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Science-Based Agriculture for Expanding Food Production and Sustainability

David Zilberman

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.

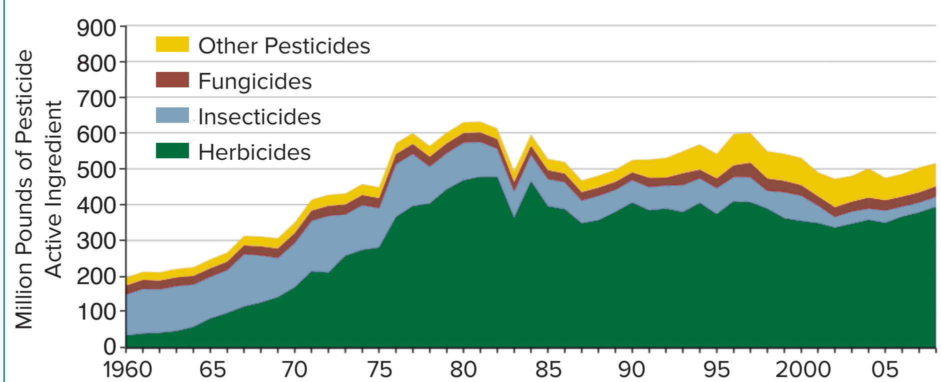
The world population has increased from about 1 billion people in 1800 to almost 8 billion people today. Per capita food production has also increased. Thus, it is remarkable that cropland has increased only threefold over that period (https://bit.ly/3BY1l1G). This has largely been due to increased yields 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.

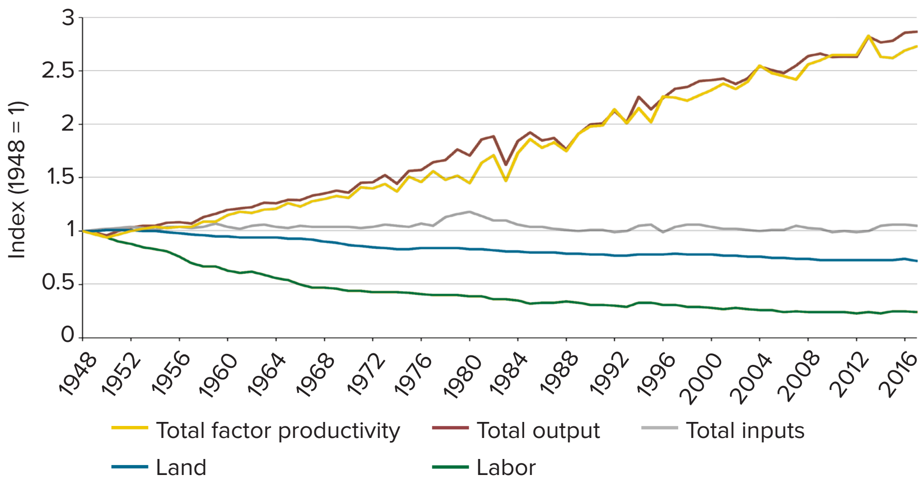
Figure 2 (on page 2) shows that U.S. agricultural output almost tripled between 1948 to 2017, and most of the

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.

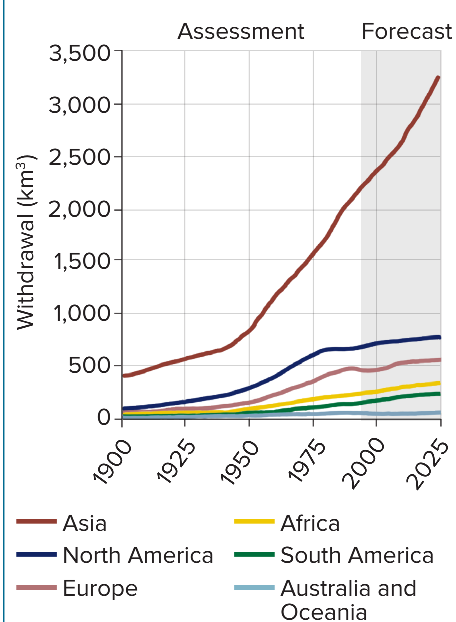
Agriculture is also a major contributor to climate change. Direct emissions from agricultural activities (e.g., livestock production, fertilizer, and energy) are responsible for 17% of annual greenhouse gas (GHG) emissions, while deforestation and other changes in land use contribute another 10%. Yet, 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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Author's Bio

David Zilberman is professor and Robinson Chair in the Department of Agricultural and Resource Economics at UC Berkeley. He can be reached at: zilber11@berkeley.edu.

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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Voter-Approved Proposition to Raise California Pork Prices

Hanbin Lee, Richard J. Sexton, and Daniel A. Sumner

California voters passed Proposition 12 in November 2018 to require more housing space for certain farm animals. We estimate that Prop 12 will cost California pork consumers about $320 million annually due to higher pork prices.

More than 63% of California voters supported Proposition 12 to set specific housing space requirements for covered animals, including egg-laying hens, breeding pigs, and calves raised for veal. Prop 12 applies to all farms that produce these covered livestock in California and to farms in other states with covered livestock connected to products ultimately sold in California. Some Prop 12 requirements were implemented on January 1, 2020, with the full set of requirements for breeding pigs and egg-laying hens to be implemented on January 1, 2022.

This article explains some economic implications of Prop 12 for the integrated U.S. and Canadian hog and pork markets, including implications for producers and consumers, especially those in California. We do not study the benefits to people—whether pork consumers or not, and whether they are in California or not—who value knowing that some breeding pigs will be in more spacious housing.

Prop 12 has no housing requirements for the fed hogs whose cuts of meat are consumed in California. Rather, Prop 12 housing rules apply to the mothers of those hogs.

Prop 12 covers all of the few breeding sows that are housed in California. But, crucially, Prop 12 will also prohibit sales in California of uncooked cuts of pork derived from pigs born from sows that are allowed less than 24 square feet of space each—except for a brief period around farrowing—no matter where those pigs are born. Pork products other than uncooked cuts of pork purchased in California are not included under Prop 12, nor is any pork mixed with other ingredients. California regulations do not apply to pork products sold outside California nor to the hogs that produce this pork.

Nonetheless, all participants in the pork value chain will be affected, at least to some extent, by Proposition 12. This includes farrowing farms, hog feeding operations, primary pork processors, secondary processors and packaging operations, wholesalers, retailers, and pork consumers.

To understand the impending implications of Prop 12 for the pork value chain, we administered written surveys and conducted in-person and telephone interviews with key personnel operating at various stages of the pork supply chain. Then, based on this input, we constructed an economic model of the North American pork industry (Canada and the United States) to assess the economic impacts of Prop 12. The model includes hog production, processing and marketing, and selling to consumers through retail and food service.

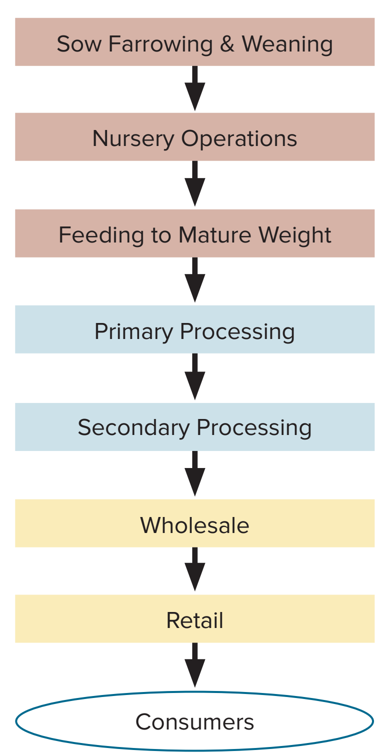
We find that Prop 12 will likely increase prices of uncooked pork cuts in California by about 7.7% and that California consumers will likely purchase about 6.3% less uncooked pork cuts as a consequence. California pork consumers will lose $320 million per year in economic benefits.

The North American Pork Value Chain

Figure 1 displays a schematic flow chart of the pork value chain. The first stage of modern hog production is farrowing, where breeding sows produce piglets that stay with their mothers for about 21 days before they are weaned. Prop 12 applies specifically at the farrowing stage, with a requirement per sow of 24 square feet of space, except during a few days before birth and a three-week period when piglets remain with the sow after birth.

Some farrowing operations, specifically those that already house sows in group pens rather than individual stalls, will have a cost advantage in converting their operations to be compliant with Prop 12. However, very few sows are currently housed in ways that are fully compliant with Prop 12's space requirements, so any farrowing operation considering converting to Prop 12-compliant housing faces substantial one-time costs. They will also face higher ongoing variable costs

Figure 1. The Hog/Pork Supply Chain



due, for example, to increased sow mortality, smaller litters, reduced rates of farrowing, and possibly, reduced feeding efficiency.

Proposition 12 will have little direct effect on nursery and hog feeding operations except, of course, that the pigs from California-compliant farrowing operations will be more expensive. These hogs must have their identities preserved, so that they may be segregated before shipping for slaughter.

Primary processors acquire market hogs mainly from their contract growers. They then slaughter the hogs and produce cuts and pork products sold directly to wholesalers, retailers, and food-service operators. They also sell pork to a variety of secondary processing operations.

Pork processors generate a variety of pork products, some of which are uncooked cuts of pork (e.g., bacon) that must come from hogs identified as Prop 12 compliant. They also produce pork products that do not require Prop 12 compliance. These include products such as ground pork and sausage, pork destined for cooked products such as lunch meats and fully cooked hams, pork used as ingredients in prepared foods such as hotdogs or pizza, and pork used in uncooked mixed products such as soups and meat mixtures.

Operations that sell to retailers will have to create new stock-keeping units (SKUs) for Prop 12-compliant products, imposing another fixed cost. To supply a full line of uncooked cuts of pork in California, processors will need to approximately double their number of SKUs in this product category. However, some respondents to our surveys indicated that the fixed cost to introduce a new SKU for each Prop 12-compliant version of a product would likely lead to reduced consumer choice in California because marketers would drop niche products from their California offerings.

Costs of Compliance with Prop 12

Given the size of the California pork market, only about 8–9% of North American sow housing, enough for about 0.7 million sows, needs to meet Prop 12 standards. About 30% of sows (2.2 million) were in group housing in 2020. Because the adjustment would be less costly for them, the farrowing operations that convert to meet Prop 12 standards will be among those that already have group housing. The one-time cost of conversion we considered applies to operations that now have group housing that does not meet the California requirements. We also compared ongoing operating costs for group-housing operations that would become Prop 12 compliant with those that remained non-compliant.

The most tangible increase in capital recovery cost per sow due to Prop 12 is from fewer sows using a facility. Based on data from the industry, we expect facility costs per sow to rise by about 20% to achieve an increase in space per sow from 20 to 24 square feet. In addition, instituting new electronic feeding and other innovations likely adds another 5% to capital costs. Given capital recovery is about 16% of the total cost, the 25% increase results in about 4% higher total costs.

Sow feed costs account for about 50% of the total costs to produce weanling pigs. Other variable costs, including labor, veterinarian services, and medicine, account for the final 34%. The main factors affecting incremental feed costs are that sow mortality is likely to be higher by about 2% and weaned pigs per sow are expected to decline by about 12%—partly due to sow mortality and partly because breeding becomes less efficient in a group setting. Overall, sow feed cost per marketed weanling pig is expected to rise by about 12% due to decreased sow fecundity, contributing a 6% increase in total cost per weanling pig.

Finally, we project that other variable costs will rise by roughly 15% because of spreading them across fewer weanling pigs and because of the need for more labor and health care per sow. These other variable costs add about 5% (0.34 X 0.15) to total costs. Combining the three categories yields a 15% increase (4% + 6% + 5%) in costs per weanling pig for California-compliant operations.

Using an average cost of about $33 per weanling pig gives a cost increase at the farrowing operation of 0.15 x $33, or approximately $5 per weanling pig. The cost of $5 per weanling pig implies a $5 increase per retail weight of 160.8 pounds of pork per pig, or about $0.03 per pound of carcass meat available for retail sales.

Additional Costs of Processing and Marketing Prop 12-Compliant Pork

The weanling pigs that leave farrowing operations move through the feeding stages to reach slaughter weights in about five months. Prop 12 requires that hogs destined for California are clearly identified so that the uncooked cuts of pork from these hogs can be segregated, labeled, and traced. Besides keeping identity preservation, there is no difference in how these hogs are housed or fed. Thus, any added costs during the feeding stages are small on a per-hog basis. However, they will likely incur higher transport costs to get their hogs to a processing plant that plans to supply Prop 12-compliant pork.

Given that California comprises only 8–9% of the market for North American pork, we expect that many primary processing operations (slaughter plants) will choose not to acquire the costly Prop 12-compliant hogs. These plants will avoid the added costs of identifying, segregating, tracing, and labeling the compliant pork separately from the rest of their production.

Those primary processing operations that do acquire and process the more expensive compliant hogs will incur additional costs to assure that they can sell this compliant pork into the California market. Pork that is destined for Prop 12-compliant cuts must be identified, segregated, and traced. The compliant hogs will be processed at different days and times from other hogs to assure that no non-compliant pork is comingled with uncooked pork cuts that are destined for the California market.

Even the most efficient scheduling plan will involve added transport, storage, and scheduling costs associated with processing California-compliant hogs. Such costs include having separate holding pens, more complicated and less flexible scheduling, interruption in plant operation between processing the compliant and non-compliant hogs, additional storage capacity so that the up-to-double SKUs of fresh pork can be kept in distinct lots, a more complicated labeling process, and more complex shipping of labeled products. The most costly among these factors is likely to be the interruption of plant operations and reduced throughput during the change-over from compliant to non-complaint hogs and pork. Our best estimate is that the additional cost is about $15 per compliant hog slaughtered.

We estimate, based on pending California Department of Food and Agriculture regulations, that about 58% of the retail meat from a compliant hog (93 pounds) will be subject to Prop 12 requirements. The added cost associated with processing is thus $15/93 = $0.16 per pound of Prop 12-compliant pork.

In addition to the higher costs incurred at the primary processing plant, other costs will be incurred for handling compliant pork throughout the downstream marketing chain. We estimate these costs to be about $0.05 per pound of Prop 12-compliant uncooked cuts of pork. Overall, we estimate the segregation, identity preservation, traceability, and other compliance costs, such as audits and registration, to be about $0.21 per pound of Prop 12-compliant pork products.

Wholesaling and retailing operations may also incur higher costs associated with Prop 12 compliance, mainly in the form of achieving segregation of compliant products in trucks and warehouses that serve outlets in multiple states and also for ensuring traceability of products and Prop 12 compliance of suppliers. California regulations include requirements for record keeping and reporting that have some compliance costs and risks of liability for potential errors.

We were able to obtain little direct information on the likely magnitude of these costs, so they consequently played no part in our analysis. Omission of these costs from our modeling means, however, that our estimates of impacts are likely conservative.

Economic Model of the North American Hog/Pork Market

The increase in market prices for hogs and pork products that are compliant with Prop 12 must be sufficient to reimburse participants in the various stages of the value chain for the initial costs they will incur to become compliant with Prop 12 and the higher ongoing costs they will incur to maintain compliance with it.

To understand how these higher costs to produce and market Prop 12-compliant pork would affect pork prices and sales in California and elsewhere, we constructed an economic model of the hog/pork market for North America. Our model includes specifications for consumer demand, farm supply, and conversion of live hogs to consumer products. We adapted key parameters from the scientific literature to specify the model and then calibrated it to actual 2018 values for the market. The model details are omitted from this brief article.

Key features incorporated in the model are: 1) only the farms and plants with lowest costs of supplying Prop 12-compliant pork will enter that market, 2) the full cost of compliance must be borne by the subset of products to which Prop 12 rules apply, 3) the costs of segregation and traceability throughout the supply chain add to the cost of compliance, and 4) competition within the supply chain will work to efficiently supply California, as well as markets outside California.

Estimated Impacts of Prop 12 on Pork Prices and Consumer Welfare

Our base case simulation involves the specific parameter values we consider to be most reasonable. Results are presented in Table 1 (on page 8). The model predicts that the average farm price equivalent of Prop 12-compliant pork will rise by 3.7%, or about $3.00 per hundredweight (cwt). However, it predicts almost no change in the price of noncompliant hogs or pork. Further, it predicts that the average price of uncooked cuts of pork in California (the regulated products) will rise by 7.7%, or about $0.25 per pound. Finally, our model predicts almost no change in the retail price of pork outside California or in the price of pork products not covered under Prop 12.

Our model suggests that the total quantity of live hogs will not significantly change because of Prop 12. However, the share of live hogs whose pork products are destined for California will decline from 8.8% to 8.3% of North American hogs. California consumers will eat 6.3% less of the regulated, uncooked pork cuts as a consequence of Prop 12. Quantity impacts for uncooked pork cuts for

Table 1. Impacts of Proposition 12 on Hog and Pork Prices and Outputs

Variable	Unit	Base	Prop 12	Percent Change
Prices				
Average price, all slaughter hogs	$/cwt	79.2	79.4	0.26
Price, hogs for California pork	$/cwt	79.2	82.2	3.74
Price, hogs for non-California pork	$/cwt	79.2	79.2	-0.04
Average retail price, uncooked pork cuts	$/lb	3.30	3.32	0.7
Retail price, California uncooked cuts	$/lb	3.30	3.55	7.7
Retail price, Non-California uncooked cuts	$/lb	3.30	3.30	-0.1
Retail price, non-covered pork	$/lb	3.79	3.80	0.1
Hog and Pork Quantity				
Number of hogs slaughtered	millions	145.0	145.1	0.1
Pork quantity (includes net exports)	million cwt	233.1	233.2	0.1
Quantity of uncooked pork cuts	million cwt	147.1	146.4	-0.5
Quantity of non-covered pork	million cwt	86.0	86.8	0.9
Share of hogs for the California market	%	8.84	8.33	-5.8
Retail Pork in North America				
Retail uncooked pork cuts	billion lb	11.95	11.88	-0.6
California retail uncooked pork cuts	billion lb	1.30	1.22	-6.3
Non-California retail uncooked pork cuts	billion lb	10.65	10.66	0.1
Retail non-covered pork	billion lb	8.55	8.55	0.1

Source: Authors' analysis based on survey and interview information and economic model results.
Note: cwt= hundredweight.

the rest of North America and for all other pork products, for which Prop 12 compliance is not required, will be negligible.

California pork consumers lose because they will pay about $40 million more, but that will buy much less pork. For the base model parameters, we project that the economic benefits for California consumers from buying uncooked pork cuts will decline by about $320 million annually, or about 7.4% of the initial expenditure on uncooked pork cuts.

The impact of Prop 12 on pork consumers in the rest of the United States and Canada will be very small because Prop 12 will cause only tiny changes to prices and outputs. We should note that our estimate of consumer loss does not account for the possibility that fewer pork products will be sold in California after the implementation of Prop 12 because it will not be worth the cost to introduce new SKUs for niche products.

Finally, we note that our model and simulation results do not incorporate impacts of temporary undersupplies or oversupplies of Prop 12-compliant pork caused by uncertainties about the needed adjustments to and resolutions of legal challenges. There is likely to be a transition period after January 1, 2022, during which markets will not yet have settled on the equilibrium price and quantity impacts. Christine McCracken, Executive Director, Animal Protein at Rabobank, cautioned us in the summer of 2021 that there is some concern in the industry that important and needed market adjustments are delayed, and that pork market disequilibrium and disruption may persist well into 2022.

Conclusion

In passing Proposition 2 in 2008 (https://bit.ly/37nI0ZJ) and Proposition 12 in 2018, California voters have shown their willingness to impose changes in housing for selected farm animals. What is likely to have been the last of the legal challenges to Proposition 12 was rejected at the end of July 2021 at the same time the state of California was finalizing details of regulations to implement Prop 12.

Advertisements in favor of Prop 12 depicted hogs, chickens, and calves confined in small enclosures. However, those farrowing operations that comply with Prop 12 will almost certainly come from farms that were already implementing group housing. Hence, Prop 12 will result in only slightly fewer sows in stalls and a bit more space for sows already in group housing. Thus, impacts on sow housing will be much more modest than claimed.

We estimate the cost of Prop 12 to California consumers is $320 million annually, through paying about 8% more for uncooked pork cuts and consuming about 6% less of that pork.

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Authors' Bios

Hanbin Lee is a Ph.D. Candidate and Richard J. Sexton and Daniel A. Sumner are Distinguished Professors, all in the Department of Agricultural and Resource Economics at UC Davis. They can be reached at hanbin@primal.ucdavis.edu, rich@primal.ucdavis.edu, and dasumner@ucdavis.edu, respectively.

The Outlook for California's Almond Market

Ellen M. Bruno, Brittney Goodrich, and Richard J. Sexton

The California almond industry has seen remarkable growth over the past couple decades. Can additional growth and high prices be sustained? We discuss expected changes in demand and supply moving forward, with implications for the success of California's almond industry.

California produces nearly all of the almonds grown in the United States and is also the world's dominant almond producer. The remarkable growth of the California almond industry represents perhaps the greatest success story in California agriculture in recent decades. California's bearing almond acreage expanded from 418,000 in 1995 to 1,250,000 in 2020. Production rose over this same period from 370 million pounds to a projected 2.8 billion pounds for the 2020–21 crop. With a farm production value of about $6.1 billion for the 2019–20 crop, almonds have vaulted to third place among California agricultural commodities, trailing only the dairy and grape industries. Both domestic and international shipments of California almonds have grown steadily from 2014–15 onward, with about two-thirds of the crop designated for export sales. The U.S. share of world export sales, which is dominated by California, also increased over 2014–18, and now stands at about two-thirds.

Such dramatic growth in the supply of an agricultural product would normally cause precipitous price decreases, and, indeed, many analysts have erroneously forecasted this fate for the almond industry. It has not happened, however. The grower price per pound fluctuated considerably from 2010–2015, ranging from a low of $1.79 per pound in 2010 to a high of $4.00 in 2014. It then settled into a very stable range in the ensuing years, with the price fluctuating in a narrow band of $2.39–$2.53 from 2016–2018 (Figure 1).

Prices dropped in 2020 to $1.83 per pound, an outcome we regard as an aberration due to multiple factors: trade disruptions and reductions in consumers' incomes caused by the COVID pandemic, trade disputes between the United States and key importing countries, as well as a record supply of almonds in 2020, due to the highest per-acre yields since 2011. Since the release of the USDA 2021 California Almond Objective Measurement Report, which projects a smaller crop than anticipated for 2021, almond prices have rebounded to pre-2020 levels. According to Merlo Farming Group, Nonpareil in-shell prices increased roughly 19% from $2.33 to $2.75 per pound between July 13, 2021 and July 18, 2021.

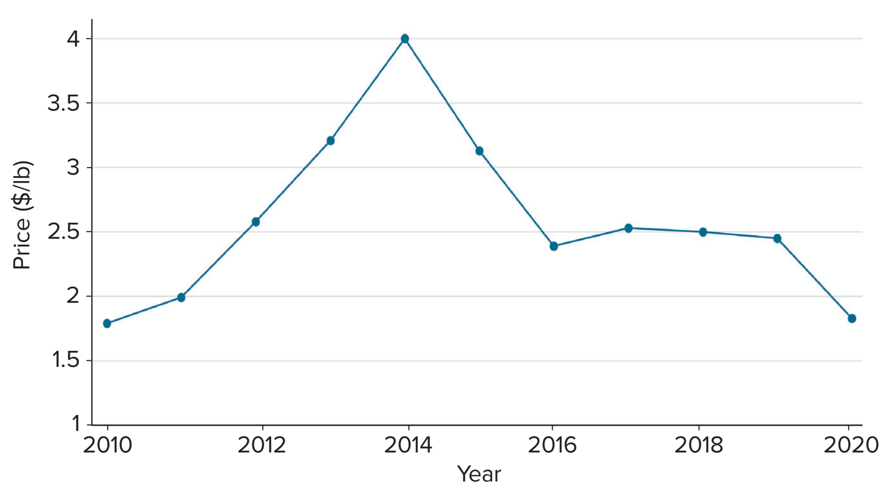
Despite the dramatic expansion in supply, prices have been relatively stable because demand has grown as fast as or faster than supply. Both domestic and export markets have experienced significant demand growth. Domestic shipments increased from 639.4 million pounds in 2014–15 to 774.3 million in 2019–20, an increase of 21.1%. Export sales expanded over this same period from 1,173 million pounds to 1,598 million, an increase of 36.2%.

Growth in Demand

Expanded sales in both China and India are key factors in international demand growth. Collectively, China and India account for about 35% of the world's population, and each country has experienced very rapid economic growth. From 2010–2019, China's annual GDP growth rate ranged from 6.1% to 9.5%. India's GDP growth rate in 2019 was 4.2%, but from 2010–2018, its growth rate ranged from 6.1% to 10.3%. By comparison, GDP growth for the United States from 2010–2019 ranged from 1.6% to 2.9%.

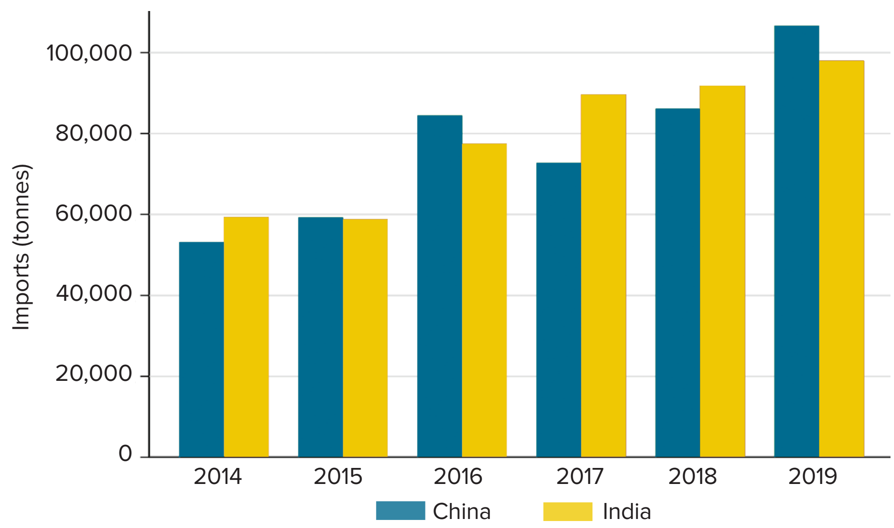
The rapid economic growth of these high-population countries has had a dramatic effect on world food markets. Consumers in both countries have sought to diversify their food

Figure 1. Real California Almond Prices, 2010–2020



Source: Authors' calculations using USDA NASS data.

Figure 2. Almond Imports, China and India, 2014–2019



Source: Authors' computations with UN Food and Agriculture Organization data.

Note: A conversion rate of 1.744 was used to convert in-shell to shelled equivalent tonnes (1,000 kg).

consumption and include more proteins in their diets. Almonds have been a primary beneficiary of these consumption trends, as illustrated in Figure 2. While world imports of almonds (shelled plus in-shell) expanded at a significant 42% over the six-year period from 2014–2019 based on UN Food and Agriculture Organization (FAO) data, almond imports to China and India (measured in shelled tonnes) expanded 106.7% and 69.6% respectively.

However, despite the dramatic increase in almond consumption in these two countries, per capita consumption in each (0.14 pounds in China and 0.16 pounds in India) is only about 6% of per capita consumption in the United States (2.33 lb). The Asia-Pacific market now accounts for 27% of California almond shipments. However, these consumption comparisons show that significant growth potential remains for almonds in these major markets, as well as for other emerging economies, as incomes grow and people seek to diversify their consumption beyond traditional staples.

Although the domestic (U.S.) and Western European markets—which have been the traditional leading markets for almond exports—are mature markets, there is also evidence of growth in these markets in recent years and potential for more growth in future years. As noted, domestic shipments of almonds expanded 21.1% over the last five years. The two leading Western European importers are Spain and Germany. Spanish almond imports expanded 32.5% in the past five years, while German demand growth has been much slower—3.5% over the past five years. Spain has historically been a major almond producer and developed a substantial manufacturing industry for almond products. As Spain's own production has waned, it has been necessary to import almonds to sustain these industries. Thus, growth in Spanish imports is both demand-based and also reflective of the decline in Spain's own production.

In addition, the almond industry benefits from the recent popularity of plant-based proteins as an alternative to traditional meat and dairy products. The Plant-Based Foods Association claims $7 billion in sales in the past year and 27% year-over-year growth in 2020. One market research firm, Grand View Research, predicts a compounded annual growth rate (CAGR) for almond milk of 14.3% through 2025 (https://bit.ly/36QC7nt).

Changes in Supply

Given the rapid growth that we anticipate in almond demand moving forward, fueled by economic growth in high-population, emerging economies and by new product uses for almonds, the remaining piece of the puzzle is to understand how supply is likely to respond moving forward. There are three essential components to consider: 1) acres of almond production in California, 2) California almond yields, and 3) almond production and exports from competing countries.

The USDA projects California bearing almond acreage to be 1,330,000 in 2021, an all-time high. However, signs indicate that the rapid growth in the California industry is abating. New plantings of almonds have decreased in magnitude each year since 2015—when 42,824 acres were planted to almonds—with only 14,808 acres planted in 2020. A common assumption in the industry is that an almond orchard has a life of 25–30 years, meaning orchards planted in the early to mid 1990s are nearing the end of their productive lives. The rapid expansion of the industry began during this period, with almond plantings from 1994–1999 averaging 25,316 annually.

The rate of new plantings experienced in 2019 (22,142 acres) and 2020 (14,808 acres), if representative of future trends, would not compensate for the acres that will be removed at the end of their productive lives, meaning that growth in California's almond acreage may soon be ending. Many factors could explain the decline in planting despite the industry's continued profitability, including concerns about access to irrigation water, a heavy reliance on the U.S. beekeeping industry for pollination services, and limited availability of lands suitable for planting almonds. California's Sustainable Groundwater Management Act of 2014 augurs likely cutbacks in groundwater availability for huge swathes of California's agricultural lands. Almonds are an especially "thirsty" crop and are likely to be impacted by these cutbacks.

Almond yields in California expanded dramatically in the 1990s, fueling the supply growth along with expanded acreage. Although yields have been variable, they continued, on average, to expand through the early 2000s, reaching a maximum of 2,540 pounds per acre in 2011. Since then, however, yields have stabilized and even may have trended slightly downwards. Declining yields are likely, in part, a result of a higher proportion of young orchards due to rapid acreage expansion from 2012 to 2015. Other potential contributors include changes to the growing-season climate and the planting of new acreage on land less suitable for almonds. Data for 2019 and 2020 indicate yields of 2,170 and 2,490 pounds per acre, 370 and 50 pounds less, respectively, than at the 2011 peak.

Exports of almonds from countries other than the United States have been stable over the past five years, with no apparent trend and, in total, represent only about half of what the United States exports. Traditional almond producers and exporters such as Spain, Iran, Morocco, Syria, Turkey, and Italy have aging, low-yielding trees and show little potential for expanded production. Today, production in these countries mainly serves their domestic markets.

The one country where almond acreage and production is expanding is Australia. The Almond Board of Australia (ABA) reports 55,000 hectares (136,000 acres) planted to almonds, with 2020 production totaling 111 thousand tonnes, the largest harvest to date. The ABA forecasts that Australian almond production could reach 175 thousand tonnes (385.8 million pounds) by 2026—approximately 13% of the 2020 California production.

Australia's almonds are mainly grown in the Murray-Darling Basin region, and over half of Australia's almond exports are to China and Hong Kong (which is a significant re-exporter). The Murray-Darling Basin is Australia's major agricultural region, but it faces many challenges due to a lack of water resources. Australia's Almond Board indicates that almond orchard expansion has slowed, and almond growers in the basin have called for a moratorium on further almond plantings in the basin due to fears of water shortages. Australia represents one of the only threats to California's hegemony in the market, but this threat is muted by water issues in the Murray-Darling Basin.

Concluding Remarks

Although market conditions for almonds deteriorated beginning in June 2019 due to the COVID pandemic, trade disputes between the United States and key almond-importing countries, and the exceptionally large 2020 California harvest, we do not regard any of these developments as reflecting a long-term trend. Normal yields and normal market conditions should cause prices to return to pre-pandemic levels; in fact, this seems to have occurred with recent rebounds in market prices.

In summary, market conditions are likely to remain strong for almonds moving forward. We anticipate continued significant growth in export sales driven by China, India, Vietnam, and other fast-growing emerging economies. The domestic market also has potential for solid growth based on the health benefits associated with eating almonds and the rapidly growing market for plant-based alternatives to meat and dairy.

We expect the growth in California's production to slow moving forward. Plantings have slowed to the point where, at the present pace, they are unlikely to match removals, as trees planted in the early to mid 1990s reach the end of their useful lives. The main threat for emergent competition in the export market is from Australia, but it appears that Australia's ability to expand production is limited due to water-scarcity issues.

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Authors' Bios

Ellen Bruno is an Assistant Cooperative Extension Specialist in the Agricultural and Resource Economics Department at UC Berkeley. Brittney Goodrich is an Assistant Cooperative Extension Specialist and Richard J. Sexton is a Distinguished Professor, both in the Agricultural and Resource Economics Department at UC Davis. They can be reached at ebruno@berkeley.edu, bkgoodrich@ucdavis.edu, and rich@primal.ucdavis.edu respectively.

For additional information, the authors recommend:

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Department of Agricultural and Resource Economics
UC Davis
One Shields Avenue
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Ria DeBiase
Giannini Foundation of Agricultural Economics
Department of Agricultural and Resource Economics
University of California
One Shields Avenue
Davis, CA 95616
E-mail: rwdebiase@ucdavis.edu
Phone: 530-752-3508

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