Chapter 17. Research, Innovation, Supply Chains, and Precision Agriculture in California

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Abstract

California agriculture has benefited from modern sciences through the educational-industrial complex where public research and extension introduce new innovations that are implemented by the private sector. Key features of modern agriculture are continuousinnovation and increased precision. Innovations result in new products and expansion of value-added provided by agrifood sector, and its implementation requires creative design of supply chains. Precision agriculture increases input use efficiency and reduces side effects. The efficiency of California agriculture is an outcome of public policy supporting research, regulating pollution, and providing education to California's agrifood sector. We highlight two cases of innovation: a process innovation, the management of powdery mildew in wine grapes, and a product innovation, precise irrigation systems, to show the transformation of research to product and adoption. We also show how new cross-sector technologies, such as remote sensing and information technology, as well as shifting consumer preferences, demand and accelerate innovation and development, especially in response to 21st century challenges.

Authors' Bios

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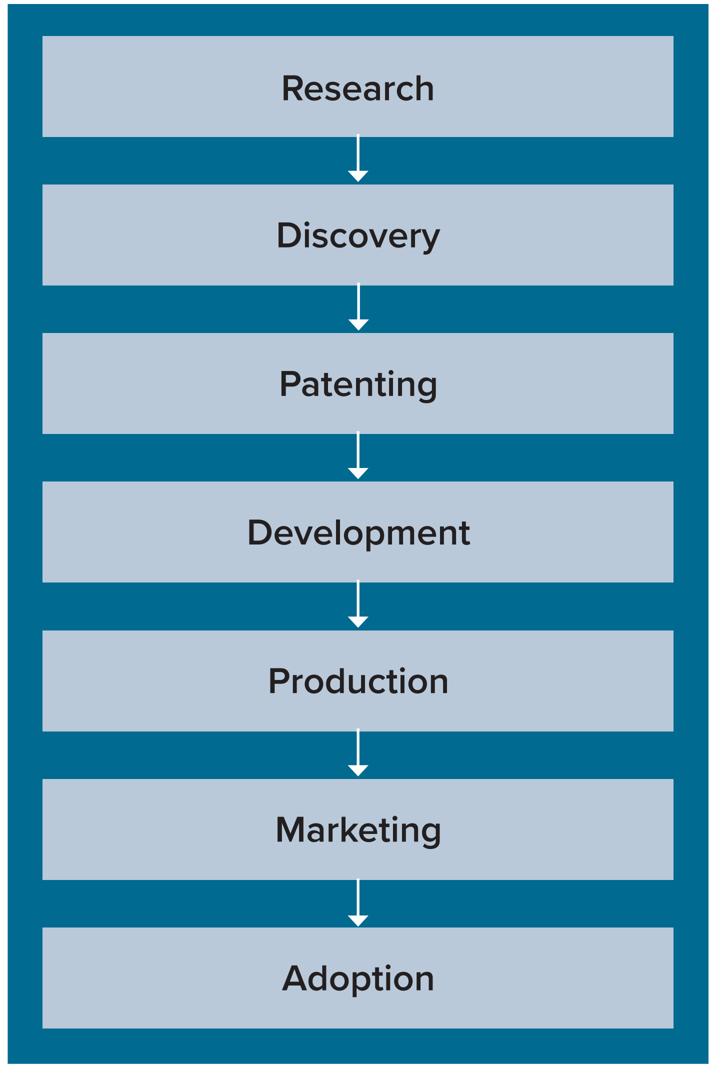
Introduction

California is known for its advanced agricultural sector, which, for more than a century, has utilized frontier knowledge to produce high-value products under adverse conditions. This chapter provides an overview of the linkages between research, innovation, technology adoption, and productivity in California agriculture. New scientific knowledge and technological capabilities have contributed to the emergence of new agricultural technologies. For example, the internal combustion engine eventually led to the introduction of mechanized innovations, breakthroughs in chemistry led to fertilizers and pesticides, and recent innovations in information, nano, and biological technologies increase productivity through increased precision.

The first part of the chapter highlights the importance of technology in California agriculture. An overview of the innovation process and the transformation of knowledge into applied technology in California agriculture will follow We will then assess the processes of technology adoption in California and their implications. We then assess the economics of precision agriculture. Finally, we overview the supply chain that transforms innovations to products. We finish with a conclusion.

Figure 1. Process of Research-Derived innovations



Innovation Supply Chain and the Educational-Industrial Complex

Innovations, which are ideas about new products, institutions, and location and processes of production, are often induced by economic conditions (Hayami and Ruttan, 1971). For instance, labor scarcity may lead to automation, and water scarcity may lead to advanced irrigation technologies. The large economic literature on innovation (Sunding and Zilberman, 2001) views innovation that leads to new technologies as a multi-stage process depicted in Figure 1. New technologies frequently start from an idea obtained through research or practice by practitioners, who have been supplanted in the past century by the educational-industrial complex. Innovations originate with university research and are often developed and commercialized by industry—a process that plays a major role in transforming California's economy and agriculture and provides a model for the world.

As Figure 1 suggests, research-derived innovations are frequently concepts proven on a small scale. These discoveries are often the source of intellectual property, which can be embodied in different arrangements for further development. Once a viable product is identified, a production system and commercialization strategy are needed to produce, market, and adopt the innovation. Of course, this is a schematic description, and the reality is more complex with an iterative process and often overlapping steps.

California's educational-industrial complex begins with research at universities and research institutes, funded by both the public and private sectors under public-private partnerships (Rausser, Amaden, and Stevens, 2016). For example, UC Berkeley had major agreements with British Petroleum to develop second-generation biofuels, and Mars has supported multiple research projects at UC Davis. Wright et al. (2014) show that this private research enhances valuable innovation.

The UC system uses several mechanisms to transfer technology to potential users. First, of course, is educating students whom, upon graduation, are employed by the industry. Graduates of the UC system embody knowledge and skills acquired at universities. University faculty provide consulting services and conduct contract-based work for the government, private sector, and non-governmental organizations (NGOs). Universities also register patents and transfer the rights to use them, as well as trade secrets, to the private sector and government.

Most research universities manage much of their intellectual property through an Office of Technology Transfer (OTT). For instance, the UC system has a portfolio of over 12,000 active inventions and has accumulated close to 5,000 active patents for various innovations including plant varieties.[1] Universities may receive compensation for the rights to use its patents, and a key objective of these offices is to ensure that university knowledge is impactful in the world (Graff, Heiman, and Zilberman, 2002).

In some cases, the innovations are transferred to major companies, while in other cases university researchers establish their own firm. These start-ups may then become major companies, or be acquired by established firms. In the life sciences, major California companies, like Genentech and Amgen, are manifestations of this educational-industrial complex. In agriculture, the University of California spawned companies like Calgene, which was then acquired by Monsanto, and Mendel, which holds major patents in agricultural biotechnology. One measure is the rate of return, while another is the location of biotechnology companies (94 percent are within 35 miles of a UC campus {King, 2007}). We see the emergence of clusters of companies around major research universities, such as Berkeley, Davis, San Diego, Riverside, Los Angeles, and San Francisco. Table 1 provides a partial list of agricultural biotechnology companies originating at UC campuses.

UC Cooperative Extension (UCCE) is a unique and important mechanism of technology transfer in California. UCCE includes specialists based on UC campuses as well as farm advisors in counties and research stations throughout the state. Extension professionals conduct applied research in collaboration with UC faculty, and provide information and technical assistance to major

1 https://www.universityofcalifornia.edu/infocenter/uc-inventions-glance

constituents that include government, NGOs, agribusiness, and farmers. Knowledge and information are key inputs for a successful agricultural sector.

Just et al. (2002) investigate the most important sources of information used by a sample of economic agents in California, Iowa, and Washington agriculture. They distinguish between end-users (e.g., farmers, processors, input suppliers) and information intermediaries (e.g., private consultants, extension, media). They also distinguish between primary data and knowledge (e.g., weather data, academic studies) and targeted information, as well as between formal information and informal information (word of mouth). They find that intermediaries rely more on formal information than farmers, and that 52 percent of information used by farmers is informal (mostly about production practices, reliability of suppliers, business opportunities, etc.). They also find that growers of specialty crops (e.g., tomatoes) with less developed formal information networks rely more heavily on informal information than farmers of major commodities (e.g., wheat).

Different intermediaries have different relative advantages. For example, the public sector is a major source of economic information (supply and demand, international forecasts) as well as of technological information. Commodity associations are especially valuable for regulatory information, while commercial vendors provide pricing information. Wolf et al. (2001) find that among intermediaries, extension provides the most informational value, as measured by the conversion rate of primary data to targeted information. Furthermore, while end-users perceive that only 30 percent of their information comes from public sector services, in reality it is 70 percent because private consultants and media rely on and transmit information from the public sector. Information provision is a crucial element of the last stage of the innovation process in the adoption of new technology or product by final users—be it farmers, agribusiness, or consumers.

Table 1. Companies Associated with University of California Campus Research

UC Campus	Company	Technology/Product
Berkeley	A/F Protein	Antifreeze proteins for control of cold-induced damage
Berkeley	Acacia Biosciences, Inc.	Biopharmaceuticals and agricultural chemicals
Berkeley	Berkeley Lights Inc.	Single cell annotation and genomics
Berkeley	Caribou Biosciences Inc.	CRISPR applications
Berkeley	Enable Biosciences, Inc.	Ultra-sensitive antibody detection
Berkeley	Molecular Dynamics	DNA sequence and analysis systems
Berkeley	Magnetic Insight	Clinical and translational research imaging
Berkeley	Ventria Bioscience	GM crop-based protein production system
Berkeley	20n Labs, Inc.	Engineered microbes
Berkeley	Juvenon	Supplements for energy and cellular health
Berkeley	Mendel Biological Solutions	Biological crop solutions to enhance yield
Berkeley	The Two Blades Foundation	Disease resistance in crops
Berkeley	GO2 Water Inc.	Reclaim water, energy, and nutrients from wastewater
Davis	Arcadia Biosciences	GM food crops to reduce environmental impact
Davis	AstRoNA	Pathogen ID with molecular biology and nanotech
Davis	AcenXion Biosystems	Polymerase chain reaction (PCR) systems
Davis	AimRNA	Improved RNA therapeutics
Davis	Circularis	Gene expression for crop and livestock traits
Davis	Glycohub	Production of complex glycans with enzymes
Davis	InnovaNutra	Stabilizer for food, supplements, and cosmetics
Davis	Inserogen	Repurpose tobacco plant for vaccines and therapeutics
Davis	Luminance Biosciences	Companion diagnostics and therapeutics
Davis	RF Biocidics	Elimination of food-related pathogens, pests, and fungi
Davis	Tule Technologies	Sub-field irrigation IT and monitoring
Davis	XTB Laboratories	Detection and response to agricultural disease infestations
Los Angeles	AvidBiotics	Proteins developed for therapeutics and livestock
Los Angeles	Aragon Pharmaceuticals	Treatment of hormonally-driven cancers
Los Angeles	ImaginAb	Antibody technology for in vivo imaging
Los Angeles	Lyxia	Microalgaue biofuel production
Los Angeles	Water Planet Engineering	Desalination and water resuse solutions
Irvine	Antigen Discovery Inc	Proteomic biomarker discovery and immune profiling
Irvine	Velox Biosystems,LLC	Food safety testing
Riverside	Biagro Western Sales, Inc.	Nutrient solutions for crops (Phosphite)
Santa Barbara	Apeel Sciences	Plant-based crop and harvest protection
Santa Barbara	Diagnostic Biochips, Inc	Biosensors for diagnostics
Santa Barbara	SerImmune	Diagnostics and therapeutics for autoimmune diseases
Santa Barbara	Spectradyne LLC	Nanoparticle analysis
Santa Cruz	Five 3 Genomics	Rapid sequence analysis algorithms
Santa Cruz	Two Pore Guys	Nanopore technologies for genome sequencing and diagnostics
Santa Cruz	Dovetail Genomics	In vitro method for long-range sequencing libraries

Source: OTT at each UC campus

Technology Adoption

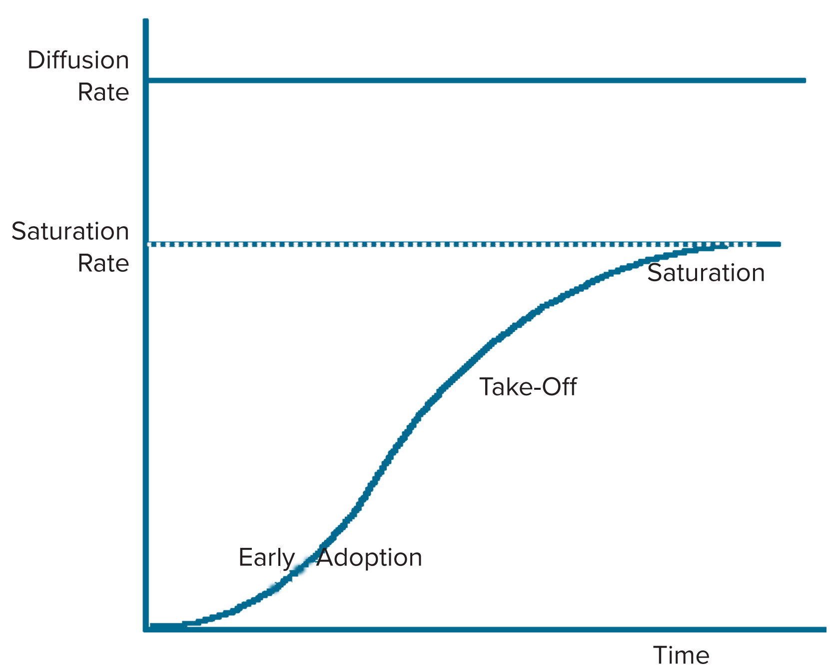
The literature on technology distinguishes between adoption (the uptake of a technology by an individual) and diffusion (measured by the percentage of users or land that use a technology). Early studies found that successful diffusion is an S-shape function of time (Figure 2), with a low adoption rate initially followed by a period of rapid uptake, and then plateauing during later stages of diffusion. There is another stage of dis-adoption of technologies and replacement by new ones. Initially, in the 1950s, adoption was modeled as a process of imitation, with few early adopters setting the way for a larger group of followers (Rogers, 2010). But the threshold model of adoption is a more complete framework (Zilberman, Zhao, and Heiman, 2012).

The threshold framework has three components. First, is individual behavior by farmers or consumers. In particular, it assumes that farmers pursue profit subject to risk and financial considerations, and consumers pursue benefits from consumption of goods and services, also taking into account risk and other constraints. The second element is heterogeneity among potential adopters. Some individuals are better positioned to adopt a technology than others. The third element is dynamic processes that include learning-by-doing by manufacturers that reduces the price of a technology, learning-by-using by adopters that increases the benefit and reduces the cost and risks of the technology, as well as network externalities where the benefit from adoption increases with the number of adopters (e.g., the internet).

Biophysical phenomena are another set of dynamic processes that may lead to adoption of technologies. They include pesticide resistance build-up leading to adoption of alternative pest control strategies, and depletion of groundwater leading to adoption of improved water management strategies. A good marketer is aware of these processes and will target a technology to the lowest hanging fruit. For example, a technology will be introduced first to regions where it will be most profitable and then move to other regions.

There are many applications that illustrate the threshold framework in California. In the case of mechanized innovation (e.g., laser levelers, combines, harvesters) the early adopters in California were large farmers, and firms that provided custom services allowing smaller farmers

Figure 2. The S-Shaped Curve of Adoption



to adopt the technology on a partial basis. Over time, consolidation of farms and the reduction of technology costs and risks led to increased technology adoption.

In the case of drip irrigation, major sources of heterogeneity were biophysical conditions such as water-holding capacity as well as the price of water and final product. Therefore, avocado growers in San Diego who were early adopters of drip, produced high-value crops on steep hills using expensive water. As drip irrigation became less expensive and more reliable, adoption moved to other crops and regions. While in 1985, 5 percent of California agricultural land adopted drip or micro irrigation, in 2014 they were used on 40 percent of land, including relatively low-revenue crops like processing tomatoes. The adoption of drip irrigation accelerated during periods of drought where the price of water was increasing and availability was declining, as well as during periods of high commodity prices (Taylor and Zilberman, 2016).

In the case of computers in agriculture, early adopters were larger farmers and packing houses that had access to a labor force with higher levels of education. Over time, use of computers became commonplace, and the intensity of adoption of computer software and applications in farming systems increased. Again, while some larger farmers adopt computerized management systems outright (e.g., irrigation scheduling), others rely on intermediary consultants that set-up and oversee these management systems.

In general, early adopters of pest control are located in regions with high levels of pest infestation. While diffusion of Bt cotton was intensive in the Mississippi Delta and areas of Texas with high rates of bollworm infestation, it was low in California where bollworm infestation is low. Alternative pest control strategies were introduced both due to regulations and build-up of resistance to chemical pesticides that increase the cost of their application and reduce their effectiveness. Weddle, Welter, and Thomson (2009) argue that resistance build-up and environmental constraints led to the gradual diffusion of biological controls and integrated pest management (IPM) in pear production in California over 50 years starting in 1960. Regulation of pesticide residue, the build-up of resistance, and the high cost of chemicals led to the adoption of IPM in other crops. University research and extension efforts that increase the effectiveness of alternative pest control strategies, diffuse information through media, and educate pest control consultants all contributed to the adoption of IPM strategies.

The availability of new technologies and improved production opportunities may lead to an expansion of the area where a crop is suitable and profitable. New technologies or other innovative arrangements may provide regions with newfound relative advantages in agricultural. Some of California's desert and water-scarce counties became world-leading agricultural regions because of large-scale water projects and modern irrigation technologies. Because of the favorable conditions of California, it has become a hub of organic farming. Meemken and Qaim (2018) find that organic farming tends to reduce productivity and increase costs. However, in some locations, the yield losses are relatively small, and the organic label can be a source for enhancing value-added from agriculture. In some moderately dry regions in California, the relatively low level of pest infestations and high level of human capital led to the adoption of organic practices, when the price premiums for production compensate for the extra costs and lower crop yields.

According to the United States Department of Agriculture's (USDA) 2016 survey on certified organic production, California had a million acres of certified organic farms, 20 percent of the U.S. acreage. A state focusing on high-value crops, California's income from organic production is about $2.9 billion, 38 percent of the U.S. total, and almost double its share in acreage. The organic sector has seen very rapid growth in recent years. According to previous surveys by the University of California, the 2016 figures represent an 80 percent increase in acreage and a 92 percent increase in sales value from 2012. California's relative agricultural strengths seem to be reflected in its organic production as well. In dollar value of sales, the state produces 95 percent of the total organic citrus, 87 percent of grapes, 84 percent of tree nuts, and 64 percent of vegetables.

Precision Agriculture

Precision agriculture is a set of technologies that are capable of adjusting input application to spatial or temporal variability at the micro level, which may be a specific field or farm operation (NRC, 1997). Both demand and supply factors contribute to the development of these technologies, and their introduction and availability became feasible as a result of improvements in remote sensing and communication technologies, improved computing power, and the emergence of big data and nano technologies. The demand for these technologies stems from the concern about climate change to reduce the footprint of agriculture, the expected growth in agricultural demand with population growth and rising incomes, as well as the emergence of the modern bioeconomy, where agricultural commodities serve as feedstocks for fuels, fine chemicals, and medicines.

Traditional labor-intensive agricultural technologies practiced by small farmers tend to differentiate input application within a field and sometimes treat every plant individually. Since the 1940s, however, developments in mechanization, increased labor costs combined with improved varieties, and low-cost chemical inputs led to the emergence of increased farm size and homogeneity in production with the uniform application of inputs at the field level based on average conditions, and thus ignoring micro variability (Sonka, 2016). For example, mechanized application of fertilizer using a conventional tractor would not vary across a field even though an incremental increase in inputs would increase yield in some segments of the field while reducing it in others. Precision technologies require investment in three elements: detection, assessment, and treatment.

Detection of variability within a field for, say, pest infestation or changes in soil quality and slope, has become feasible through alternative means of remote sensing, including satellites, airplanes, and now drones, and light detection and ranging (LIDAR) (Mulla, 2013). Monitoring results using fine-scale, time-dependent mapping of various biophysical conditions that provide an essential input for precision intervention and input application. Detection tools of precision farming allows the identification of plants, and especially livestock, as individuals and the ability to treat them accordingly. For example, they allow development of a personalized diet or medical treatment to each cow. However, assessment is needed to translate the detection to specialized treatment, as well as to determine the magnitude, timing, and distribution of intervention.

However, the computation of the intervention requires a decision rule that uses both principals of science as well as estimates of effectiveness of different responses under different conditions. Determining these estimates frequently requires advanced statistical techniques as well as availability and reliability of data. The reduction in the cost of computation and the emergence of big data, and new tools like cloud computing as well as machine-learning techniques, expand the range and quality of estimated treatment (Weersink et al., 2018). Farmers may be slow to use precision methods because of the difficulty of applying a prescribed treatment. For example, remote sensing may alert a farmer to a small-scale weed infestation within a certain field, and the appropriate remedy may be known. But the costs of applying treatment with traditional machinery may be prohibitive. However, with the availability of new means (such as drones) to apply treatments, precision treatment becomes more feasible.

Zilberman, Cohen-Vogel, and Reeves (2006) argue that adoption of precision agriculture methods increases variable profits (revenue minus cost of production), but requires additional investment and adoption occurs when the discounted risk-adjusted gain from added variable profit is greater than the investment cost. Precision agriculture, in most cases, tends to reduce variable input use and, in many cases, to increase aggregate output compared to conventional farming. In some cases, the input savings are substantial enough that adoption of precision methods would reduce the output of a field.[2]

2 For example, take a field where a portion of the land produces very little output and production requires a certain amount of fertilizer per unit of land. After the adoption of precision technologies, the farmer may not apply any fertilizer to the less productive portion, thus foregoing its small level of output, but will continue to apply input to the productive segments. So overall input use efficiency increases, but total output declines.

Furthermore, precision agriculture may also reduce pollution caused by excessive application of inputs. The average fertilizer use efficiency in North America is estimated at two-thirds. However, precision agriculture may greatly reduce both water quality contamination and greenhouse gas emissions (Weersink et al., 2018). Adoption of precision technologies is likely to increase when (i) the costs of variable inputs, such as fertilizer and water, are increasing, (ii) the price of output is increasing if precision raises output, (iii) stricter environmental regulations are introduced, and (iv) reduction in the cost of or increase in effectiveness of precision technologies. Tozer (2009) suggests that precision agriculture that allows better monitoring is likely to reduce farmers' uncertainty, which suggests that risk-averse farmers are likely to adopt it. Policies that provide credit availability or subsidies for adoption may further enhance the diffusion of precision technologies.

Some of the more recently developed agricultural technologies that have been heavily adopted in California, like IPM and drip irrigation, have strong features of precision technologies. The key feature of IPM is that, instead of a preventive application of pesticides on a pre-determined basis, the application level is adjusted for actual infestation levels or based on observed and forecasted indicators (e.g., humidity, temperature).

Figure 2 depicts the evolution of IPM as a concept that was introduced by UC researchers in the 1930s, and its use was enhanced significantly by increased concerns about chemical pesticides with the publication of "Silent Spring." Extension specialists operationalized and implemented this concept through the UC IPM program,, which combined research and extension in the 1970s. The program has grown significantly, and the use of modern information technology has enhanced its impact. The introduction of IPM requires investment in monitoring by scouts or equipment. One of the major contributions of the California Irrigation Management Information System (CIMIS) is actually in pest control. Its network of weather stations throughout the state and historical weather data provide information used for both when and how to intervene. Based on a few case studies, Schatzberg and Zilberman (2016) estimate that adoption of UC IPM contributes between $300-$500 million annually.

Figure 3. Timeline: UC IPM

- 1939 – Michelbacher writes "Recommendations for a More Discriminating Use of Pesticides," beginning a concept of IPM
- 1959 – Stern, Smith, van den Bosch, and Hagen outline sustainable pest control systems
- 1962 – Rachel Carson's "Silent Spring" published
- 1972 – Council on Environmental Quality defines IPM
- 1972 – First PCAs licensed
- 1976 – Environmental impact report required for hazardous pesticides
- 1979 – UC IPM founded
- 1979 – Center for Integrated Pest Management initiated
- 1980 – UC IPM first staffed
- 1980 – IPM manuals established
- 1981 – IMPACT system operational
- 1988 – 88 percent of growers own IPM manuals
- 1988 – PCA licensing exam study materials published by UC IPM
- 1988 – Farmworker safety training begins
- 1990 – IPM manuals for gardeners published
- 1994 – IPM website launched
- 2009 – Funding for competitive research grants ends

Source: Center for Integrated Pest Management (CIPM)

The adoption of the Gubler-Thomas Powdery Mildew Index (PMI) for preventing powdery mildew outbreaks on grapes is one example of the UC IPM technology that became a standard for managing the most costly disease affecting grapes. Grapes were the highest-value crop in California in 2016, with a farm gate value of about $5.5 billion. Powdery mildew management accounts for the majority of total pesticide applications (around 74 percent of total pounds of active ingredient) by California grape growers and a significant share of total pesticide use in

California agriculture (about 17%) (Sambucci et al., 2015). The pecuniary costs of managing powdery mildew depend on various factors such as the location of production and the end-use for the grapes, but these costs typically represent a large share of the total costs of production—in the range of 3–7 percent of the gross value of production in places where powdery mildew pressure is significant (Fuller et al., 2014).

PMI became available to growers in 1996, through a combination of private weather service providers, CIMIS weather station network, and personal weather stations, and is now ubiquitous as a part of any weather service or weather station software. The PMI is a temperature-based forecasting index that predicts the rate of reproduction of powdery mildew spores and recommends the corresponding fungicide spray intervals. In field trials, using the PMI to adjust spray intervals was shown to eliminate two to three applications of fungicides per year, a significant reduction both in the pesticide application costs and in the environmental burden from powdery mildew control (Gubler et al., 1999, Thomas et al., 1994). However, heterogeneity among the producers of grapes in California and the behavioral response to risk by growers came into play once the growers began adopting the index in commercial vineyards.

Recent work on the use of the PMI by grape growers suggests that growers not only adjust the spray intervals, but also the choice and dosage of the pesticide products. However, they may eventually use more sprays or higher dosage over the course of the year than the field trials suggested, and increase their costs of managing powdery mildew as a result (Lybbert et al., 2016, Sambucci and Lybbert, 2016, Sambucci, 2015). While there are no official data on the loss of crop due to outbreaks of powdery mildew, outbreaks are devastating. Outbreaks are most common in vineyards with highly susceptible varieties, such as Chardonnay, and in regions favorable to fungal disease (e.g., the Central Coast). Therefore, an increase in the cost of managing powdery mildew serves as a proxy for an increase in private benefits to growers adopting an improved powdery mildew management strategy.

The adoption of drip and micro-irrigation systems is associated with the increased use of adaptive water application based on monitoring of evapotranspiration (ET), temperature, and soil moisture. More precise application of water, as well as fertilizer and other inputs, contributes significantly to increases in yields in California, water savings, and reduced drainage. The additional income gain to California agriculture associated with adoption of drip and micro-irrigation is estimated to be between $313 and $1,130 million annually (Taylor, Parker, and Zilberman, 2014). In both IPM and precision irrigation, a significant portion of the gains is associated with the use of CIMIS and improved decision rules that are a major component of precision agriculture. It is important to note that UC Extension specialists and researchers contribute significantly to the development of IPM, CIMIS, and irrigation management formulas, which enhances the precision of California agriculture.

U.S. agriculture commonly uses some tools of precision agriculture, such as GPS-based technologies, yield monitors, and variable application rate fertilizer systems. Adoption of these tools had modest impact on farm income. Managerial challenges have limited their impact on productivity, crop biodiversity and farm structure. Furthermore, high capital costs and limited access to high-speed internet in rural regions continue to limit adoption of advanced features of precision agriculture. The rate of adoption of GPS technologies varies among regions and applications, reflecting both the gains from specific applications and socioeconomic factors. One advantage of precision farming is that it can reduce the cost of traceability. Detection of individual units within farms and linking of farming operations to information systems provide a good foundation to the introduction of traceability. As concern about food safety and consumer interest in the production and source of food increase, there is growing value to traceability (Weersink et al., 2018).

One of the major challenges of agriculture is increasing precision of pesticide application. Pesticide residue, which may contaminate water or harm beneficial organisms, tends to increase when pesticide use efficiency is declining. Precision agriculture that monitors pests, like weeds or insects, and applies treatment as needed is a major priority. Weed control is a major area of automation. One approach is the use of co-robots, machines that can augment humans in weeding, and some experiments have shown that they save more than 50 percent of labor (Gallardo and Sauer, 2018). More advanced technologies use "see and shoot" where a robot pulled behind a tractor detects noxious weeds and applies high-precision squirts of herbicide at the weeds, or pulled robots that detect weeds and remove them with a mechanized hand. One application of the see and shoot technology is the LettuceBot that is now used by 10 percent of California lettuce production (Simonite, 2017). Precision methods can play an important role in controlling pests in organic farming systems using permitted chemicals and mechanical approaches. Fennimore et al. (2016) introduced a weed robot that uses sensing technology to detect weeds and then mechanically eliminates them (i.e., a "weed knife").

Many plant metabolism processes depend on environmental factors, such as temperature and day length. For California pistachios, warming winters are threatening a successful, timely exit from dormancy, which is crucial for commercial output. Researchers in UC Extension have proposed a solution for this problem: treating dormant trees with a kaolin clay mix, which reflects sunlight and lowers effective temperatures in the tree buds. This approach, generally termed "Micro-Climate Engineering" (Trilnick, Gordon, and Zilberman, 2018), depends on constant weather monitoring. The actual temperature influence on the trees is not the mean winter temperature, but the more elusive metric of chill portions. These portions are accumulated only in hours where temperatures are within a certain range, and stop accumulating when daytime temperatures are too high. Thus, close monitoring of hourly temperatures, especially in the beginning of winter, is required to estimate the eventual chill portion count and set an optimal treatment schedule for orchards. Combining climate change predictions with a model of the pistachio market, Trilnick et al. assess the expected yearly economic gains from the kaolin technology by the year 2030 in the range of $1-4 billion.

Precision harvesting of fruits and vegetables is a major area of research and development of new technologies motivated by increasing labor costs as California and other states increase the minimum wage and see growing constraints on labor migration. The growing blueberry industry has relied on manual harvesting. Blueberries can be divided into processing and fresh products, where fresh require a higher-quality product regarding firmness, color, and nutritional content. Takeda et al (2017) suggest that there are several generations of blueberry harvesters that vary in their precision and ability to protect the quality of the harvested fruit. Automated harvesters are mostly used with processing blueberries, but California continues manual harvesting for its fresh blueberry industry.

However, new technologies that allow more precise discrimination of fruit and avoid catchment damage are being developed and are expected to improve harvesting efficiency by 10–20 times compared to hand-picking. There have been many attempts to automate the harvesting of citrus, cherries, and apples using robotics, but the design of robotics for harvesting systems is challenging because of complex tree structures and inconsistency of fruit size and maturity. Yet, harvesting systems are improving and are likely to be introduced first in fruit for processing and then in fruit for the fresh market (Gallardo and Sauer, 2018).

Mechanized harvesting has made some advances in grape vineyards in California. Growers of premium wine grapes are the most resistant to adopting this practice, partly due to the challenge of operating large machinery on the terrain characteristic of premium grape regions. Most of the grape acreage and production by volume is located in other areas of the state, and there harvesting is almost entirely mechanized. A recent estimate suggests that mechanical harvesting represents 85 percent of wine grapes in the state, and nearly 100 percent of lower to mid-priced grapes (Fichette, 2017). The main concern with mechanized harvesting, as with other mechanized practices in premium vineyards, is the impact of the technology on the quality of grapes and wine.

At a recent information session at the Unified Grape and Wine Symposium, the industry's largest annual event, growers from vineyards of varying price points discussed their experience with mechanization. In addition to mechanized harvesting, other operations such as mechanized pruning and shoot and leaf thinning are gaining momentum. These operations are a tougher sell with the growers of premium grapes partly because cultural practices have an effect lasting for more than one harvest season, unlike a harvester. Growers at Unified shared the belief that while mechanical pruning and harvesting are unattractive techniques, they do not negatively affect the quality of the crop or resulting wine.

Labor shortages, which drive adoption of mechanized practices for all growers, may be particularly costly to growers of premium grapes because it is difficult to schedule management operations or harvesting at preferred times. A mechanical harvester can work through the night with minimal crew, while a grower may be forced to harvest a week earlier or later than preferred based on the availability of a human harvesting crew. A week early or late may be an unacceptable variation in timing for a grower producing grapes for artisanal wine.

Precision agriculture also has major applications in livestock production. There are applications for automation of almost all processes in the dairy industry, from feeding to milking. In most dairies in California, cows are electronically tagged and many aspects of their health are monitored, which allows for personalized treatment regarding nutrition, breeding, and health (Edan, Han, and Kondo, 2009). The most important 21st century innovation in dairy farming is the milking machine. Northern European dairy farms utilize the majority of automatic milking machines, due primarily to high labor costs and weather conditions, but adoption in California is increasing. Research finds that adoption of milking machines reduces labor requirements overall, but shifts labor from milking to other activities and increases the freedom and flexibility of farmers. Adoption requires a minimum herd size to be profitable and the significant equipment costs are covered by labor cost savings, increased yield, and improvements in cow health.

The experience in Europe suggests that more advanced farmers tend to be early adopters and that there is significant peer group learning that benefits the gains from adoption and reduction of risk (in terms of labor availability). Automation and rationalization led to the concentration of production and reduced costs of egg, poultry, and swine sectors, and continues to improve with enhanced monitoring capabilities (Gallardo and Sauer, 2018). Concern for animal welfare is leading to modification of production systems in both swine and poultry sectors. But new precision livestock management technologies that include continuous monitoring of broilers' health through real-time sound and image analysis that can lead to an immediate response, aims to meet improved animal welfare standards and overall productivity (Berckmans, 2014).

Precision agriculture has been heavily integrated into vertical farming systems (farming indoors with multiple layers of production), which can be quite profitable in the production of high-value crops, such as microgreens and lettuce. Two San Francisco Bay Area companies have obtained hundreds of millions in investment and started to sell lettuce and greens in multiple cities, and the industry is set for a major take-off. Vertical farming emphasizes precise application of inputs, including the use of different light colors to affect the growth rate, taste, and appearance of products.

Vertical farming is a high-energy technology, but in locations with low-carbon electricity production, it may reduce greenhouse gases compared to outdoor growing. The technology is in its infancy and has much room for new technologies and interaction with existing ones (e.g., solar). For example, retail supply chains integrate vertical farming to capture consumer preference for freshness and local foods. Vertical farming also plays a role in food retail and distribution, which may lead to integrated food retail and vertical farming hubs for companies like Amazon and Walmart.

Product Supply Chain

Innovations have led to the development of new technologies, but implementation requires commercialization, production, and marketing. A product supply chain is a system of organizations that transform raw inputs to a final product for end-users. In traditional societies, food supply chains were rudimentary, where either farmers consumed food at home or sold it in the market directly to consumers. Farmers or consumers exerted most of the effort in this arrangement. In modern systems, the effort of producing food products and much of food preparation has shifted from the farmer and consumer to the agrifood sector.

Zilberman, Lu, and Reardon (2017) suggest that a simple agricultural supply chain includes input suppliers that provide the inputs to farmers that produce agricultural feedstocks, which is then processed and distributed to wholesalers and retailers. Innovations are new ways of doing things, and may include new products, new production methods, or new locations to produce a product. One of the challenges of an entrepreneur that controls a technology is to design a product supply chain to capture profits adjusted for risk from their innovation.

One of the major features of agricultural food systems is the transition from commodities to differentiated products, and the increased reliance on contracting and vertical integration to capture benefits from new innovations. Contract farming represents a majority of specialty crop production. There has been major consolidation of the poultry and swine sector, either through vertical integration or a contracting relationship between a major corporation and farmers (MacDonald, Korb, and Hoppe, 2013). As production technologies become more science-based, the processors who purchase feedstock from contracted farmers will provide physical inputs, and/or direct production specifications, and monitor farmers' activities.

Over the past 50 years, poultry processors, such as Foster Farms, automated distribution of feed to animals and are producing a diverse set of final poultry products that enhance convenience and nutrition. Despite progress in automation of meat processing, it still heavily relies on physical labor due to a large extent on the inherent biological variation and complexity of animals.

California has been the hub for animal-free meat, an industry that aims to address environmental and animal welfare concerns and ultimately reduce the cost of meat. Animal-free meat consists of animal tissue fabricated using improved molecular biology and tissue engineering technologies. Burgers fabricated by Memphis Meats (San Leandro) and Impossible Foods (Redwood City), companies that rely on UC and Stanford research, are already sold in restaurants. Finless Food (San Francisco) is applying the same concept to seafood. Their workspace and finance, in part, are provided by IndieBio, which is a major seed biotechnology business accelerator.

These companies are part and parcel of the educational-industrial complex as university research, knowledge, and inventions provide the foundations for new enterprises that either result in major companies or they are absorbed by existing agribusinesses. Animal-free meat increases input use efficiency of meat production by reducing significantly the amount of grains, energy, and other inputs needed to produce meat products, thus reducing land use and greenhouse gas emissions associated with livestock and improving food safety (see survey by Bhat and Bhat, 2011).

The value-added of fruits and especially vegetables have benefited significantly from science-based innovations that increase convenience to consumers. A key example is prepackaged salads introduced by Fresh Express. The chief scientist was Jim Lugg, who started as a UC Extension specialist. Bruce Church, a major vegetable grower, wanted a technology to lower the instability of lettuce market prices and increase the value of the product by increasing shelf life, increasing the convenience of preparation, and reducing consumer waste. Development of prepackaged salads was built on research from UC Davis, Cornell, and other universities on the atmospheric parameters for extending the shelf life of fruits and vegetables, and adapted the controlled-atmosphere technology developed by Whirlpool for shipping fruit. Lugg and his team, in collaboration with UC scientists and graduates, calibrated the parameters of gases that allowed for preservation of vegetables for more than 10 days.

Pursuing a strategy of "relentless innovation," the team first developed prepackaged lettuce for restaurants, and soon realized that consumers would pay premium prices for prepackaged salads. Bruce Church, Inc., faced a dilemma: vertically integrate their supply chain or establish contractual relationships with suppliers. To achieve economies of scale in processing, Bruce Church, Inc., sold the farm and established contractual relationships with networks of farmers to provide the vegetables to processing facilities around the U.S., and to add salad dressing and other condiments. Today, Fresh Express produces over 400 types of mixed salads. Overall sales of prepackaged salads in 2016 reached $3.7 billion. While iceberg lettuce was a dominant lettuce variety in the 1970s, romaine, kale, spinach, and other leafy green varieties are now more prominent. Furthermore, the introduction of packaged salads reduced uncertainty to farmers because they were assured a price through contracts rather than depending on variable prices in the spot market (Lugg, Shim, and Zilberman, 2017).

Consumers have a choice between eating at restaurants and eating at home. Improvements in storage, as well as increased precision in inventory and temperature control, allow for access to fresh food products throughout the year. Kimes and Laque (2011) surveyed 326 U.S. restaurant chains and found a gradual adoption of electronic ordering by consumers. This technology reduces transaction time and increases sales but may increase peak time load. Restaurant chains, like San Francisco's Eatsa, are introducing a labor-saving, information-intensive innovation. They buy highly processed foods (e.g., prewashed and precut vegetables and fruit and precut and seasoned meats) assembled by robots to provide customers with a customizable menu of meal options (Gallucci, 2016). U.S. consumers still eat roughly 80 percent of their food at home. Supermarkets, which have introduced automation and precision to their inventory management, are now experimenting with reducing shopping time by nearly eliminating the check-out process.

Amazon is experimenting with using automated monitoring of consumer selection from shelves and charging consumers' accounts. Improved communication technologies, including data storage, and development of computer-aided logistics reduce the cost of shipping. This cost may be further reduced with the adoption of autonomous vehicles. Finally, automation enables expansion of food delivery from restaurants, including new innovations for the provision of on-demand food at different degrees of preparation. Some companies offer subscription meal kits, such as Blue Apron and Sunbasket, with predetermined delivery dates. These companies contract with farmers, maintain their own preparation service, and develop optimized delivery strategies. Recipes are a key asset of these companies, which enable consumers to cook gourmet food at home. These automated and individualized food channels are in their infancy, and are likely to diversify and improve over time. California agriculture and Silicon Valley play a major role in both providing the raw materials as well as the software and hardware used by these companies.

Conclusion

The transformation of agricultural food systems has resulted in more diversified food products and more channels that provide food to consumers. The interplay between researchers generating basic knowledge, entrepreneurs creating supply chains to commercialize and scale innovative products, farmers adopting and refining technologies, Cooperative Extension refining practices, and consumers providing feedback have all contributed to this transformation. The ability to address concerns like climate change, a growing population and increasing demand, both in scale and scope, will rely on the ability of agriculture to continue its transformation. This paper shows how precision agricultural technologies addressed certain challenges in California, increased productivity in some crops, and provided new opportunities for growers, processors, and consumers. Generally speaking, all aspects of agriculture, in California and elsewhere, can benefit from this process of translating research to new products and processes.

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