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Science-Based Agriculture for Expanding Food Production and Sustainability

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Agriculture in this century will be challenged to feed at least 3 billion more people while reducing greenhouse gas emissions, protecting biodiversity, and improving rural well-being. Critics of modern agriculture contest the use of chemicals and biotechnology solutions and promote local, organic, "ecological" agriculture. This paper argues that science-based modern agriculture has been a major success, yet has its drawbacks. We recommend that agriculture pursue a "sustainable growth policy," blending local knowledge with modern science to develop solutions that recognize heterogeneity across locations and societies.

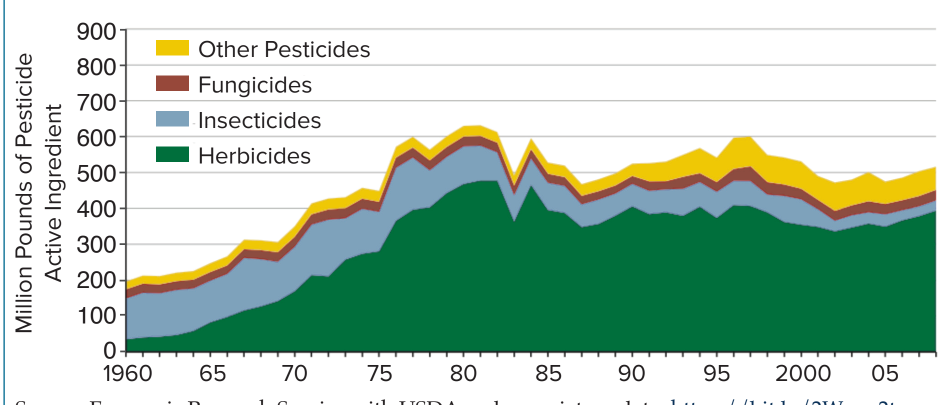
The world population has increased from about 1 billion people in 1800 to almost 8 billion people today. Per capita food production has also increased. Thus, it is remarkable that cropland has increased only threefold over that period (https://bit.ly/3BY1l1G). This has largely been due to increased yields per acre. For example, corn yields in the United States increased from about 20 bushels per acre prior to WWII to about 180 bushels in 2021. Increased reliance on science-based agriculture, including fertilization, mechanization, and improved crop breeding—i.e., hybrid, and later genetically modified (GM) varieties—has led to these yield increases. These improvements have been especially pronounced in the developed world, which has largely embraced these science-based methods.

Developing countries have also benefited from these modern technologies. The Green Revolution laid the foundation for increased food supply in Asia and Latin America; today Brazil and Argentina serve as breadbaskets for the rest of the world. However, corn yields per acre are still five times greater in the United States than in sub-Saharan Africa.

Modern agriculture has reduced land and labor inputs through improved knowledge, chemical inputs, and other innovations. Figure 1 shows that the use of pesticide active ingredients grew by 150% between 1960 and 2008, due in considerable part to the increased use of herbicides, which substitute for the back-breaking labor of manual weeding.

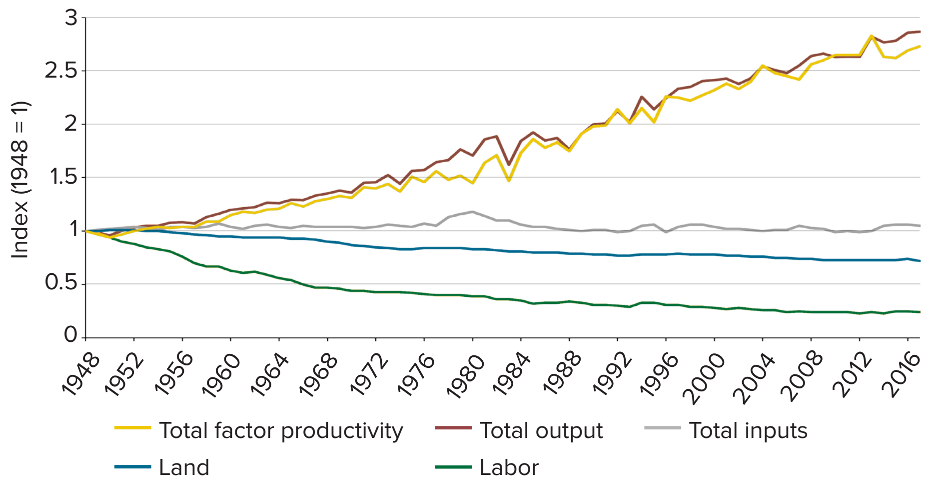
Figure 2 (on page 2) shows that U.S. agricultural output almost tripled between 1948 to 2017, and most of the

Figure 1. Pesticide Use in U.S. Agriculture for 21 Selected Crops, 1960–2008



Source: Economic Research Service with USDA and proprietary data. https://bit.ly/2Wxqy2t.

Figure 2. U.S. Total Factor Productivity Growth: 1948–2017



Source: USDA, Economic Research Service using data compiled from the National Productivity data series, 1948–2017.

growth was due to increased productivity. Overall land use declined slightly, and labor use declined by about 70%. The increase in productivity has contributed to more affordable food and improvements in the economic well-being of farmers.

Affordable food produced with less labor enabled the expansion of education around the world and provided resources to develop non-agriculture sectors. These developments contributed to the increase in life expectancy—three months every year on average—throughout the world. However, the progress associated with the modernization of agriculture has had significant negative side effects that we should recognize and address.

The Drawbacks of Modernization

The expansion of agricultural production to accommodate population growth has led to significant increases in agricultural land use, though at a much slower rate than population growth. This expansion has occurred the most in developing countries where yields per acre are smaller than in developed countries. Crop and pasture land expansion, along with increased chemical use, have contributed to significant declines in biodiversity. The Living Planet Index (LPI), a measure of global biological diversity, indicates that the monitored wildlife population declined by more than 60% between 1970 and 2016.

Freshwater species, particularly, have been harmed, with populations declining by 83%. Increased irrigation is one major contributor to the growth of agricultural production. However, its increased use has contributed to the tripling of global water withdrawal in the last 50 years, and this has harmed freshwater species. As Figure 3 demonstrates, the expansion of irrigated agriculture has led to overpumping, especially in Asian countries like China and India, but also in the United States; irrigated agriculture in these countries is unsustainable under current practices. On the other hand, there is significant potential for increased irrigation in Africa.

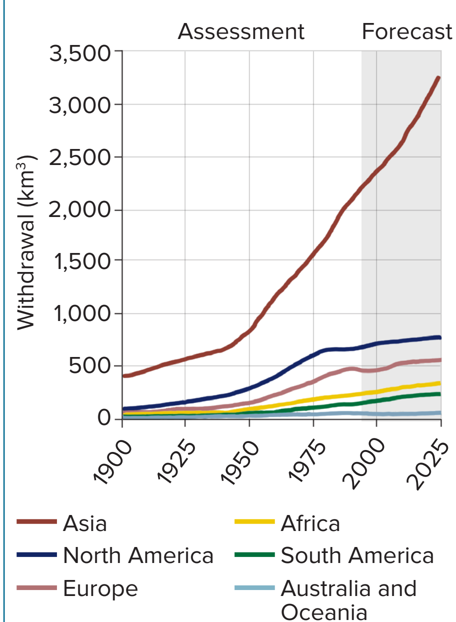
Agriculture is also a major contributor to climate change. Direct emissions from agricultural activities (e.g., livestock production, fertilizer, and energy) are responsible for 17% of annual greenhouse gas (GHG) emissions, while deforestation and other changes in land use contribute another 10%. Yet, agriculture has the potential to help alleviate climate change through sequestration of carbon by soil and trees.

Thus, while modern agriculture has improved the human condition immensely, it has also contributed to threats to human existence. The challenge now is to continue expansion of agricultural production, while curtailing its negative side effects. The literature on sustainable development provides a foundation for establishing sustainable agricultural growth.

Elements of Sustainable Development

The concept of sustainable development was introduced by the Brundtland Commission on March 20, 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Thus, sustainable development aims to balance growth with conservation. It expands traditional approaches to economic growth by taking into account the natural environment; these dual objectives provide economists the opportunity to apply broader policy-making frameworks that consider the

Figure 3. Global Water Withdrawal Trends



Source: United Nations Environmental Program, Vital Water Graphics, 2002.

Available at: https://bit.ly/3j9kPI5.

co-evolution of economic and natural systems.

Research has identified several factors that have contributed to increased agricultural productivity and economic growth. First is science-based technologies. Throughout history, most innovations were developed by practitioners. However, over the last few centuries, scientific discoveries by dedicated researchers have spurred technological innovations. Second is globalization and democratization. Free trade and the exchange of knowledge among nations, as well as the empowerment of individuals to pursue their ideas, led to the emergence of new perspectives and problem-solving approaches. Third is the blending of market forces with government action. Government support for basic and applied research and extension led to the emergence of innovations that were then commercialized. In California, as in other states, clusters of innovation have developed around universities.

The development of science-based technologies has several distinguishing features. First, it relies on facts and experimentation. Second, it takes calculated risks. Scientific theories are constantly tested and refined, yielding discoveries that lead to new and unproven ideas. These innovations may be risky. However, a precautionary approach that aims to avoid all risks will suffocate research and innovation. The challenge is to balance risks with benefits. Third, it is based on adaptive learning: that is, continuous assessment of a technology's performance, leading to its modification and improvement.

Modern technologies rely on understanding inner processes, including the workings of atoms, molecules, and, more recently, the cell and DNA. They aim to enhance input-use efficiency, or the amount of output per unit of input. Higher input-use efficiency reduces residues and pollution. The pursuit of input-use efficiency can lead to enhanced precision—with inputs applied more precisely where and when they are needed—as well as miniaturization, such as the advancements in computational power that enabled the transition from mainframe computers to personal computers. However, to be introduced and adopted, technology needs to be profitable to a supplier of equipment and users of the technology. Continuous investment in research, producing new technologies, and learning by doing, is likely to enhance their introduction and adoption. Government policies may affect profitability by financial incentives—e.g., rewarding the reduction of GHG emissions—or regulation.

Towards Sustainable Agricultural Growth

Attaining sustainable agricultural growth will require several adjustments. First, the introduction and adoption of precision systems must be adapted to agro-ecological conditions. For example, drip irrigation increases water-use efficiency, while adapting application rates to land quality and weather conditions. It has improved over time and has been utilized to apply chemicals. Its application tends to increase yields while reducing water and chemical use and leaching.

Diverse agricultural systems have begun to use precision technologies. For example, vertical farming produces high-value crops in urban settings, and plant-based meats reduce the agricultural land needed to provide high-quality protein. However, there is still great potential for developing precision technologies for evolving agricultural conditions that take advantage of improved remote sensing, information and communication technologies for timelier and more precise pest control and soil, plant, and livestock management.

Second, and related, is recycling. While precision systems aim to reduce residues from production activities, these residues are likely to persist. Technologies that enable the reuse and recycling of residues will reduce the environmental burden of agricultural activities. In California, as well as in Israel and Spain, there is an increased reliance on the reuse of wastewater, reducing the water constraint in these regions. Agriculture relies on non-renewable chemicals used for fertilizer and soil improvement. But increased precision, as well as recycling of waste products, will reduce the economic and social cost of these inputs.

Third is the use of renewable energy. Fossil fuels can be replaced by solar power, wind power, and hydropower. Solar and wind energy are land-intensive, and when appropriate, farms can incorporate the production of renewable energy with their other activities as part of a diversified farming operation.

Fourth is the bioeconomy—where biomass and living organisms are used to produce goods and services. The bioeconomy includes traditional agriculture, as well as farming of fuels, fine chemicals, and pharmaceuticals. The new bioeconomy relies on modern molecular knowledge and biotechnologies to produce foods and new materials. These new biotechnologies have been widely used in medicine (e.g., the production of COVID-19 vaccines).

Genetic engineering has been used in the production of corn, soybean, cotton, and papaya, among others. Biotechnology contributes to increased yields, while reducing the footprint and chemical inputs of agricultural production. But the use of biotechnologies in agriculture is constrained by government regulations. It is rarely used in food products, and it is effectively banned in Europe and many African countries. Genetic traits that improve nutritional contents of food and enhance photosynthesis have been developed, but their implementation has been stalled by regulatory barriers. New forms of biotechnology, in particular gene editing through CRISPR, have been introduced and are constantly improving. However, heavy regulation may restrict their use, especially in Africa, where biotechnologies can provide immense benefits.

Policy Reforms

Multiple studies indicate that with existing—and certainly with future—technologies, global agriculture is capable of meeting future food demands, reducing GHG emissions, sequestering carbon, and producing feedstocks for chemical, energy, and pharmaceutical industries. The challenge now is to introduce policies that will trigger the needed changes. Three types of policies are essential.

First is investment in research, education, and extension. The successes, as well as challenges of the modern world, reflect the outcome of development and application of scientific knowledge. However, support for public agricultural research is waning and is minuscule in areas that need it the most. Private and public research are, for the most part, complementary, and increased basic knowledge and innovation will trigger private sector investment.

The Consultative Group on International Agricultural Research (CGIAR) centers support much of the research in agriculture and natural resources for the developing world. These centers should be expanded to become world-class agricultural land-grant universities, combining research, teaching, and extension. Providing improved capacity to address climate change and food security are global public goods. Countries and non-governmental organizations in developed countries should invest in expanding capacity to develop and introduce science-based solutions in emerging nations.

Second is incentives to modify behavior. Reduction in GHG emissions, as well as pollution, will not occur unless firms have the economic incentives to adopt the appropriate technology. From an economic perspective, a carbon tax is ideal, but it is not easily implementable. However, with improved technological capacity and awareness, it is more likely to be implemented over time. Mechanisms like tradeable permits, as well as California's low-carbon fuel standards, have already triggered desired modifications in behavior and should be expanded. The "polluter pay" principle should be introduced and enforced to control pollution and waste, and the provision of ecosystem services should be rewarded.

Third is enlightened regulation. Current regulations of biotechnology, agricultural practices, and trade are major obstacles to the development and adoption of biotechnologies that can enhance sustainable growth. Regulation of various kinds is essential for the effective functioning of food systems. However, excessive regulations in the name of precaution have hindered progress, resulting in trillions of dollars of economic damages. The Philipines only recently approved commercial production of genetically modified "Golden Rice," after 20 years of regulatory delays that contributed to widespread misery and loss of lives. This outcome, we hope, is a good first step towards the future.

Conclusion

Humanity is challenged to address problems of climate change and food security, given the growing human population. We argue that science-based agriculture, supported by sound policies, is capable of meeting these challenges. The principles that we outline here are consistent with alternative agricultural paradigms. The notion of a circular economy and some forms of regenerative agriculture are consistent with enhancing input-use efficiency. Organic agriculture may also make a major contribution if it can incorporate modern biotechnology to replace chemical pesticides. However, some of the alternatives to modern agriculture, especially those that aim to reduce reliance on modern science, are counterproductive.

The United States, and especially California, are crucial to guiding the transition towards sustainable agricultural growth. Many of the fundamental innovations behind the biotechnology revolution started in the United States, where we have developed a tradition of collaboration between public universities and the private sector. These partnerships spawned new companies which are now launching the new bioeconomy. Hopefully California and the United States will continue to lead the way in transitioning the world to sustainable agricultural growth by investing in science-based entrepreneurship and research that supports the burdgeoning bioeconomy.

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For additional information, the author recommends:

Zilberman, David. 2014. "Fellows Address: The Economics of Sustainable Development." *American Journal of Agricultural Economics* 96, No. 2: 385-396. Available at: https://bit.ly/2X4BMvO.

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