high	151	209

Population projections in Table 1 are from the United Nations (UN 2008). Many demographers view the assumptions underlying the "low" and "medium" projections as most likely, and they use the medium variant for projecting population (Tweeten and Thompson 2009). That variant calls for global population to grow at 0.82% per year in 2025 and at 0.36% per year in 2050. World population growth rates have been slowing for some years and several experts believe that global population will have already begun to fall by mid-century, as shown by the negative growth rate of –0.17% per year under the low population growth variant in Table 1.[3]

After year 2000, projected world demand growth for farm output per capita is calculated as the average compound rate of growth in population plus 0.25% annually due to income growth and 0.10% annually due to sources other than food and fiber. (See next section for elaboration on bioenergy demand underlying the especially elusive 0.10 number.)[4] Based on the medium population variant and including nonfood demands, overall demand for farm products is projected to be 143% of year 2000 output in 2025 and 179% of 2000 output in 2050 (Table 1). The demand projected from the high population variant seems unlikely, but the more plausible demand under the medium UN population projection requires a near doubling of agricultural output from 2000 to 2050. Because of their high income elasticities of demand and rapid population growth, developing countries will increase demand for farm output much faster than the world average.

BIOENERGY AND BIOPRODUCTS BRING A NEW PARADIGM FOR AGRICULTURE

As petroleum becomes a more limited and expensive resource, and with recognition that agriculture can contribute to the energy challenge, any consideration of agricultural policy must take into account bioenergy and bioproducts. Until energy became such a relevant issue, agriculture was thought of in terms of food for humans, feed for livestock and companion animals, fiber for clothes and homes, and "flowers" for

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[2] In technical terms, stability occurred as slow increases in demand from wealthy countries with falling income elasticities of food demand and rising incomes were offset by more robust increases in demand from developing countries with relatively high income elasticities of food demand (Tweeten 2007, p. 183).

[3] Recent evidence of rising fertility rates in the most affluent developed countries raises the unsettling prospect for food demand that the demographic transition does not culminate in zero or negative population growth but rather in positive population growth (Best 2009).

[4] The food demand projection is consistent with those of other analysts (Runge et al. 2003; World Bank 2008). The future agricultural demands for ethanol, projected to grow 0.1% per year in Table 1, depend on technology such as for cellulosic ethanol, the price of oil, and federal subsidies. In 2009, the U.S. Department of Energy projected the price of oil to be $121 per barrel for ethanol in 2025 and $130 per barrel in 2030, numbers well above the break-even estimate of $80 per barrel for ethanol to be competitive (USDOE 2009). Although demand for crop-based ethanol is virtually limitless, the quantity supplied will in fact be severely constrained by farming resources and technology. The reader may wish to examine alternative ethanol demand growth scenarios to that in Table 1.

our enrichment and the landscape. The new paradigm adds fuel (energy and various bioproducts) and carbon sequestration to that portfolio.

As this process evolves there will be competition for resources. Use of land, nutrients, and water will require hard choices and result in conflict, as evidenced in the United States in 2008 with the sometimes heated "food vs. fuel" debate. Indeed, one of the most critical issues facing all nations is achieving a greater degree of sustainable energy security.

In view that petroleum is a highly fungible good (one that is substitutable in kind), energy should be viewed from a global perspective. The United States, as well as many other countries worldwide, is establishing goals and plans that will address this concern, including the use of approaches that capture the potential of wind, hydro, geothermal, solar, nuclear, river and ocean currents, and ocean waves, as well as bioenergy. The sun's energy can be captured directly by photovoltaic cells, photothermal plates, and through green plant photosynthesis. Each of these approaches has merit and, in time, will contribute to solving the energy challenge; but harvesting the sun's energy through green plant photosynthesis—one of the most promising approaches—if widely implemented, will greatly impact the future needs and expectations of agriculture.

Although demands on land, water, and plant nutrient resources will provide mankind with awesome challenges, the sun provides a limitless source of clean energy for the next 3 to 5 billion years. The challenge is how best to harvest the sun's energy in a readily useable form. In desert environments around the world, photovoltaic cells and photothermal plates would be the approaches of choice, whereas in other regions green plant photosynthesis—that is, agriculture—would be most appropriate. Current exploitation of photosynthesis includes burning wood and other biomass for its heat and converting crops such as corn and sugarcane to ethanol. Researchers in the United States and around the world are working vigorously to develop more efficient means of converting wood and other biomass such as straw, stover, or grass into liquid transportation fuels like ethanol.[5]

Biomass energy also can be used to generate electricity, but its lower density means it is more expensive to transport, limiting its feasibility. Probably the greatest advantage of capitalizing on the sun's energy is that all nations have access to this energy source so that with feasible technology and adequate capital, energy from the sun could be converted everywhere into the electricity and liquid fuels all countries require. Whereas only certain nations are blessed with such energy resources as fossil, wind, geothermal, nuclear, and hydro energy, every nation on earth has and can use the sun's energy. Although the sun's energy is not the total solution to the energy challenge, it can be a major contributor.

EMERGING CONSTRAINTS ON FUTURE AGRICULTURAL PRODUCTIVITY IN THE UNITED STATES

A wide variety of issues pose challenges for future agricultural productivity; those issues include soil erosion, water use, bioengineered plants, animal welfare and livestock production practices, endangered species protection, fertilizer use, and global warming. Agriculture faces increasing competition for land and water from urban populations and industry in and around U.S. cities and competition for the environmental services that space and water provide to society as a whole.

Agricultural production entails environmental externalities (unintended consequences) that are attracting increased attention from society. This attention is leading to government interventions in markets in the form of local, state, national, and even international policies that influence the management of soil, water, air resources and, increasingly, animal husbandry and land. In recent decades, as more large-scale farms emerged and the nature of farming externalities changed, the public has demanded policies to address issues such as crop genetic engineering and animal agriculture. Policies related to climate change loom on the horizon.

Soil, Water, and Crop Issues

Soil Erosion

The most serious environmental problem of agriculture dating back at least to the 1930s was soil erosion. In the post-World War II era, land set-asides and conservation measures were used to address erosion and decrease the surplus production encouraged by crop price supports. More recently, the attendant problems of water pollution from sediments, synthetic chemicals, and pesticides have become of great concern. By 1983, government programs had diverted 31.6 million hectares (78 million acres) of cropland, many of them highly productive, to soil-conserving uses (APAC 2001). Under pressure of growing demand, the land in the Conservation Reserve fell to approximately 12.1 million hectares (30 million acres) and government programs such as Sodbuster and Swampbuster have been added.[6]

The wide adoption of reduced tillage on row crops also has reduced soil erosion. High-yield technology has obviated the need to crop fragile and highly erodible lands. Once the moldboard plow was used to prepare most corn land, but by 1991 only 15% of corn acreage was tilled by a moldboard plow. Reduced tillage keeps carbon out of the atmosphere and sequesters it as organic matter, useful for retaining moisture and nutrients in the soil.

Excess production capacity (apparent in land diverted from crop production by government programs) is now minimal for responding to growing demands for agricultural output. But emerging technologies can prompt reconsideration of policies. For example, the Conservation Reserve might be reduced if cellulosic ethanol becomes economically feasible. Feedstocks of perennial grasses and trees can be produced on erodible land with minimal soil erosion or other damage to the environment.

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[5] Harvesting of crop residues as feedstock for cellulosic ethanol can conflict with environmental goals if cropland erosion increases and water quality declines.

[6] These are programs administered by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS).

Water Quality and Quantity

Historically, irrigation was the largest user of water. In the United States in 2005, however, cooling for thermoelectric power generation was the largest use of water, accounting for approximately half the 410,000 million gallons per day withdrawn, 92% of that used on a "once-through" basis (USGS 2009). Irrigation was the second largest use, accounting for 39% of the total, and public water supply, industrial uses, aquaculture, and livestock uses comprised the balance. Water not withdrawn from rivers and streams provides important environmental services including the required protection of endangered aquatic species.[7]

Farming can have a serious impact on water quality. An Environmental Protection Agency (EPA) survey in the 1990s found that 2% of rural water wells contained nitrate levels in excess of EPA safety standards and 0.6% of wells exceeded the pesticide safety level (Tweeten 1996). Modern precision farming with global positioning systems, yield monitors, weather-dependent fertilizer application rates, and other computer-assisted tools helps farmers avoid overuse of chemicals by tailoring applications to crop needs.

Bioengineered Crops

Plants bioengineered to resist pests can decrease the need for synthetic pesticides. The first bioengineered crops presented a challenge to the U.S. regulatory system because they had aspects that fell under the purview of the USDA, the Food and Drug Administration (FDA), and the EPA (US Regulatory Agencies 2005). Those challenges have been worked out and such crops are deployed widely in the United States with evident benefits to the environment. For example, modern "three-stack" corn hybrids contain bioengineered genes that confer rootworm and earworm control as well as glyphosate tolerance that facilitates weed control. The result is better water quality due to less applied synthetic pesticides.

Bioengineered crops decrease soil erosion by facilitating no-till practices and improving water quality as less mechanical cultivation is needed to control weeds. Research on plants bioengineered to cope better with heat, salinity, and moisture stress offers substantive new benefits not only for the United States, but especially for tropical and subtropical areas.

Significant voices still oppose the use of genetically engineered crops in the United States. In Europe those voices have been strong enough to effectively limit the use of bioengineered crops. Europe followed a different public policy approach with regulations focused on processes used rather than on the resulting products. Many African and Asian countries fear genetically engineered crops and have not established regulations governing their use, effectively banning them. Bioengineered crops need to be monitored for safety, but excessive caution can seriously undermine U.S. and global efforts to serve future demands on agriculture.

Animal Welfare Issues

Growth of large farms has brought to the fore issues concerning livestock production practices. The development of agricultural operations where animals are raised or kept in confinement or on a small land area with feed delivered rather than the animals grazing has led to the development of EPA regulations on concentrated animal feeding operations (CAFOs) (US Regulatory Agencies 2005). These regulations can significantly increase capital requirements and costs in dairy, hog, and other livestock production systems.

State and local regulations stemming from animal welfare concerns have a similar effect of raising production costs. If costs increase too much, livestock production will shift to jurisdictions without such regulations. Thus, federal regulations may drive production overseas and state regulations may drive production into other states with lower animal welfare standards (see Textbox 1).

When markets alone do not provide desirable levels of environmental protection or animal welfare, a public role may be appropriate. The usual avenue for public policy is through state or national legislators. Alternative agriculture advocates (political consumers) increasingly turn to the *plebiscite democracy* of the referendum rather than the traditional *representative democracy* of legislatures to achieve their objectives. Unless voters are informed by science and education, unintended consequences may result from plebiscite democracy. For example, requirements for costly facilities and equipment mandated for U.S. poultry and livestock producers can drive production elsewhere. Another example is organic food that, by rejecting genetically modified varieties and synthetic herbicides, fertilizers, and pesticides, can cost substantially more than conventionally produced foods (Knutson et al. 1990). Such examples are not used here to condemn political consumerism, but to caution that science and education need to attend the decision process to avoid counterproductive outcomes.

Labeling of products for practices used to produce them, such as organic, fair trade, non-genetically modified organism (non-GMO), or non-bovine somatotropin (non-BST), is a productivity-enhancing and hence resource-saving alternative to costly statewide or national government mandates. With products labeled as to how they are produced, consumers can vote with dollars in the marketplace for the practices they are willing to pay for. To the extent that such labeled production practices sometimes require more resources and hence are higher cost, they constitute further

Textbox 1. Animal welfare issues in California

California voters passed Proposition 2 mandating that as of January 1, 2015, it shall be a misdemeanor for any person to confine a pregnant pig, calf raised for veal, or egg-laying hen in a manner not allowing the animal to turn around freely, stand up, lie down, and fully extend its limbs. A laying hen has a wingspan of 3 feet, hence would require 9 square feet per bird, more than 10 times the current average cage space per laying hen. Compared with current practices, egg producers likely would see cost increases of 20% or more for larger cages, 26% for raising hens in barns, and 45% for free-range poultry production (Sumner et al. 2008).

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[7] In some places these are substantial issues. For example, the quantity of water pumped into the California aqueduct was the subject of a lawsuit (see Textbox 2).

demands on agriculture.

Endangered Species Act

In many countries, particularly in the United States, there is great concern about the increasing loss of plant and animal species. Preserving natural resources and maintaining diversity of the planet's flora and fauna is important. Protection of species, however, comes at considerable cost (see Textbox 2). Preserving diversity poses one of Earth's most serious dilemmas. The planet's resource base is critically needed for production of food, feed, fiber, and energy, while land resources also are required for the multitudes of plant and animal species. Again, this issue can be addressed by more definitive research on how best to preserve plant and animal species with minimal impact on the land and water resource base.

Fertilizer Resources

Among principal commercial fertilizer resources, nitrogen is plentiful in the air but currently is made available to agriculture through petroleum feedstock. Although fertilizers are effective in driving crop yield improvements, they also frequently have a negative impact on the environment. Because most plants are able to use only a portion of the nitrogen fertilizer applied by growers, much of the remaining nitrogen fertilizer is lost through volatilization or leaches into the soil and water and pollutes lakes, rivers, aquifers, and oceans.

A significant portion of the unabsorbed nitrogen fertilizer volatilizes in the form of nitrous oxide. In fact, agriculture is the second largest industrial contributor to global greenhouse gases (GHGs)—ahead of the transportation sector and behind only electrical and heat generation.

One of the most visible examples of the harmful environmental effects of nitrogen fertilizers is the creation of "dead zones" in the world's oceans. Dead zones result from the death and decomposition of massive algae blooms that are fed by excessive nutrient runoff. When algae populations get too large, they die and their natural decomposition depletes the water of oxygen. This creates a condition called "hypoxia" and results in suffocation and death of fish.

A 2004 United Nations Environment Program report identified dead zones as one of the most significant global environmental threats facing the world. According to the report there are more than 146 dead zones around the world that range in size from between one square kilometer to more than 70,000 square kilometers.

Textbox 2. An Endangered Species Act example

> In 2009, the amount of water being pumped into the California aqueduct has be dramatically reduced because a small fish, the Sacramento River smelt—an endangered species—cannot be screened out from the pumps. In some cases only 15% of the normal supply of water is being provided. Farmers currently are cutting down almond orchards or are leaving the land fallow because there is not enough water to grow a crop. It is an example of unintended consequences or an incomplete cost/benefit analysis, where some of the most productive farmland in the United States can no longer be used at a time when the state is in a dire economic condition.

Potassium reserves are abundant. Phosphorus derived from phosphate rock is a limiting mineral resource in crop production. The United States extracted 31 million metric tons (mmt) of phosphate rock in 2008 from a reserve base[8] of 3,400 mmt, or a 110-year supply at the 2008 rate of production (United Nations 2008). This supply is not a comfortable margin for an element so basic to crop production, and the United States eventually will become a net importer of phosphate. World phosphate production totaled 167 mmt in 2008 from a reserve base totaling 47,000 mmt, or a 281-year supply at the 2008 production rate. Nearly half the world's phosphate rock reserves are in Morocco and the Western Sahara.

Overuse of phosphorus creates a less sustainable agriculture and causes environmental damage as water is contaminated. Production and consumption of phosphate rock will increase in the future, but known reserves will expand as phosphate rock prices rise with increasing rock scarcity. The ocean floor holds unrecorded large reserves, but mining such reserves is expensive. There is no substitute for phosphorus in plant growth, but some plants require more phosphorus than others and plant breeding can decrease nutrient use per unit of crop production.

Global Warming

Global warming influences the demand for natural resources. Although overall agricultural output and cropland area may not be affected materially in the United States, the location of crop production and land in crops will change (Rosenzweig and Hillel 2005). With adaptation to global warming, cropland area and production are expected to increase especially in the Lake States and also in the Northeast, Cornbelt, Mountain, and Pacific regions and to decrease especially in the Southeast, but also in the Delta and Southern Plains regions. Overall rainfall may increase and be more variable with warming. Water shortages are evident already but will intensify, notably in the Colorado and Rio Grande river basins and the Ogallala aquifer of the Great Plains.

MAJOR ISSUES FACING FUTURE AGRICULTURAL PRODUCTIVITY OUTSIDE THE UNITED STATES

Worldwide, issues that will pose challenges for future agricultural productivity include natural resource costs, food demand vs. food supply, and climate change.

Natural Resource Costs

The world will not run out of natural resources but their cost rises as marginal reserves are used. For example, millions of hectares of land are available for cropping in Brazil and Africa, but only under a rising supply price to compensate for needed investment in roads and other infrastructure. The lowest-cost sources of irrigation water already have been developed, and regions such as North Africa and the Middle East will experience severe water shortages as agriculture competes with urban uses for water and land. As with other

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[8] The reserve base includes resources that are currently economic, marginally economic, and some that are currently subeconomic.

natural resources, the thrust needs to be on achieving greater productivity from existing resources rather than from expansion of resource utilization.

Food Demand vs. Food Supply

Both increases in land area farmed and increases in productivity have contributed to keeping food production ahead of population growth. Yield per hectare (or yield per acre) is the most familiar and widely available measure of productivity. Tweeten and Thompson (2009) reported that global cereal yields increased at approximately 3% annually in 1961, 2% annually in 1975, and 1.4% annually in 2000; yields of vegetable oil crops increased at about 4% annually in 1961, 2.6% annually in 1975, and 1.58% annually in 2000. The weighted total of all livestock and crop yields grew at 2.4% per year in 1961, 1.7% per year in 1975, and 1.13% per year in 2000.[9] Other analysts find similar patterns, as shown for "land productivity" (excluding China) in Table 2. Global agricultural labor productivity (excluding China) grew at 1.23% per year from 1961 to 1989 and at 0.42% per year from 1990 to 2005. The story in China clearly is different, with labor productivity growing faster in the second period, perhaps because China has followed unique policies for the past half-century.

Judgments about the future global food situation come down to comparing the rates of growth in food demand and food supply. During the twentieth century, the rate of growth in supply exceeded that of demand; as a result, food prices in the United States and the world generally fell during that period as illustrated in Figure 1. The sharp upturn since 2005 is evident, but food prices turned down again in 2008. The reversal of the secular downtrend of real prices between 2005 and 2008 led to strong concerns about the prospects for meeting future needs. China, Brazil, and India suffered from insufficient agricultural growth in the not-too-distant past, but in the most recent two decades turned around their performance. Sub-Saharan Africa, the epicenter of famines in the 1980s and 1990s, continues to be a cause for concern.

Table 2. Growth in agricultural land and labor productivity worldwide, 1961–2005 (Alston, Beddow, and Pardey 2008)

Group	Land Productivity 1961–1989	Land Productivity 1990–2005	Labor Productivity 1961–1989	Labor Productivity 1990–2005
Developing countries	2.60	3.00	1.60	2.56
Excluding China	2.47	2.29	1.49	1.49
Developed countries	1.71	0.27	3.81	2.89
World	2.04	1.84	1.12	1.37
Excluding China	1.93	1.20	1.23	0.42
Excluding China and USSR	1.93	1.58	1.14	0.73
Top 20 producers	2.08	2.18	1.14	1.78
Excluding China	1.98	1.38	1.32	0.63
Other producers	1.83	0.88	1.08	0.07

Climate Change

Developing country agriculture is likely to be impacted more negatively by global warming than temperate zone agriculture. Night temperatures and longer dry periods are expected to increase in areas close to the equator, and these changes are expected to be relatively more intense than in temperate regions and hence stress crops relatively more in tropical than in temperate regions.

Country/Regional Examples

Four countries (or regions) are particularly relevant with regard to agricultural policy for the twenty-first century. China and India represent exceedingly large population centers of the future world. Brazil has the greatest still-untapped potential of agricultural productivity. Sub-Saharan Africa represents the region on the planet with the greatest challenge with regard to sustenance for its people.

China

Rapid income growth in China was well established by the mid-1990s and

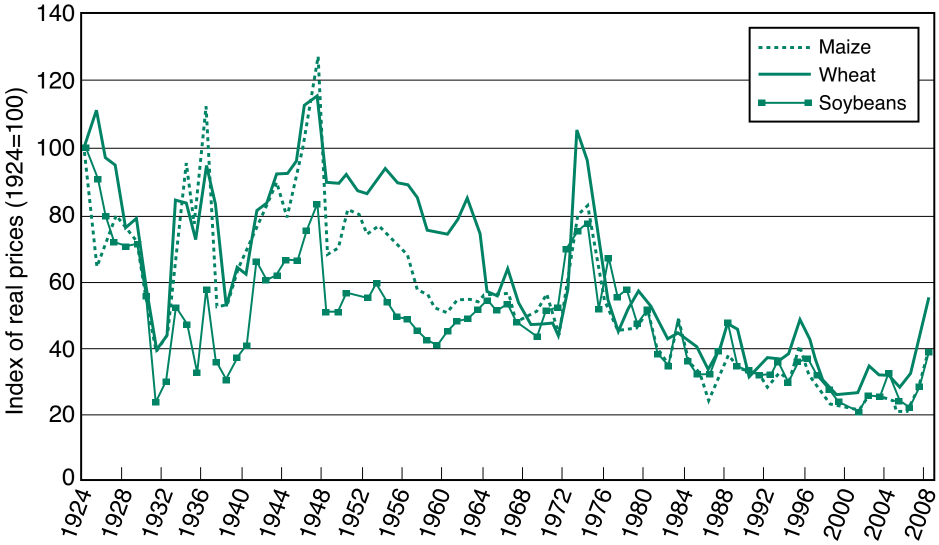

Figure 1. Real U.S. prices of maize, soybeans, and wheat, 1924–2008 (Alston, Beddow, and Pardey 2008).

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[9] Rates are expressed for a single year because Tweeten and Thompson measured them along linear trend lines.

led some people to question whether the world had the ability to meet the expected growing Chinese demand for food, especially meat, fruit, and vegetables. Some projections held that net import demand might reach 400 mmt of feed grains by 2030 (Fan and Agcaoili-Sombilla 2002), and many people worried about the impact such demand would place on the global ecosystem (Brown 1995). In 1975, China's per capita consumption of calories, fats, and protein were all well below the world average, but by the late 1990s they exceeded the world average and continue to increase.

Confounding those earlier expectations, during the past decade (despite accelerating income growth) China has not greatly increased its demands on the world food market. Its imports of rice and wheat have been modest, and it continues to export corn, aquatic, and horticultural products. Consumption of chicken rather than pork has increased dramatically (Gale and Henneberry 2009).

Some of the muted increase in demand is attributed to price changes and resulting consumer adjustments. For example, in 1991 the retail price of eggs was 12 times the price of flour, whereas by 1995 egg prices were only about 3 times the price of flour. These and other changes in the relative prices of pork, eggs, and chicken have shaped demand and greatly decreased the need for corn, but have increased the imports of soybeans. China increased its annual total corn consumption from 125 mmt to 160 mmt from 2000 to 2009 and met that increase from internal production, decreasing its exports from approximately 10 mmt to less than 1 mmt and with less than 0.2 mmt of imports (USFAS 2009). China's imports of soybeans were 28 mmt in 2005–06 and grew to 38 mmt in 2009–10, with soybean production of 16 mmt in 2005–06 and essentially the same amount in 2009–10.

India

The story of production, productivity, and food security in India is somewhat similar to China's but less buoyant. India's general economic growth accelerated somewhat later than China's and to less lofty levels; but India's food production growth rates began to accelerate earlier than China's, beginning in the mid-1960s, and have continued through the beginning years of the twenty-first century, driven by increasing crop yields and fertilizer efficiency (Evenson, Pray, and Rosegrant 1999).

Concerns in India now focus on the government's crop price supports, subsidies to fertilizer, and subsidies to electricity used to pump irrigation water, the latter especially leading to overexploitation of groundwater (Shah and Verma 2009). Careful analysis indicates that the marked historic discrimination against agriculture created by trade and other policies has evolved to approximate neutrality between their agricultural and non-agricultural traded sectors (Gulati and Pursell 2008). On a simple yield basis, India, with average grain yields of approximately 3 metric tons per hectare (mt/ha), would seem to have much greater potential to increase production than China, with national grain yields already exceeding 6 mt/ha.

Brazil

During the past 40 years Brazil's agriculture has grown rapidly. Driven by incentives that encouraged exploitation of savanna and tropical forest, from 1970 to 1990 Brazil's production of soybeans, corn, rice, edible beans, and wheat rose to 54 mmt, double the level of 1970. In the 1990s, Brazil instituted new macro-economic policies that ended decades of hyperinflation, thereby improving market incentives. From 1990 to 2005 production of major crops again doubled. Brazil has become the world's second largest exporter of soybeans and the largest exporter of orange juice, sugar, beef, poultry, coffee, and ethanol.

Brazil is using only one-third of its potential arable land, suggesting that continued growth of agriculture is possible (Valdes 2006). To realize that possibility, Brazil will need to ensure a favorable macro-economic environment and adequate investment, and to deal with continued opposition to clearing the Amazon and exploiting its savanna. But the physical capacity exists to increase production and exports considerably.

Sub-Saharan Africa

Sub-Saharan Africa is composed of more than 45 countries including 15 with fewer than 5 million people. Many of these countries are landlocked; many have fragile governments, limited transportation, and inadequate communication. The countries of sub-Saharan Africa have experienced decades of slow economic growth. With more than 120 million "ultra poor" people, rapid population growth, civil violence, a rampant HIV/AIDS epidemic, and recurrent food crises, Africa's challenges are deep and persistent.

Between the 1960s—when most African countries achieved independence—and the 1980s, population growth outpaced food production, reducing per capita food availability. Africa is the most rural of global regions with 65% of its workforce in agriculture, so regardless of the assistance it may (or may not) get from the rest of the world, increasing the productivity of its agriculture will be absolutely necessary if Africa is to work its way out of its problems.

The growth rate of the agricultural gross domestic product (GDP) per person was close to zero in the 1970s and negative through the 1980s and 1990s. But with positive growth rates in the past 10 years, this trend has been reversed, suggesting that the stagnation in sub-Saharan agriculture may be over (World Bank 2008). To prosper, sub-Saharan Africa has significant challenges to overcome. Investment in human resources, irrigation, marketing systems, transportation, agricultural technology, and computer network infrastructure are critically necessary if the region is to continue to accelerate its agricultural output.

STRATEGIES TO MEET FUTURE NEEDS FOR AGRICULTURAL OUTPUT

The basic framework of strategies to meet future needs for agricultural output is straightforward.

Harness Market Power

No country can meet the demands for agricultural output without harnessing the power of markets in directing what, how, when, and where to produce. Even a country with a sound, market-based food system has disadvantaged persons who lack access to food, housing, and other items essential for a productive and healthy life. But markets perform poorly without a supportive institutional structure. Key elements of that structure are government provision for equity and for public goods and services.

Support Research

The public sector makes provision for public goods and services because the private sector acting alone underinvests; firms are unable to capture enough of the (perhaps considerable) social benefits to cover costs. Examples are infrastructure such as roads, as well as education and basic research. Sound economic policy is to subsidize activities such as research and education that have positive externalities and to tax activity such as smoking that has negative externalities. A strong case can be made to publically support research on alternative energy technology such as cellulosic ethanol and other agricultural technologies outlined in the Appendix.

Basic research that has no immediate application but a potentially large future value tends to be underfunded by the private sector. Public agricultural research has a proven record of high payoffs in the past and much promise for the future. The high rates of return, frequently 40% or more on investment, indicate that agricultural research has been underfunded in the past by the public sector (Alston et al. 2000; Gardner and Lesser 2003; Huffman and Evenson 2006.) The private sector has stepped up research in recent years but will not fund research with a large public but small private payoff.

Assist Less-Developed Countries

The foregoing remarks apply to rich and poor countries alike, but given the dire food insecurity in developing countries in sub-Saharan Africa, it is useful to review opportunities for the United States to help less-developed countries (LDCs) meet their need for food and other agricultural output (Tweeten 2007).

- The United States will continue to provide humanitarian food and medical support to deal with crises of hunger and disease in LDCs. But the priority is for poor countries to follow sound economic policies, thus raising living standards so that no country perennially needs to depend on donor charity.
- LDCs need continuing help to build institutional and intellectual capacity so they can avoid or treat economic, social, and environmental problems. In many instances this will mean bringing students from LDCs to study in U.S. universities. But increasingly, education of such students will take place in LDC institutions assisted by modern electronic communication with advanced institutions of education and research.
- Some environmental solutions must come multilaterally through international agreements—given the “free rider” problem[10] and the global consequences of air, water, and land degradation.
- One of the highest payoff policies is open international trade and investment markets. Freer trade in most cases pays off whether done unilaterally, bilaterally, or regionally, but is best done multilaterally. Nine recent and past studies reviewed by Huff, Krivonos, and van der Mensbrugghe (2007) predict that global international trade liberalization would add $12 billion to $155 billion (1997 U.S. dollars) annually to world income. Interestingly, the largest gains to developing countries come from liberalizing their own markets. Multilateral negotiations need to work toward farm commodity price and income support programs that, if used at all, give access by other countries to local markets and avoid dumping commodities abroad at subsidized prices.
- Sub-Saharan Africa and many other poor regions desperately need improved technologies to raise agricultural productivity. Although agricultural and environmental technology has been found to have a high payoff, poor countries (aside from notable exceptions such as Brazil, China, and India) do not have the economic means or political will to sustain the necessary research. Africa spends less than 0.5 % of its agricultural GDP on agricultural research, in part because countries do not recognize the high payoff from investing more and in part because they cannot afford more. Wealthy nations spend 2 to 4% of their agricultural GDP on agricultural research, a growing part of that by the private sector.

The United States and other developed countries do a great service by performing basic research, often with wide possible application. Considerable adaptive research development and dissemination are required to apply results of basic research to the disparate agricultures and environments of LDCs. Small developing countries especially need assistance in adapting basic research to local environments.

Falcon and Naylor (2005) document the alarming shift of international support away from agricultural research and development (R&D). Globally, the real value of R&D aid to agriculture in the late 1990s was down one-third from its level a decade earlier. The U.S. Agency for International Development cut its agricultural staff by more than two-thirds from its peak in 1990. The budget of the Consultative Group on International Agricultural Research (CGIAR) system—the institutional father of the green revolution estimated to have saved 1 billion lives—stagnated at approximately $350 million in nominal terms from 1992 to 2001, implying that annual funding fell in real terms. The CGIAR’s comparative advantage, which is its productivity-enhancing agricultural research, accounted for just one-sixth of its budget, and expenditures fell 6.5 % annually in real terms from 1992 to 2001.

Africa is a continent characterized by so-called “orphan crops.” Countries that grow these crops have limited resources and consequently do not adequately fund R&D; these countries are largely bypassed by the green revolu-

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[10] A free rider takes no action, expecting to benefit when other countries take needed action to protect the global environment.

tion. Agricultural R&D expenditures in these countries from all sources total only $1.5 billion annually. Given the high returns to public agricultural R&D, these trends imply missed opportunities that warrant reexamination of donor assistance priorities.

The “Next Green Revolution”

Future agricultural policy for this nation and, indeed, for all nations must include a strong commitment to science if the nations are to meet the coming challenges successfully. It is not sufficient to just understand the dynamics of the existing conditions and the factors that impact success; it is equally critical that agricultural policy identify satisfactory means of changing the dynamics based on information and knowledge. It is the responsibility of science to develop such information, knowledge, and technology through research to allow decision makers to make the changes that reflect the new realities of existing conditions. Dr. Borlaug clearly understood that science was a key part of agricultural policy to alleviate hunger in some regions of the world. That is why in his last writings he called for a “Second Green Revolution.”

Norman Borlaug’s work illustrates Thomas Edison’s maxim: “Success is 10 percent inspiration and 90 percent perspiration.” Beginning in Mexico in 1943, Dr. Borlaug—employing the latest developments in science and technology—used hard work, innovative techniques, and a great deal of perseverance to breed highly productive cultivars of wheat. The new cultivars led to increased productivity, personal income, and food availability for hundreds of millions of people in Mexico and South Asia from the mid-1960s to the 1990s.

Increases in population and rising expectations have nearly expended this enhanced productivity, and today the world awaits a renewed green revolution. Innovative, yet classical plant breeding played a central role in the first green revolution and will continue to be needed, but biotechnology that generates GMOs will have an increasingly important role in the second and future green revolutions. The following list suggests additional areas of ongoing scientific research that—if successful—will improve agricultural productivity worldwide. (More complete descriptions of these topics are provided in the Appendix.)

- Enabling C_3 plants to utilize the C_4 photosynthetic pathway
- Introducing nitrogen fixation in nonlegumes
- Incorporating the process of apomixis into crop plants
- Enhancing water and nutrition efficiency of crop species
- Developing processes for more efficient conversion of cellulose, hemicellulose, and lignocellulose to fuel
- Improving pest resistance in plants
- Improving energy efficiency of plants
- Developing commodities with increased health benefits
- Seeking new innovations

What is the Commitment to Agricultural Research to Bring about Another Green Revolution?

Evidence of the highly positive contribution of agricultural research to agricultural productivity growth is clear (Evenson and Gollins 2003). Hundreds of country-specific studies reported in professional agricultural economics literature (Alston et al. 2000) reveal a strong association between agricultural productivity improvements in a given year and spending on agricultural research and extension during the previous 30 years and more (Alston, Beddow, and Pardey 2008).

In an era of intense budget scrutiny, at issue is how to pay for research and development to improve the productivity of agricultural resources. This report offers no definitive answers, but opportunities for U.S. government budget savings are apparent (see Textbox 3 for examples). Just as Borlaug labored for 20 years before his wheat varieties were ready for widespread adoption, today’s support must be sustained for decades, to obtain high payoffs (Griliches 1964).

Since the green revolution of the mid-1960s, significant assistance has been directed at developing-country agriculture, growing from $4.7 billion a year in 1973 (in 2002 dollars) to more than $12 billion a year in 1983–87. Approximately 3% of that amount went to support agricultural research, both in national programs and through the centers of the CGIAR. Beginning at essentially zero in 1970, development assistance for agricultural research by developing-country governments reached $456 million in 1983–87 (Herdt 2009).

Textbox 3. Opportunities for U.S. government budget savings

Examples are the government programs to address instability, arguably the principal economic problem of commercial farmers. To address this very real problem, billions of dollars are spent each year on an array of fragmented and often redundant farm programs, including direct payments, countercyclical payments targeting mostly price, the Average Crop Revenue Election (ACRE) program targeting price and yield, the Supplemental Revenue Assistance (SURE) and ad hoc disaster assistance programs, marketing loans, loan deficiency payments, and myriad government-subsidized crop insurance programs. Consolidating these overlapping efforts into a cost-effective safety net could serve farmers while freeing billions of dollars to fund agricultural research and development.

From the mid-1980s until about 2000, however, development assistance to agriculture was drastically and steadily cut from $12 billion to $4.8 billion, back to approximately the level of the 1970s. Aid for agricultural research fell along with aid for general agricultural development. Funding for the CGIAR centers grew from their creation in 1960 to approximately $40 million in 1970 and further to approximately $300 million in 1988 and then grew slowly thereafter. United States aid to agriculture followed the same general pattern over time, making up between 9 and 14% of the Organization for Economic Co-operation and Development’s total. The sharp fall in aid to agriculture after 1992 is difficult to explain in terms of needs. Whereas there was evidence of vigorous agricultural growth in Asia by the 1980s, the opposite was true in Africa. Since about the year 2000, there has been a gradual increase in aid to agriculture and agricultural research.

Globally, in 2005, public agencies invested $23 billion in agricultural research annually, a 50% increase over the 1981 level. In the United States and other high-income nations, the development of deoxyribonucleic acid (DNA)-related tools and intellectual property rights has permitted a great increase in the precision with which the products of plant breeding can be identified (Herdt 2006), leading to a rapid increase in private investments in breeding crop varieties. In 2005, private companies invested $16 billion annually in agricultural research, essentially all (96%) in the high-income countries of the world. The CGIAR is, of course, focused on developing countries, and its investment reached approximately $400 million annually by 2004 (Beintema and Stads 2008), about 2.5% of what private companies invest in research in the more developed countries.

In 2009, influential voices advised the new administration to increase its development assistance for agricultural research and education for developing countries (Bertini and Glickman 2009). The Obama Administration did declare its intention to increase aid substantially to help millions of the world's poorest farmers grow enough food to feed themselves (Baker and Dugger 2009) and the leaders of industrialized countries, known as the G8, pledged increased aid to agriculture. The Bill and Melinda Gates Foundation is making substantial contributions to agricultural and nutritional research, particularly in Africa.

Even assuming these aid efforts are successful, the authors contend that the United States will need to make additional investments to raise the productivity of U.S. agriculture, given the almost unlimited demand for liquid biofuel that can be unleashed by policies designed to reduce oil imports and the possible effects of global climate change. During the period 1950 to1970, percentage growth rate of U.S. public agricultural research and development spending approached 4% per year. It was less than 2% during the next 2 decades and fell to approximately 1% during the period 1990 to 2007 (Alston, Beddow, and Pardey 2008).

Any country and industry would be remiss not to have a contingency plan for a future in which global greenhouse gas control has failed, for whatever reason. Policies "for all seasons" are a critical backstop for agriculture; they include research on genetically modified cultivars to resist heat and drought stress, infrastructure to facilitate farm input and output movement, and open trade so that food can move from regions of abundant supply to regions of diminishing supply due to global warming. Because cropland is less promising than land in trees for carbon sequestration and climate control (trees sequester 4 to 8 times more carbon than crops), a useful policy is to promote high crop yields to minimize crop area so that areas in forests can be retained and expanded.

CONCLUSIONS

Numerous factors are converging to make "the perfect storm" in global food and agriculture. While population growth rates are falling in most countries, global population is still increasing and national populations are expected to increase in many developing countries for the next several decades. Approximately 1 billion people in poor countries today do not receive enough dietary energy, and another billion do not get enough protein, fat, important minerals, or essential vitamins. In addition to those increasing demands for food from developing countries, developed countries are increasing their demands on agriculture for fuel and ecosystem services and to offset negative effects of technologies used in the current global industrial economy.

The United States has the land resources and the science capacity to equip American agriculture to meet a large portion of the coming challenges—if the nation takes the right policy steps. We must recognize that the era of living beyond our means is coming to an end, and the end of cheap, plentiful energy from petroleum is driving that demise. United States agriculture is being called on to supply much of that energy, but without substantial increases in research and development, those energy supplies will come at a huge cost. The potential may exist, but today's technology is not able to convert potential into usable energy at a reasonable cost.

Agricultural supply of conventional commodities is of concern as well. The global annual average increments in crop and livestock yields for all major commodities have stagnated or declined in recent decades (Tweeten and Thompson 2009). At current commodity prices, the opportunities to meet food demands without additional cropland and irrigation are constrained. Global warming threatens to decrease agricultural production, especially in tropical and subtropical regions where most poor people live.

The dire predictions of political economist Thomas Malthus have failed to materialize, but complacency is unwarranted given the many warning signs of tighter future agricultural supply–demand balance, rising real food prices, and the increasing role of agricultural commodities in meeting energy needs. The convergence of so many challenges at one time is unprecedented. Increasing the productivity of resources available to agriculture is critical. The typical lead time for investments in science and technology to raise agricultural productivity is 10 to 20 years; hence, delays in investment constitute a cost in foregone output a nation can ill afford.

Responding to needs is not solely the province of the President, Congress, industry leaders, and state governments. The public will have to actively support political action, particularly on such broad issues as global climate change, regulations on the welfare of animals in agriculture, natural resources, and investments in agricultural research and education.

The greatest concern felt by the authors of this paper is the apparent lack of commitment by the United States and other countries to make the research and education expenditures needed to address the problems affecting our survival on this planet. Agriculture can provide the food we eat, the feed for our livestock and companion animals, fiber for our clothes and homes, "flowers" for the environment, and the fuel we need—if we develop the needed information, knowledge, and technology through research and education. It will take a strong and constant public commitment to adequate funding. Indeed, we have no other alternative if we are to gain success.

APPENDIX

The following examples suggest areas of ongoing scientific research that—if successful—will improve agricultural productivity worldwide and could help to bring about the "Next Green Revolution."

Example 1. Enabling C_3 Plants to Utilize the C_4 Photosynthetic Pathway

There are two basic forms of photosynthesis. In one form, the first compound resulting from photosynthesis has three carbons (3 phosphoglycerate), hence C_3 photosynthesis. In the other form of photosynthesis, the first compound is a four-carbon compound (oxaloacetate), hence C_4 photosynthesis (Hatch and Slack 1966). C_4 plants such as corn, sorghum, sugarcane, and bermudagrass are much more efficient at fixing carbon (producing more biomass such as grain, straw, or root mass) than C_3 plants are. The unique structure of C_4 plants enables them to divide the reactions of photosynthesis between two types of cells. This mechanism greatly decreases photorespiration, a process whereby "fixed carbon" is released to the atmosphere. Given that some of the most important crop plants such as wheat, soybeans, and rice are C_3, the capacity to convert C_3 plants into C_4 plants holds great promise for increasing productivity.

Example 2. Introducing Nitrogen Fixation in Nonlegumes

Nitrogen fertilizers enable farmers to achieve the high yields that drive modern agriculture. The use of nitrogen fertilizer will continue to increase substantially as global population and food requirements grow. One of the most critical plant nutrients, nitrogen, alone comprises more than 78% of the atmosphere. Despite its abundance, nitrogen is not cheap when converted into a form useful to plants. Nitrogen fertilizer constitutes a major cost of producing crops such as corn and sorghum. Some major crops such as soybeans and alfalfa have the capacity to "fix" atmospheric nitrogen in a form that supports growth of the plant or, on decay, returns it to the soil profile for future crops. The symbiotic relationship of nitrogen-fixing bacteria in legumes that evolved through long periods of time is a complex process; however, finding a way to imbue nonlegumes to fix their own nitrogen would greatly stimulate productivity. Recent research in phytoplasmas could be a successful means of introducing nitrogen fixation in non-legumes by using the nitrogen-fixing mechanism of certain microbes that possess this capacity.

In addition to developing crops that can biologically fix nitrogen, research should focus on increasing the efficiency with which crops are able to mine nitrogen from the soil. Plants with this high extraction efficiency require less nitrogen and also decrease potential contamination of groundwater from nitrogen fertilization.

Example 3. Incorporating the Process of Apomixis into Crop Plants

The requirement of annual hybrid seed production can be circumvented by the process of apomixis, which is production of seed without fertilization by the male gamete in pollen grains, resulting in progenies identical to the seed-bearing hybrid plant. Hybrid vigor has enabled some crops to achieve an exceedingly high level of productivity as evidenced by hybrid varieties of corn. Unfortunately, the development of hybrids such as corn is expensive because of the requirements for planting different inbred lines to produce the hybrid seed every year. Without this annual reproduction of first-generation hybrid seed, productivity in subsequent generations would continually decline due to inbreeding depression. This practice would enable hybrid crop plants to maintain hybrid vigor at no additional cost (i.e., the annual hybrid seed production field is unnecessary if the hybrid plant is apomictic.)

Example 4. Enhancing Water and Nutrition Efficiency of Crop Species

Given the potential for global climate change, improving efficiency of production assets and improving plant and animal tolerance to adverse growing conditions and stress become important considerations. Several approaches are possible. For example, breeding plants with greater drought, heat, or submergence tolerance is a long-sought goal.[11] Water is an increasingly important factor in agricultural productivity in many regions of the world. There are estimates that 40% of corn crop losses are due to a lack of water (Boyer 1982; Boyer and Westgate 2004). Water will become a more serious factor affecting productivity with further progression of global climate change. Considerable research is under way that holds promise of conferring remarkable levels of drought tolerance to corn (Castiglioni et al. 2008; Nelson et al. 2007).

Soil salinity is one of the major abiotic stresses impacting agricultural productivity in many parts of the world. The problem is exacerbated by irrigating with water that has high salt concentrations. Two main approaches to improving crop salt tolerance are (1) developing more salt-tolerant cultivars through natural genetic variation either through direct selection in stressful environments or through mapping quantitative trait loci and (2) subsequent marker-assisted selection. Another approach is through the generation of transgenic plants to introduce novel genes or to alter expression levels of existing genes (Yamaguchi and Blumwald 2005).[12]

Recent developments suggest the possibility of sustainable bioenergy production through pyrolysis of biomass with the use of the biochar co-product as a soil amendment, which may increase nutrient and water use efficiency and enhance productivity especially for

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[11] An excellent example of overcoming stress is the recent identification of a tolerant-specific allele named Sub1A-1 and an intolerance-specific allele named Sub1A-2. Over-expression of Sub1A-1 in a submergence-intolerant species conferred enhanced tolerance to flooding in the rice genus *Oryza* (Xu et al. 2006). Introduction of the genetic material Sub1A-1 into current cultivars of rice gave these new varieties tolerance to submergence for up to two weeks.

[12] Salt tolerance in plants can be enhanced by increasing solute concentrations in the vacuoles of plant cells thereby increasing the vacuolar osmotic potential. This would result in a decrease of the cellular water potential such that it would favor water movement from the soil into the plants (He et al. 2005).

degraded and problematic soils (Laird et al. 2009).

Example 5. Developing Processes for More Efficient Conversion of Cellulose, Hemicellulose, and Lignocellulose to Fuel

It is becoming more commonly accepted that a portion of agricultural output will be used to produce readily usable forms of energy such as transportation fuels and bioproducts. Conversion of sugar to ethanol using yeast fermentation is one means of converting an agricultural product to a usable energy form. This conversion is done in Brazil using sugarcane and in the United States using corn (after hydrolyzing starch to sugar). A major research effort is under way to develop effective and efficient means of converting cellulosic biomass directly to transportation fuels and various bioproducts. This approach would permit the use of nonfood biomass and many types of waste that presently are not being used for productive purposes.

Example 6. Improving Pest Resistance in Plants

Considerable progress has been made in developing plants with resistance to certain insects and diseases. The *Bacillus thuringiensis* (Bt) gene is an excellent example, but only the beginning. This type of plant improvement alone will not bring about another green revolution, but certainly could contribute. Scientists must continue to seek new and novel ways of giving plants desirable traits, such as the use of phytoplasmas. Although infection of a plant by phytoplasmas often causes a disease, phytoplasmas have great potential for introducing genetic material into plants that can express a desired outcome, such as pest resistance. The classical means of incorporating new genes into plant cells is by using the bacterium *Agrobacterium tumefaciens*. Of course, in either case, the undesirable aspects caused by these organisms must be disarmed.

Another novel approach involves the development of a different mode of action by using a process called ribonucleic acid (RNA) interference (RNAi) by such organisms as Bt. This would be valuable for managing insect resistance. For example, ingestion of double-stranded RNAs supplied in an artificial diet triggers RNA interference in several coleopteran species, leading to larval stunting or mortality (Baum et al. 2007). Additional research in these approaches is warranted.

Example 7. Improving Energy Efficiency of Plants

Plants are quite inefficient in capturing energy from the sun. Calculations show that less than 3% of sunlight absorbed by the leaf is converted to chemical energy; frequently, it is less than 1%. This number is in contrast with photo voltaic cells (solar panels) that routinely capture 10 to 15% of light. With new technology in solar panels, efficiency may become even greater, up to 20%. Most crops capture light in the range of 400 to 700 nanometers (nm). On the other hand, throughout nature there are organisms that capture light from 400 to 900 nm. The light harvesting mechanism (grana) of crops could be improved through genetic engineering. Genes could be transferred to improve energy efficiency either by enhancing the light-harvesting capabilities or by expanding the wavelength of light being captured.

Example 8. Developing Commodities with Increased Health Benefits

Another means of enhancing agricultural productivity is by developing "better" commodities. This may include food commodities that have unique properties such as increased health benefits. Recent advances in several areas of basic sciences provide an optimistic basis for developing foods with unique and desirable properties such as a specific amino acid profile or particular antioxidants, vitamins, or minerals. Once such desirable traits are identified, they can be incorporated into an array of foods to meet dietary and ethnic requirements. Vegetables, fruits, and nuts especially contain many of the highly desirable nutrients and properties that contribute to a healthy diet.

Example 9. Seeking New Innovations that Offer Possibilities

In addition to the foregoing ideas that represent areas of ongoing research that could contribute to the next green revolution, the authors are quick to offer the possibility of other innovative ideas. For example, the emerging discipline of phonemics[13] could provide the basis of quantum increases in plant efficiency. Another promising technology is bioengineered algae that convert the carbon dioxide waste from coal-fired plants into biofuel. One of the greatest opportunities for powering the next green revolution is "farming the world's oceans." When considering the simple fact that there is a lot of ongoing photosynthesis in the oceans and recognizing the tremendous expanse of the oceans, it is not surprising that developing farming practices for ocean crops would provide a quantum increase in agricultural output. Although there are many approaches that could be considered, developing floating perennial crops that produce seeds or biomass holds great promise.

And researchers should not overlook the micro innovations that could bring about environmental adjustments that taken individually have only a modest impact, but combined can have a tremendous impact. These innovations include such things as improved tillage systems, better irrigation efficiency, new crop species, and more effective use of manures.

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[13] While genomics is the study of a genome of a given species and proteomics is the study of a species' entire complement of proteins, phenomics is that branch of science that integrates all available information into a holistic picture of the species. It is the systemic study of phenotypes on a genome-wide basis, usually implying a high-throughput approach of capturing phenotypes and associating those phenotypes with either genomic or proteomic differences.

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