

# The Diffusion of Process Innovation: The Case of Drip Irrigation in California

**Abstract:** This article uses drip irrigation to illustrate the evolution of process innovations during their diffusion—undergoing several waves of improvements and coevolution with other production practices in order to move across applications and locations over time. First we integrate multiple data sources to trace the rich history of drip in California. We find that drip's evolution has been consistent with 1) the threshold model, which emphasizes the tendency to first adopt a technology at locations where it is most valuable and 2) the real option value model, which suggests that crisis situations trigger major transitions. We highlight the role of the private and public sector in adapting process innovations to local needs and show the necessity of historical analysis and perspective in assessing a technology's impacts. Second, we empirically investigate the productivity impacts of drip irrigation in California, focusing on changes in crop yields and farm income. We estimate a yield effect of drip ranging from 16-48%, depending on the crop and location, and an increase in farm income between 2.6-7.4% annually. On whole, we show that the diffusion of drip was gradual, Cooperative Extension was essential, and the gains for California agriculture were substantial.

**Keywords:** Process innovation, Technology diffusion, Drip irrigation, Historical analysis

**JEL codes:** Q16, N52

Innovation, adoption, and diffusion have long been studied as important determinants of economic growth. One category of innovation is the *process innovation*—the implementation of improved production methods that may be embodied in new technologies or procedures. Process innovations, while not necessarily impacting attributes of the final product, generate benefits in the production process such as increasing productivity and decreasing costs. David (1990) argues that diffusion of process innovation evolves within and across sectors and emphasizes the importance of historical studies in understanding them. He demonstrates his approach comparing the diffusion of the computer to that of the dynamo 100 years earlier. Olmstead and Rhode (1995; 2001) also take a historical perspective on the diffusion of two mechanical process innovations—the reapers and the tractor in the U.S. during the 19<sup>th</sup> and 20<sup>th</sup> centuries—and show how the technologies, as well as markets and institutions, evolved to facilitate diffusion. This article aims to expand this literature by focusing on the diffusion of drip irrigation—a process innovation which enhances water use efficiency compared to traditional flood and furrow irrigation systems. Concentrating on drip irrigation in California, we examine how diffusion of a technology undergoes multiple waves of improvements and coevolution with other agronomical practices. We highlight the role of the private and public sector in adapting process innovations to local needs and show the necessity of historical analysis and perspective in assessing a technology’s impacts. Lastly, given that the adoption of process innovations is often motivated by growth in productivity, we empirically estimate the impact of drip irrigation on crop yields and net farm income in California.

Drip irrigation conveys water to plants through a network of pipes and emitters, and allows slow and controlled application of water. It is more capital intensive than traditional irrigation technologies, but allocates a smaller volume of water per unit of time with higher

precision. Modern drip irrigation was first introduced in California in the late 1960s. By 1988—a little over 20 years later—it was adopted on only 5% of irrigated land. Yet fast-forward another twenty years and by 2010 over 40% of the irrigated land in California is irrigated using drip systems (Tindula, Orang, and Snyder 2013). Having spread across diverse crops and regions in a non-linear trajectory, drip irrigation is a prime example of a process innovation whose diffusion, as we will show, is explained by the theory laid out in the threshold and the real option value models.

We focus on drip irrigation for three reasons: First, drip was selected as one of the major success stories over the last 100 years by an informal survey of California County Directors. Second, it is timely to study a technology whose adoption has been shaped by droughts during a period with a severe California drought. Third, it is first study of this kind for a technology that aims to conserve a natural resource (water) and the lessons of its diffusion may apply to similar technologies.

This article integrates multiple data sources in order to trace the dynamics of the diffusion of drip irrigation over time. We begin by summarizing the conceptual background on technology adoption and diffusion. In particular, David (1966) introduced the threshold model of technology diffusion, which—in sharp contrast with imitation models of adoption—argued that adoption is an explicit economic choice. However, a shortcoming of much of the conceptual literature on the threshold model is the lack of explicit consideration of the coevolution of the technology and complementary production processes and the contribution of private and public sector to this coevolution (Olmstead and Rhode 2008). For a process innovation to be widely adopted among potential users the technology may require adaptation to the needs of heterogeneous clientele. Furthermore, the other components of production (fertilizing, seeding) may require adaptation to

the new technology. In agriculture, this coevolution often involves joint efforts of the private and public sector. Given the vital, and often neglected, role of public sector R&D in the diffusion process, we pay particular attention to institutions (i.e. Cooperative Extension) and the complementarity of public and private efforts that affect the direction of diffusion.

Second, we outline the evolution of drip irrigation in California and highlight the linkages between empirical evidence and theory. To construct the narrative we rely both on existing literature and personal interviews with Irrigation Specialists and Farm Advisors who were influential in drip's diffusion in California. With these first-hand accounts, this narrative offers a unique compilation of published works and previously undocumented oral histories.

Third, we juxtapose our historical analysis of drip's diffusion in California with an empirical analysis of the effects of drip irrigation on crop productivity (namely, the yield effect) and farm income. One major concern about process innovations has been quantifying their impact on productivity. For instance, David (1990) pointed out that the popular phrase, "computers are everywhere but in the productivity statistics," could have been said also for the dynamo 100 years prior. Since we also find that drip irrigation appears to be everywhere in Californian agriculture today—with broad adoption across locations and crops—we ask whether the value of drip irrigation adoption can be quantified in the productivity statistics. In particular, what has been the effect of drip irrigation adoption on crop yields? We focus on quantifying the yield effect because it is one of the most discussed and often unexpected advantages of adopting drip irrigation. Our empirical research design endeavors to answer whether the benefit of a positive yield effect can be quantified (1) by surveying the published agronomic literature on the yield effects of drip irrigation, and (2) by employing two distinct panel datasets on drip adoption in California to estimate correlations between adoption and yield. We then use our estimated

yield effects to perform back-of-the-envelope calculations of drip's effect on California net farm income from crop production. Specifically, we estimate a yield effect of drip ranging from 16-48%, depending on the crop and location, and an increase in the earnings of crop production in California between 2.6-7.4% annually.

This article analyzes the history of drip irrigation in California to provide 1) a conceptual framework for understanding the evolving diffusion of a process innovation and 2) estimates of the value of process innovation adoption and diffusion. We show that the diffusion of drip was gradual, Cooperative Extension was essential, and the gains for California agriculture were substantial.

### **Literature on Adoption and Diffusion**

There is a time lag between the introduction of a technology and its use. *Diffusion* is the process by which a technology is adopted over time. At any given period, diffusion is measured by aggregating over all the adopters of the technology. Rogers (1962) modeled diffusion as a process of imitation and estimated the diffusion curve as an S-shaped function over time. Griliches (1957) launched the economic literature on adoption by finding that the shape parameter of the diffusion curve is affected by economic considerations, such as profit. David (1966; 1969), in sharp contrast, introduced the threshold model of technology diffusion, arguing that adoption is an explicit economic choice and that the S-shape is a result of heterogeneity among individual agents. David (1966) introduced the threshold model of technology diffusion to explain adoption of mechanical grain reapers in the U.S. in the nineteenth century. David's model assumed that farmers are choosing between hand methods with high variable labor costs and machine methods with high fixed costs. Farmers vary in farm size and on small farms the

fixed costs of the mechanical technology outweigh the value of the labor saved, making mechanization unprofitable. Using this elegant and simple model, David found the threshold farm size at which it becomes profitable to adopt. Sunding and Zilberman (2001) expanded and formalized the threshold model. They argue that the specific parameters of the adoption process are affected by 1) *the microeconomic behavior of the agent*, e.g. profit-maximization, expected utility maximization, etc., 2) *sources of heterogeneity*, e.g. size of operation, human capital, location, etc., and 3) *dynamic processes* e.g. learning by using of the farmer.

Since adoption decisions may involve irreversible investment choices and uncertainty, another line of research has adapted the real option value model of Dixit and Pindyck (1994)<sup>1</sup> to study technology adoption choices (Farzin, Huisman, and Kort 1998; Hall 2004). These studies suggest that at a given moment decision-makers do not simply make a choice about whether or not to adopt, but also consider the option to delay the decision until better information is available or the real price of the technology drops. Therefore, adoption may be triggered by critical values of key variables, such as the price of outputs and inputs and the cost of the technology.

Much of the literature on technology adoption in agriculture has emphasized *demand* factors in explaining diffusion processes—such as characteristics of the farmers, prices of outputs and inputs, risk and risk preferences, credit constraints, and learning by using<sup>2</sup>—while less attention has been given to *supply* factors—such as adaptation of the technology to the needs

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<sup>1</sup> Dixit and Pindyck (1994) developed and popularized option value models in regards to investment under uncertainty. These models recognize the option value of waiting for better information before making the decision to invest.

<sup>2</sup> See an extensive survey by Feder et al. (1985), and more recently surveys by Foster and Rosenzweig (2010) and Zilberman et al. (2012).

of various users and coevolution with complementary technologies. Olmstead (1975) argued that the threshold model emphasized the demand side determinants of diffusion without explicitly considering supply side and institutional elements affecting diffusion. For instance, Olmstead (1975) found that the diffusion of the mechanical grain reaper had benefited from a two decade accumulation of numerous technological refinements, reducing friction and horsepower needs, and the introduction of cooperative sharing of the technology among farmers. David (1990) also emphasized the importance of the evolution of technologies during periods of adoption and their adaptation to different locations and situations. David (1990, p. 356) traces the evolution of process innovations as “the emergence of an extended trajectory of incremental technical improvements, the gradual and protracted process of diffusion into widespread use, and the confluence with other streams of technological innovation.”

#### *Literature on the Adoption of Drip Irrigation*

Next we examine the literature specifically on the adoption of irrigation technologies, which is a large body of literature all on its own. Caswell and Zilberman’s (1985; 1986) conceptual analysis of the adoption of drip irrigation modeled drip as a land quality augmenting technology which enhances the water-use efficiency (fraction of water consumed by the crop) of applied water. In other words, drip irrigation is a process innovation for the delivery of inputs. Caswell and Zilberman (1986) showed that by increasing input use efficiency, drip irrigation makes effective water cheaper, which in turn increases profit maximizing yield. If the yield effect is sufficient, adopting drip may increase the quantity of the water demanded, and potentially counteract any water savings from increased efficiency.<sup>3</sup> Thus the adoption of drip will have a positive yield

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<sup>3</sup> This phenomenon is often called the Jevons paradox—after English economist William Stanley Jevons—

effect but not necessarily a water saving effect.

Another advantage of drip irrigation is that it allows better control of the timing of irrigation. Shani et al. (2009) developed a model for the allocation of water application over time. With furrow and sprinkler irrigation the frequency of irrigation applications is relatively low. With drip irrigation timing can be much more frequent, which stabilizes soil moisture leading to increased yield with less water. Thus the increased precision of drip augments the yield and water saving per unit of land of drip irrigation. Moreover, the models explained above can be expanded to several inputs (e.g. fertilizer or pesticides). For example, drip can increase the input use efficiency of fertilizer and pesticides through processes called fertigation and chemigation, which use the drip technology as a delivery system for these substances, reducing both labor and input costs. Additionally, Caswell, Lichtenberg, and Zilberman (1990) derived the extra gain from reducing drainage. The residue water not consumed by the plant may be a source of drainage, and drip can slow the resulting processes of water logging, which occurs when residue water accumulates underground and reduces the viability of the system in the long run (Kan, Schwabe, and Knapp 2002).

Altogether the literature on the adoption of drip suggests it tends to increase operational profit, which is revenue minus the cost of variable inputs, however, drip requires a larger investment in capital. The tradeoff between the operational profit and investment is crucial in determining adoption. Adoption is likely to increase with higher output and water prices, and as the cost of variable inputs declines (Schoengold and Zilberman 2007). With heterogeneity of land quality, drip is more likely to be adopted on regions with lower water holding capacity (land

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who observed that technology advances which increased the efficiency of coal-use, also led to the increased consumption of coal in a wide range of industries.



with sandy soil or hills) as well as on locations with higher water or crop prices. In some adopting regions adoption occurs because of the intensive margin effect, where producers transition from a traditional technology to drip, and in others because of the extensive margin effect, where new lands enters into production using drip technology. When the extensive margin is significant, adoption of drip, while reducing water use per unit of land, may increase aggregate water demand (Pfeiffer and Lin 2014). In the case of groundwater pumping, adoption of drip irrigation may increase over time as the level of the aquifer declines, water prices increase in other regions, or if there is a reduction in the fixed cost of the technology because of learning and new innovations (Shah, Zilberman, and Chakravorty 1995). Since water and agricultural commodity pricing are volatile, adoption of technologies like drip is likely to occur in periods of high water scarcity (Carey and Zilberman 2002).

The literature on modern irrigation technologies richly describes and assesses the demand considerations associated with adoption and diffusion. However, as the work of David (1990) and Olmstead and Rhode (1995; 2001) suggests, understanding the dynamics of supply and the coevolution of the technology throughout the diffusion process will also be crucial in building a complete picture of drip's diffusion.

### **The Evolution of Drip Irrigation in California**

This section explores the evolution of drip irrigation in California over its 45 year history, linking it to the conceptual framework described above. While the history of drip was well documented in the literature up through the mid-1980's, the most recent part of the story had several missing pieces. Therefore, to fill-in these holes and build a complete narrative, we sought out first-hand accounts from the Irrigation Specialists and Farm Advisors who were influential in

drip's diffusion in California. With these first-hand accounts, this narrative offers a unique compilation of the existing literature and previously undocumented oral history.

### *The Importance of Irrigation in California*

Irrigation is critical to California agriculture. California grows more than 200 different commercial crops, with a net farm income of approximately \$16 billion in 2012 (USDA 2014). Of the 9.6 million acres of cropland in California, 7.4 million acres (77%) are irrigated (USDA 2014). The agricultural sector uses between 29-52% of California's total water supply, depending on whether it is a wet or a dry year, and 75-80% of the developed water supply (Hanson 2009). On average, irrigated cropland in California is valued at more than 3 times that of non-irrigated cropland—\$12,000 per irrigated acre vs \$3,550 per non-irrigated acre (USDA 2012). However, there is a large difference in the value of production per unit of water between high value crops (truck farming, fruits and nuts) and low value crops (field crops like cotton and rice). And the value of production per unit of water also varies by location (Hanak et al. 2011).

Even though irrigation is crucial for California agriculture, the prior appropriation water right system (“Use it or lose it; First come, first serve”) common throughout the western U.S. does not encourage water conservation (Gardner, Moore and Walker 1997). Coupled with a low cost of energy, this led to investment in gravitational and sprinkler irrigation systems as irrigation expanded in California (Pisani 1984). However, after the energy crises in the 1970s and 1980s, there was growing value to water- and energy-saving irrigation technologies, which set the scene for the diffusion of Low Volume Irrigation (LVI) methods, such as drip irrigation.

### *Early Development and Adoption: 1965-1980*

Drip irrigation was first introduced to California on a small 5-acre experimental avocado orchard in San Diego County in the late 1960's, after a UC farm advisor had witnessed drip's success in Israel.<sup>4</sup> Frequent meetings were held at the UC Extension Service in order to disseminate information on drip irrigation and by 1974, San Diego hosted the International Drip Irrigation Congress, drawing over 2,000 persons from 29 countries and approximately 70 exhibitors (Gustafson 1979). As figure 1 suggests, during the 1970s drip acreage increased and in 1976 there were between 60,000 and 65,000 drip-irrigated acres in California (Marsh 1977). This growth continued through the 1980's with 305,000 acres irrigated by drip technologies in 1980 and 350,000 acres in 1985 (Casterline 1992). The increase in acreage between 1976 and 1980 was to a large extent due to the major drought of 1976-78—where the associated high shadow price of water rose—supporting the “real option” model of drip irrigation adoption (Carey and Zilberman 2002) which states that firms will wait to adopt until periods where water price are sufficiently high. Following theory, drip irrigation was adopted first in high value tree crops—like avocado—and in high value truck crops—like strawberries and fresh tomatoes—that were expanding into locations with high-cost water or fairly saline water and hillside plantings (Highstreet, Nuckton, and Horner 1980).

### *Slow down and build up: 1980-1989*

As figure 1 suggests, the acreage of drip irrigation increased only marginally between 1980-1988.

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<sup>4</sup> The first drip irrigation system was invented and brought to fruition by the Israeli water engineer Simcha Blass. After discovering that a slow, balanced water drip led to extraordinary plant growth—and subsequent years of testing drip devices—Simcha Blass established the Netafim Irrigation Company in 1965. With advantages in water savings, labor savings, and increased yields, drip systems quickly spread across Israel.

Delving into the determinants of drip adoption, Caswell and Zilberman (1986) suggest that most of the adoption of drip was on land using groundwater with high value crops, and the likelihood of adoption increased with well depth. In a later study, Dinar, Campbell, and Zilberman (1992) confirmed these results with 1989 data. They found that adopters included growers in the California Coastal regions who faced high water prices and grew tree crops, strawberries and fresh market tomatoes. Many of the farmers in California's Central Valley who had ample water rights or access to cheap surface water did not find the technology attractive. With ample water, the yield effect of the technology was not very pronounced and the water-saving was not economically meaningful to the farmer. Adoption in the Central Valley was also slowed by a handful of the disreputable manufacturers offering poorly designed equipment, giving drip a risky reputation (Caswell 1983).

However, as a result of both public and private research and development activities, the capabilities of the technology were expanded to include precision application of fertilizer (fertigation) and pesticides, and Cooperative Extension developed management strategies to adapt the technologies to local conditions. For example, extension specialists discovered that the use of drip irrigation in conjunction with pesticides allowed effective control of nematodes in tree and vine crops in the Central Valley.<sup>5</sup> Fresno State's *Center for Irrigation Technology* (est. 1980) and Cal Poly's *Irrigation Training and Research Center* provided objective testing and evaluation of equipment, and developed human capital for designing and effectively utilizing drip. The University of California also developed the California Irrigation Management Information System (CIMIS) which enabled farmers to adjust irrigation to water conditions and

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<sup>5</sup> Source: Personal communication with Michael McKenry, Emeritus Nematologist and Cooperative Extension Nematology Specialist.

was especially effective when used with drip.<sup>6</sup> Thus, over the course of the 1980s, the technology and its capabilities improved, and these supply side changes lowered the real cost of drip systems. However, improved technology does not necessarily imply immediate and widespread adoption. Instead, according the threshold and option value models discussed in Section 2, adoption is triggered by events that make the technology especially appealing. For drip irrigation, momentum for adoption came in the form of a natural disaster: the 1987 to 1991 California drought.

#### *California Drought: 1987-1991*

Between 1987 and 1991 California suffered a severe drought where annual precipitation averaged less than 50 percent of normal. Severe water shortages, especially in the third and fourth years of the drought, led growers to make a number of difficult decisions. A UC Berkeley survey in 1991 revealed that the drought intensified the adoption of drip irrigation in crops that used them before and led to their adoption on crops normally grown with traditional irrigation methods (Zilberman et al. 2002). Drip acreage in fruits grew from 25 to 40 percent during the drought, while drip acreage in processing vegetables grew from 0 to 10 percent (Zilberman et al. 2002). The drought also led water districts to offer assistance to growers for irrigation scheduling and subsidized loan programs for changing their irrigation methods. The drought not only boosted the adoption of modern irrigation technologies, but the Central Valley Project Improvement Act was introduced in 1991 after the drought, which transferred water from agriculture to the environment and enabled water trading among farmers that belong to the Central Valley Project. Trading increased the opportunity cost of water and, as a result, the

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<sup>6</sup> Source: Personal communication with Richard Snyder, Cooperative Extension Biometeorology Specialist.

attractiveness of drip irrigation (Zilberman et al. 2002).

### *Adapting Drip to Other Crops and Regions: 1992-Present*

After the drought, adoption of drip among high-value tree crops and vegetables for the fresh market reached close to its limit. Both industry and Cooperative Extension realized that further diffusion of this technology could only come through its adoption in lower-value crops, particularly vegetables and fruits for processing<sup>7,8</sup>. This realization led the research and development agenda for drip irrigation in the ten years before and after the new millennium. The manufacturers focused on innovations to improve their equipment and systems and to lower the price of the equipment. For instance, when surface drip was first introduced on vegetable crops, it was labor intensive to layout and remove drip tapes on and off a field. In response to this issue, the private sector invented hydraulic systems for laying-down and rolling-up the tapes. Another invention of private firms is a splicing machine, which can splice drip tapes into pieces and then re-melt them together later. This made drip tapes more affordable as growers could now reuse tapes 8-10 times instead of just once or twice.<sup>9</sup>

Complementing the work of private firms, UC Cooperative Extension focused on researching methods of water, fertilizer, and chemical management using drip for various crops grown in different soil conditions. Several research projects implemented by UCCE personnel during the 1990's and 2000's were influential in spreading drip irrigation in fresh market fruits

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<sup>7</sup> Source: Personal communication with Naty Barak, Chief Sustainability Officer of Netafim, and Michael Cahn, UCCE Farm Advisor for Irrigation and Water Resources.

<sup>8</sup> California produces 95% of the processing tomatoes in the U.S. and approximately 35% of world production (Rickard and Sumner 2006).

<sup>9</sup> Source: Personal communication with Michael Cahn, UCCE Farm Advisor for Irrigation and Water Resources.

and vegetables (e.g. strawberries, lettuce, broccoli, cauliflower and fresh market tomatoes), as well as various low-value (e.g. processing tomatoes and cotton). A prime example is the work UCCE did in adapting drip technologies to processing tomatoes. Canning companies were resistant to buying drip-grown fruits and vegetables because as yields go up, soluble solids and fruit sugars go down. This resistance stimulated the work of UCCE to find a balance between high yields and acceptable levels of soluble solids—identifying a field sampling protocol when fruit first ripen that serves as a gauge for soluble solid projections, so that deficit irrigation can be imposed without extreme sacrifice of yield.<sup>10</sup>

Another crucial contribution of UCCE in drip irrigation originated from a field study on the effects of drip irrigation on processing tomatoes in the salt affected soil of the San Joaquin Valley (Hanson et al. 2009). The results showed that—by helping farmers overcome both saline and drainage problems—there is high potential for drip irrigation to increase profits over furrow and sprinkler technologies. The growers in the experiment saw yields of 40 tons per acre using drip compared to 25 tons per acre with furrow. This was a tremendous yield gain and success for drip irrigation, and since growers were involved in the study and saw its success first hand, they promoted the results widely in the region.<sup>11</sup> Today, the vast majority of processing tomatoes in the San Joaquin Valley are grown using drip irrigation. With the cooperation between private sector companies and UCCE, drip irrigation in processing tomatoes has gone from 0% in 1987, to 5% of growers in 1995 to 85% of growers in 2011<sup>12</sup>.

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<sup>10</sup> Source: Personal communication with Gene Miyao, UCCE Farm Advisor for Vegetable Crops.

<sup>11</sup> Source: Personal communication with Blaine Hanson, UCCE Irrigation and Drainage Specialist.

<sup>12</sup> Source: Personal communication with Gene Miyao, UCCE Farm Advisor for Vegetable Crops.

### *Discussion of the Evolution of Drip Irrigation*

This narrative of the evolution of drip in California is consistent with much of the conceptual literature on technology adoption and diffusion. David (1990) and Olmstead and Rhode (1995; 2001) emphasized the evolution of the adopted technology over time in order to accommodate heterogeneous potential adopters. In the case of drip irrigation, we observe *coevolution* of the adopted technologies with complementary technologies (e.g. irrigation with fertilizing and pest control technologies, sampling protocols, crop spacing). However, the narrative also highlights shortcomings of the conceptual literature and in particular the threshold models. For instance, the literature has not emphasized the importance of continuing applied research and extension throughout the diffusion process. In the case of drip irrigation in California, the coevolution of irrigation equipment and farming practices has involved joint effort of the private and public sector. For instance, while agricultural manufacturers modify the technology to the specific needs of adopters, public sector Cooperative Extension advisors and specialists re-optimize complementary production practices, enabling adopters to adjust to the use of drip.<sup>13</sup>

The history of drip irrigation in California showcases the adaptation of a new technology to local needs in order for it to spread across space and time to the benefit of a wide variety of users. In order to visualize this diffusion, we map the percent of irrigated acres using drip irrigation by county in 1975, 2001, and 2010 in the top 3 panels of figure 2. In 1975, only five years after the introduction of drip in California, the technology remained mostly in the south

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<sup>13</sup> Coevolution and joint private and public R&D efforts are exemplified in the adaptation of drip irrigation to processing tomatoes discussed above. To enable adoption of drip in low-value crops, such as processing tomatoes, drip manufacturers made drip systems more affordable by developing technologies so growers could reuse drip tapes. Concurrently, since original production of processing tomatoes with drip irrigation resulted in unacceptably low levels of soluble solids, UCCE Agronomists identified field sampling protocols to project soluble solids and adapted irrigation regimes under drip in order to produce the optimal qualities of the tomatoes.



where it was introduced, but was beginning to be seen in the San Joaquin Valley. Fast forward 25 years to 2001 and drip had been adopted widely across the state. This diffusion pattern continued through 2010. We also map, in the bottom two panels of figure 2, counties by the percentage of their crop acreage that is high value<sup>14</sup> as well as by the water cost they face. Comparing all five panels once again provides evidence that drip was adopted first among high value crops and in areas with high water costs. However, something that is evident in the narrative above which is not captured in these maps is that the introduction of a technology is only part of the diffusion story and that research and development may need to be on-going through much of the life of the technology for it to reach its potential.

### **Empirical Analysis of the Value of Drip Irrigation Adoption in California**

As mentioned in the previous section, while the aim of David (1990) was to convince economists of the value of historical studies, his impetus was to respond to the phrase, quite popular at the time, that “computers are everywhere but in the productivity statistics,” by pointing out the ways in which the same could have been said for the dynamo 100 years prior. Since we also find that drip irrigation appears to be everywhere in Californian agriculture today—with broad adoption across locations and crops—we ask whether drip’s benefits can be seen and quantified in the productivity statistics. In particular, if drip is everywhere, what have been its observable effects on crop yields?

Drip was initially perceived as a conservation technology, but was also quickly valued for its contribution to increased productivity, crop quality and pest control. Our empirical research design uses data for one of the most discussed, and often unexpected, advantages of adopting

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<sup>14</sup> We denote high value crops as those with revenues over \$1000/acre.

drip irrigation—the potential for improved yields (Ayars 1999). Drip improves yields by increasing effective water for the crop and by decreasing water applied to unwanted weeds and pests. Increased yields from drip can also occur when it is used as a delivery system for fertilizer and pesticides. The following analysis endeavors to answer whether the benefit of a positive yield effect can be quantified, first, by surveying the published agronomic literature on yield effects from drip irrigation. Second, we exploit two distinct panel datasets on drip adoption in California to estimate correlations between adoption and yield: (1) county-by-crop level data on drip adoption and yields in two years (2001, 2010) and (2) sixteen years of adoption and yield data from one Californian county across 24 crops. While this article and others have performed analyses comparing published studies on crop and location specific yield effects, no one to our knowledge has systematically examined the effects of drip on yields using variations in adoption across locations, crops, and time. Lastly, we will use our estimates of the yield effect to perform back-of-the-envelope calculations of the increases to net farm income from drip adoption.

### *Survey of Studies on the Yield Effects of Drip Irrigation*

Numerous field studies have examined how drip irrigation affects yields on a particular crop and location. Camp (1998) performs a comprehensive review of 61 published studies on subsurface drip irrigation across 30 crops and finds that crop yields for subsurface drip are equal to or greater than those for other irrigation methods. Similarly, agronomists from Netafim<sup>15</sup> analyze 112 studies of drip irrigation versus flood irrigation in comparable situations and find that yield effects range from 18-50% (Durand and Birrell 2010). Given that Camp (1998) focused on the

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<sup>15</sup> Netafim is among the largest irrigation companies in the world, and one of the top providers of drip and micro-irrigation products.

yield effects of subsurface drip alone, and not on all forms of drip irrigation, and the potential biases of the Netafim report, we perform our own comparison of published studies (table 1). Comparing 31 studies covering 15 crops, we also find that drip irrigation leads to equal or greater yields than those of other irrigation methods. Half of the studies in our analysis report not finding a statistically significant difference in yields between irrigation methods. The other half of the studies report positive yield effects, ranging from 12% to 66%. The average yield effect across all studies is 16%. Another thing to note is that these types of field studies are generally performed when a technology is first being introduced and evaluated in an area. Thus it is no surprise that the most of the older studies are from the U.S. and many of the newer studies are from developing countries.<sup>16</sup>

#### *Yield Effects of Drip Irrigation Adoption in California (County-by-Crop Data)*

Our measures of irrigation technology adoption come from statewide surveys of growers' irrigation methods, conducted by the California Department of Water and Resources (CDWR) in 2001 and 2010. A one-page survey form was developed by CDWR and mailed to 10,000 growers to collect irrigated land (acres) by crop and irrigation method. From this data we are able to create measures of the percentage of acres using various irrigation methods by county and crop in 2001 and 2010 across crop categories. Irrigation technologies are defined as follows:

- *Gravity technologies* include wild flood, border, basin, furrow irrigation without sprinklers, wheel line sprinklers followed by furrow irrigation, and hand move sprinklers followed by furrow irrigation.
- *Sprinkler technologies* include solid set, hand move, linear move, wheel line, hose pull

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<sup>16</sup> The interested reader can find a complete list of these 31 studies in the supplementary appendix online.

and other types of sprinklers including center pivot, gun-type, etc.

- *Drip technologies* include all low volume irrigation methods such as surface and buried drip irrigation and micro/mini-sprinklers.
- *Other irrigation technologies* include all remaining types of irrigation technologies such as underground pipes or open ditches which are blocked to back up water and force it into a crop root zone.

Next we use data from the County Agricultural Commissioner’s Report for California. These reports provide data by crop, county and year on yield, acres harvested, price per ton, and revenue. These reports span from 1980-2010, but we again focus on 2001 and 2010. Matching these two datasets using the broad crop categories from the irrigation surveys, we focus on nine different crop categories—Alfalfa, Almond & Pistachio, Corn, Cotton, Dry Beans, Onion & Garlic, Tomato (fresh and process), and Vineyard—across 51 counties in California. These crops were chosen because they are each grown in five or more counties and have experienced at least some level of adoption of drip irrigation over the sample period. Table 2 shows the percent of irrigated acres by irrigation method and crop in 2001 and 2010. Note that the percentage of acres using drip increases in all crop categories between 2001 and 2010, with process tomatoes, garlic & onions, cotton and beans witnessing the largest percent increases. In addition, figure 2—by mapping the percentage of irrigated acres using drip by county in 2001 and 2010—once again shows how drip adoption has varied across locations (and not just across crops).

To estimate the effects of drip irrigation on crop yields, we use the following fixed effects panel regression:

$$(1) \quad \ln Y_{ict} = \beta_1(\%Drip_{ict}) + \beta_2(\%Sprink_{ict}) + \beta_3(\%Other_{ict}) + \beta_4(\%HarAcres_{ict}) + \alpha_{ic} + \delta_{it} + \theta_{ct} + \varepsilon_{ict}$$

The subscript  $i$  refers to the crop,  $c$  refers to the county, and  $t$  refers to the year.  $Y$  denotes yield, measured in tons per acre.  $\%Drip$  is the percent of irrigated acres of crop  $i$  in county  $c$  and year  $t$

using drip irrigation, *%Sprink* is the percent using sprinkler irrigation, *%Grav* is the percent using gravity irrigation and *%Other* is the percent using the remaining other irrigation methods. Since we are particularly interested in the transition from gravity to drip, *%Grav* is the omitted irrigation category in this model. We hypothesize that increases in the percent of drip irrigated acres relative to gravity irrigated acres will be associated with increases in yields, and thus our coefficient of interest,  $\beta_1$ , should be greater than zero.

We also control for the share of harvested acres in a county that each crop comprises over time (*%HarAcres*), since changes in harvested acres may be correlated with both drip adoption and yield. For instance, adoption of drip irrigation may be associated with increased irrigated acreage, as marginal lands that were not productive under traditional irrigation technologies become productive under drip irrigation (Caswell and Zilberman 1985). If the new land is of lower quality than the existing land, increases in acreage consequently may be associated with lower average yields.<sup>17</sup>

Lastly we include crop-county fixed effects, crop-year fixed effects, and county-year fixed effects. These fixed effects allow us to control for county specific time shocks (i.e. weather) and crop specific time shocks (i.e. new seed varieties) as well as time-invariant crop-county characteristics. An econometric concern in estimating this model is that unobservable variables that vary over time and county and crop may still bias our coefficients. In particular, we would worry that the  $\beta_1$  estimate is biased upward if there are both 1) positive correlations between drip adoption and omitted factors that vary across crop and county and time and 2)

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<sup>17</sup> In our sample of counties, the share of statewide harvested acres of almond & pistachios increased by almost 2 percentage points between 2001 and 2010, whereas the share of cotton decreased by 6 percentage points. All other crops saw more modest changes in share of harvested acres.

positive correlations between yield and these omitted factors.<sup>18</sup> Given the possibility for upward bias, we take the estimate  $\beta_1$  lightly, viewing it as the correlation between drip adoption and yield.

Table 3 presents the results from three specifications of the model. In column 1 we include only the irrigation technologies and crop-county fixed effects. Our estimated  $\beta_1$  is equal to 0.2164 and is statistically different from zero at the 10% significance level, indicating that switching from gravity irrigation to drip irrigation is correlated with a 21.64% increase in yields. In column 2 we additionally control for the share of harvested acres, and in column 3 we add crop-year and county-year fixed effects. In column 3—our preferred specification— $\beta_1$  is still positive and statistically significant and is slightly larger in magnitude than the other two specifications at 0.2657. In none of the specifications do we find that sprinkler and other irrigation technologies have statistically different yield effects than gravity irrigation.

#### *Yield Effects of Drip Irrigation Adoption in California (Monterrey County Data)*

One drawback of the analysis above is that we only have drip adoption data by crop and county at two points in time—2001 and 2010. To fully understand drip's impact over time, we would

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<sup>18</sup> Growers' expectations of future input prices and of future output prices are examples of omitted and unobserved factors that may vary over crop and county and time and may be correlated with both irrigation choice and yields. To illustrate, studies have found that crop yields respond positively to their own prices and negatively to the price of inputs (Huang and Khanna 2010). If omitted output price expectations are positively correlated with switching to drip irrigation and positively correlated with yield, then we would have an upward bias on the drip irrigation coefficient. Conversely, if omitted input price expectations—in particular water prices—are positively correlated with adopting drip and negatively correlated with yield, then we would have a downward bias. Therefore, it is unclear in which direction omitted price expectations bias our coefficients. Moreover, including output prices in the model is not a satisfactory solution, since output prices are an endogenous variable for which we do not have an adequate instrument.

ideally have *yearly* adoption data by county and crop. While this ideal data does not exist, we do have irrigation adoption by crop and year for one county—Monterey County. This county offers an excellent test case because it's farmers in and around the lush Salinas Valley produce a virtual cornucopia of products.<sup>19</sup> The Monterey County Water Resources Board reports, in their annual *Ground Water Summary Report*, irrigation technology adoption across 5 different crop categories—1) Vegetables, 2) Field Crops, 3) Berries, 4) Grapes, and 5) Tree Crops. These reports are available online for the years of 1993 and 1996-2012.<sup>20</sup> By comparing our empirical results using the Monterey panel data with the results from the cross-county data described previously, we will be able to test the robustness of the previous yield effect estimates.

First we will look at the types of irrigation technologies used in Monterey County, over time and by crop type. Figure 3 shows the types of irrigation methods used in Monterey County between 1993 and 2013. In 1993, the irrigation technology used on the most acres was Sprinkler, either alone or in combination with Furrow. Drip was the third most used technology at that time and Furrow by itself was used very little. Over the entire sample period, Drip has grown in acres while Sprinkler acreage has retreated. In 2003 Drip's acreage first surpassed that of the Sprinkler & Furrow and as of 2013 Drip is used on more than 4 times the acreage of any other irrigation method in Monterey County. Furthermore, total acreage irrigated (the thick black line in figure 3) has stayed relatively constant over time. In 1993, total irrigated acreage was 195,000. It fell to 140,000 in 2002 and recovered to 170,000 in 2013.

We again use crop production data from the County Agricultural Commission's Report, which contains information at the county-crop-year level. We drop all crops that do not have at

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<sup>19</sup> Monterey County's Salinas Valley is often dubbed "The Salad Bowl of the World."

<sup>20</sup> <http://www.mcwra.co.monterey.ca.us>

least 13 years of data in Monterey County, giving us a total of 24 different crop commodities produced in 1993 and 1996-2010 in Monterey County. Matching these 24 crops from the production dataset into the 5 crop categories of the irrigation dataset, allocates two crops into the Berries category, one crop in Field, one crop in Vine, two crops in Tree, and 18 crops in Vegetable.<sup>21</sup>

To estimate the effects of drip irrigation on crop yields in Monterey County, we use the following fixed effects panel regression:

$$(2) \quad \ln Y_{it} = \beta_1(\%Drip_{it}) + \beta_2(\%SprinkFur_{it}) + \beta_3(\%HarAcres_{it}) + \alpha_i + \delta_t + \varepsilon_{it}$$

The subscript  $i$  refers to the crop and  $t$  refers to the year.  $Y$  denotes yield, measured in tons per acre.  $\%Drip$  is the percent of irrigated acres of crop  $i$  in year  $t$  using drip irrigation,  $\%SprinkFur$  is the percent using sprinkler with furrow irrigation, and  $\%Other$  is the percent using the remaining other irrigation methods.  $\%Other$  is the omitted irrigation category in this model. Thus the  $\%Drip$  parameter,  $\beta_1$ , corresponds to the yield effect of increasing the percent of drip irrigated acres relative to the omitted other irrigated acres. We again hypothesize that increases in the percent of drip irrigated acres relative to the other category of irrigated acres will be associated with increases in yields and therefore  $\beta_1$  should be positive.

Table 4 presents the results from three specifications of the model. In column 1 we include only the irrigation technologies and crop fixed effects. We estimate  $\beta_1$  equal to 0.2563, however, it is not statistically different from zero. In column 2 we additionally control for the share of harvested acres, and in column 3 we add year fixed effects. In column 3—our preferred specification— $\beta_1$  is now statistically significant at a 10% significance level and equal to 0.4790.

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<sup>21</sup> The 24 crops include strawberries, raspberries, hay, wine grapes, avocados, walnuts, artichokes, asparagus, broccoli, cabbage, carrots, cauliflower, celery, kale, leeks, lettuce head, lettuce leaf, romaine lettuce, onions, green onions and shallots, bell peppers, radicchios, radishes, and spinach.



This indicates that switching from other irrigation technologies to drip irrigation is correlated with a 47.9% increase in yields. In none of the specifications do we find that sprinkler with furrow has statistically different yield effects than other irrigation methods.

### *Value of Drip Irrigation to California Agricultural*

When considered together, the results from our survey of the literature and our two empirical exercises—which produced yield effect estimates of approximately 16%, 27%, and 48% respectively—provide strong evidence that the adoption of drip irrigation has increased crop yields.<sup>22</sup> Next, we use these yield estimates to produce back-of-the-envelope calculations of the impact of drip on California’s net farm income—an important macroeconomic measure of the performance of the farm sector.<sup>23</sup> Net farm income is gross farm income—the return to farm operators for their labor, management and capital—less all production expenses. We look at net farm income instead of gross farm income because the costs of adopting and using drip irrigation practices are accounted for in this measure. The effect of drip on revenues is smaller than the effect of drip on yields because higher yields will result in negative price effects. We calculate revenue effects corresponding to our estimated yield effects in the following manner: If  $R$  represents revenue and  $Y$  represents yield, then we can show that:  $\Delta R/R = \Delta Y/Y (1 - 1/\varepsilon_D)$  where  $\varepsilon_D$  represents the absolute value of the elasticity of demand. In the case of California agriculture, a plausible range of elasticity of demand is -0.5 to -2 (Nuckton 1978). Given that drip adoption is highest among more price elastic high-value crops, we will assume  $\varepsilon_D$  is 1.5.

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<sup>22</sup> These results are consistent with the findings of Durand and Birrell (2010) and Camp (1998).

<sup>23</sup> Schnepf (2014) describes net farm income as “the single most watched indicator of farm sector well-being, as it captures and reflects the entirety of economic activity across the range of production processes, input expenses, and marketing conditions.”

Then if the yield effect is 16%, the revenue effect is  $5.3\% = \left(0.16\left(1 - \frac{1}{1.5}\right)\right)$ . If the yield effect is 27%, the revenue effect is 9.0%, and if the yield effect is 48%, the revenue effect is 16.0%. Therefore, we calculate that the effect of drip on net farm income across all crops where it is applied would be between 5% and 16%.<sup>24</sup>

Using this range of income effects, in table 5 we explore the impact of drip on net farm income in California under a 5%, a 9% and a 16% income effect. In 2010, crop production comprised roughly 68 percent of California's \$10.7 billion net farm income (revenue excluding input costs, etc.), which equate to \$7.3 billion respectively (USDA 2011). Given statewide adoption of 60% among high value crops—which produce roughly 86% of the total agricultural income—and adoption of 15% among low value crops, the value of the yield effect of drip in California lies between \$187 million for an income effect of 5% on net income,<sup>25</sup> and \$541 million for an income effect of 16%.<sup>26</sup> In other words, the positive yield effect of drip irrigation increases the net farm income from crop production in California by between 2.6-7.4% annually.

It is important to note that these results do not take into account all the benefits of drip to producers, consumers, or the environment. While the quality-enhancing and water-saving advantages of adopting drip are commonly held, quantifying them is challenging. First, quality changes associated with the introduction of novel technologies often go unmeasured. This is particularly problematic for drip irrigation, where its adoption in certain crops is justified by increases in quality and not quantity. For instance, the qualities of wine-grapes and processing

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<sup>24</sup> We could have calculated the impact of drip on revenue directly, but then we will need to adjust to variation in prices over time. Here we compute it on yield and use elasticity to translate it to revenue.

<sup>25</sup> \$187 million = \$7.3 billion \* (0.60 \* 0.86 + 0.15 \* 0.14) \*  $\left(\frac{0.05}{1+0.05}\right)$ .

<sup>26</sup> \$541 million = \$7.3 billion \* (0.60 \* 0.86 + 0.15 \* 0.14) \*  $\left(\frac{0.16}{1+0.16}\right)$ .

fruits and vegetables are often measured by the level of soluble solids in the crop at harvest. While drip irrigation has been shown to affect these levels (Johnston et al. 2005), this type of quality augmentation is difficult to parse out in the productivity data.<sup>27</sup> Second, new technologies, like drip, have a significant extensive margin effect that may expand production on marginal land, which may in turn cause average yield effects to appear lower than in reality.<sup>28</sup> Third, data on applied water-use by crop, location, and irrigation method has not been well-documented on a wide scale, and there is a lack of information about effective water-use by different crops across locations over time.<sup>29</sup> These deficiencies make it difficult to quantify the aggregate water saving effect of drip.

Nevertheless, there is some evidence that the introduction of drip has a significant water-saving effect. First, while there have been no studies on the aggregate effects of drip on water-savings, numerous micro-level studies have shown positive water-savings effects. In particular, 11 of the 31 agronomic studies we examined for yield effects also mentioned positive and significant water savings effects of drip irrigation compared to flood and furrow—the average of which was 35% water-savings. Second, while total water use in California has not changed by much over time, its allocation has fluctuated. Studies on the response in California to the drought of 1988-92 suggested that one third of the reduction of surface water allocation to agriculture

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<sup>27</sup> One can assess it from prices of crops, like grapes, but it is outside the scope of this article.

<sup>28</sup> This is similar to the findings of Olmstead and Rhode (2008). To illustrate, drip irrigation is often used to grow crops on lands that are unproductive under traditional irrigation technologies. On these marginal lands, drip irrigation increases yields from zero to some positive amount. However, the new yields may still be lower than on high-quality land. Thus even though the effect of drip on yields is positive, the average yield effect may appear to be zero or negative if the expansion of production into marginal land is not taken into account.

<sup>29</sup> Even with this information, the water saving effect of drip would be difficult to measure since although drip has higher input use efficiency than the alternative technologies, the water residues of other technologies may be reused.

during the drought of 1991 was accommodated by water conservation (largely by the adoption of drip). After the drought, the Central Valley Project Improvement Act was introduced and reallocated water from agriculture to the environment (Zilberman et al. 2002). Yet even though the amount of water allocated to cities and the environment has increased, there has still been expansion of agriculture in some regions—some of which is directly associated with the adoption of drip. Thus drip irrigation has been important in allowing California agriculture to survive 10% reduction of the water allocated to agriculture by the Central Valley Project and rising ground water pumping costs (Zilberman et al. 2002). However, quantifying these effects goes beyond the scope of this article. Our restricted ability to examine the potentially significant effects of drip irrigation on water savings, crop quality, and crop acreage directed us to concentrate on yield effects. However, we mention these constraints not as a hindrance to the study, but instead to highlight the conservativeness of our estimates of drip's effect on income reported above.

## **Conclusion**

Our analyses of the diffusion of drip irrigation in California validate the insights—raised in David (1990) and Olmstead and Rhodes (1995)—that diffusion of a technology may go through multiple waves associated with sequential improvements, and consequently, a long term historical perspective is required to understand the full impact of a new innovation. Ten years after the introduction of drip, it was viewed in California as a specialized technology only suitable for particular locations. Over time, it has become a mainstay of California agriculture. We show that the diffusion of drip irrigation evolved and migrated among activities (e.g. irrigation, fertigation, chemigation, deficit irrigation), crops (e.g. high-value, low-value), and

regions (e.g. Southern Coast, Central Valley). The evolution of its diffusion is consistent with insights of major models introduced in the literature—1) the threshold model, which emphasizes heterogeneity of potential adopters, learning by farmers and technology manufacturers, and the tendency to first adopt a technology where it is most valuable and 2) the real option value model, which suggests that crisis situations trigger major transitions. In the case of drip, crises came in the form of droughts.

Other lessons from the adoption of drip are the importance of Cooperative Extension and the complementarity of public and private research and outreach efforts. While the private sector improved the technology, the public sector's research adapted agricultural practices to benefit from the opportunities presented by drip irrigation. Cooperative Extension played an important role in leading the effort to shift the technology among crops and regions. These research and extension efforts led to coevolution of drip technologies and complementary activities.

The diffusion of modern drip irrigation technologies continues today within California, the U.S., and globally. Future research should emphasize understanding the diffusion of these technologies globally, especially through the developing world. Studies have shown that modern input efficiency-enhancing technologies may have larger impacts on productivity in developing countries, where pressures from resource scarcity are often stronger (Qaim and Zilberman 2003). However, high capital costs of modern technologies in conjunction with technical, human capital, and economic constraints, often make the adoption of these technologies infeasible. Despite the constraints, drip is moving globally, with several companies, such as Driptech and Netafim, already designing and manufacturing low-cost drip-irrigation systems for small-plot farmers in Africa, Asian and South America. Thus we may be on the cusp of seeing the familiar patterns of technology diffusion through adaptation to specific locations in the developing world.

While the emphasis of this paper is the diffusion process—we obtain a simple and rough estimate of the economic impact of drip irrigation in California. While only assessing the income effect of drip irrigation through increased yield, we conservatively estimate that adoption of drip increased gross and net income of California agriculture by between 2.6-7.4%. This analysis suggests that drip irrigation is everywhere and, unlike the computer and the dynamo mentioned by David (1990), after 40 years drip irrigation *is* in the productivity statistics.

This article is only an initial investigation and the economic impact of drip irrigation should be further analyzed. With respect to future work, we point to the importance of quantifying the potential gains of drip irrigation in terms of water saving, fertilization and pest control. Moreover, our analysis was hampered by lack of consistent data on adoption patterns and water use. If agencies continue to improve data collection on technology choice and input-use at the farm plot and crop level, and consistently monitor this information over time, a more rigorous statistical analysis of the diffusion process and its outcomes will be possible in the future.

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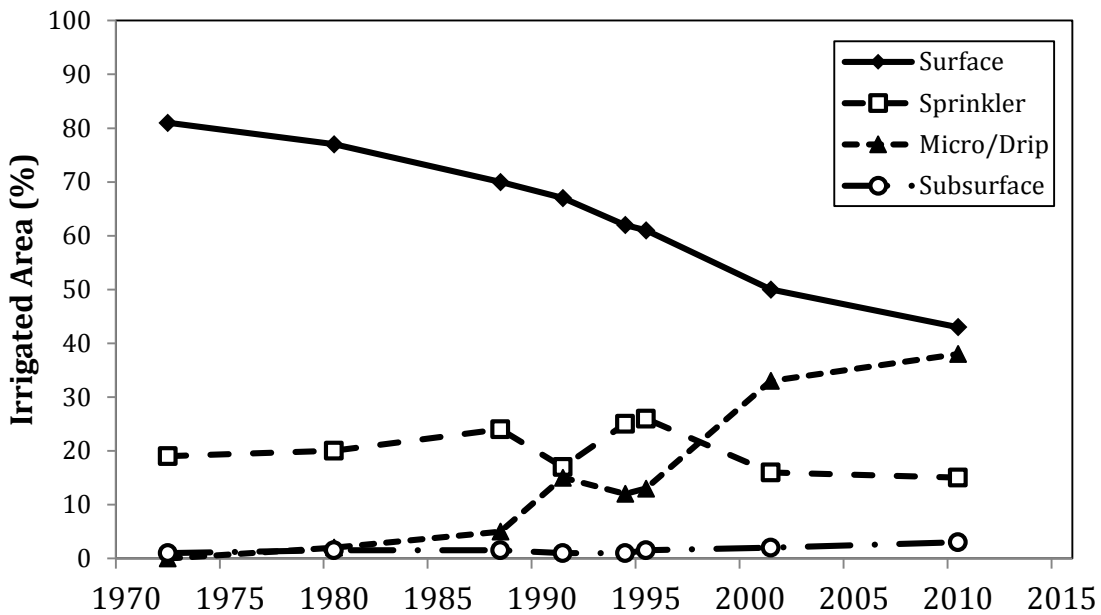
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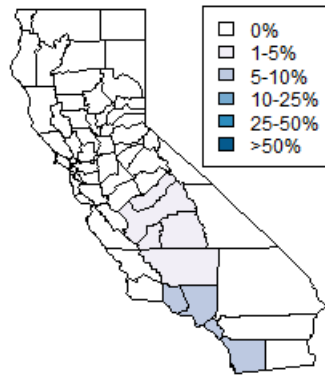
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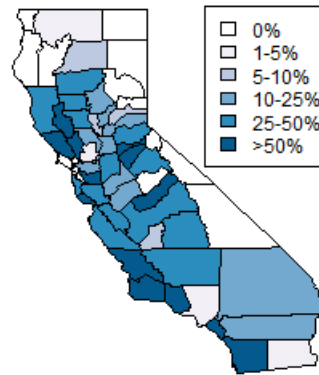
**Figure 1: Trends in irrigated area (percent) by irrigation system category**

Source: Tindula, Orang, and Snyder (2013)

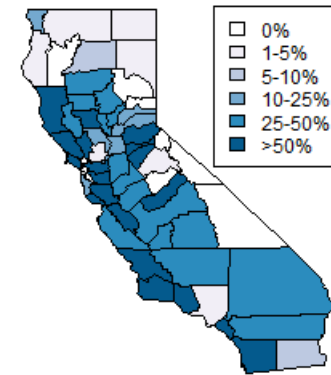
(a) 1975 Drip Irrigation (% of Irrigated Acres)\*



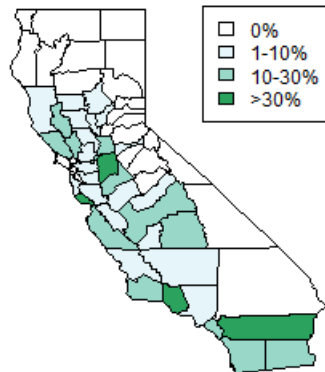
(b) 2001 Drip Irrigation (% of Irrigated Acres)\*\*



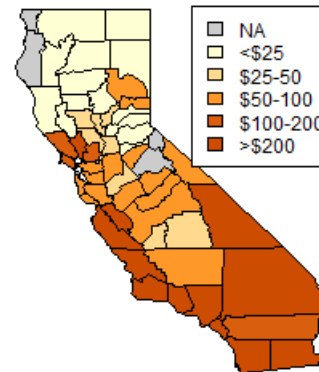
(c) 2010 Drip Irrigation (% of Irrigated Acres)\*\*



(d) % Crop Acreage that is High Value, 2001^



(e) Water Cost by Acre (\$/acre-foot), 2001^^



Sources: Highstreet et al. (1980).\*

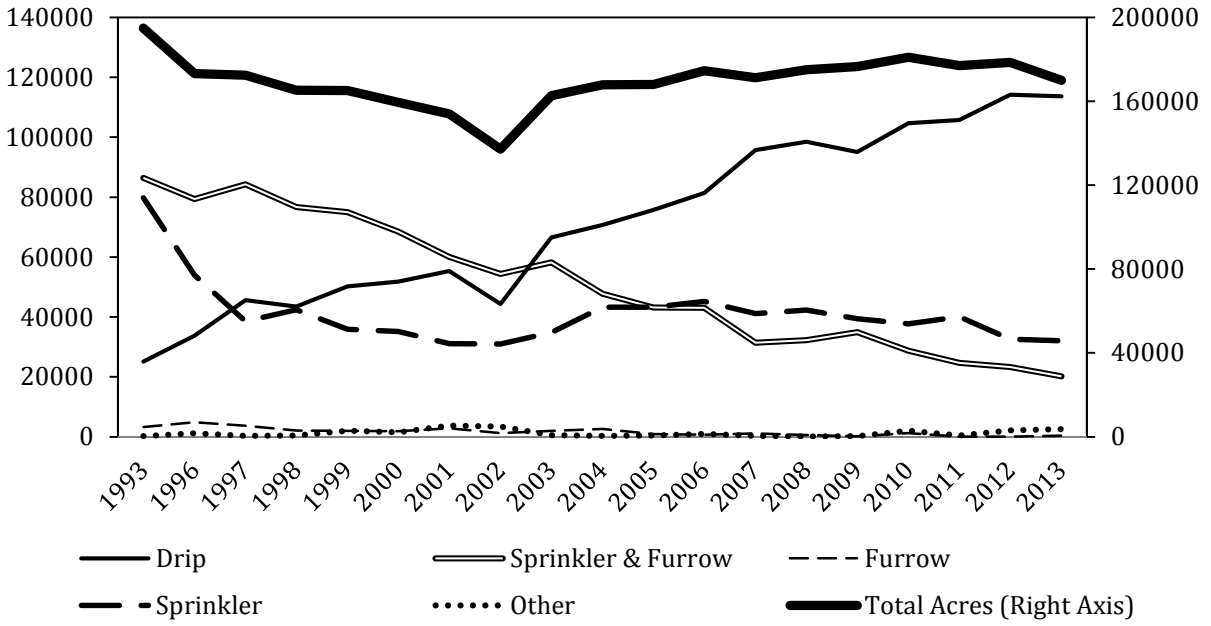
California Department of Water Resources Irrigation Surveys, 2001 & 2010.\*\*

County Agricultural Commissioner's Report for California, 2001.^

CDWR Bulletin 132: Management of the California State Water Project.^^

High value crops are denoted as those with revenue greater than \$1000/acre.

**Figure 2: Irrigation and crop characteristics by county and year**



**Figure 3: Irrigation methods (acres) in Monterey County**

Source: Monterey County Water Resources Board, *Ground Water Summary Reports*.

Table 1: Agronomic Studies Comparing Yields Under Drip to Other Irrigation Methods

Crop	Paper	Location	Yield Effect	Comparison
Alfalfa	Bui & Osgood, 1990	Hawaii	-	sprinkler
Alfalfa	Hutmacher et al., 1992	California	19-35%	furrow
Cabbage	Bucks et al., 1974	Arizona	-	furrow
Cabbage	Rubeiz et al., 1989	Arizona	29%	furrow
Cabbage	Tiwari et al., 2002	India	62%	furrow
Cantaloupe	Bucks et al., 1981	Arizona	-	furrow
Carrot	Bucks et al., 1981	Arizona	-	furrow
Cotton	Howell et al., 1987	California	-	furrow
Cotton	Phene et al., 1992	California	13%	furrow
Cotton	DeTar et al., 1994	California	-	furrow
Cotton	Henggeler, 1995	Texas	20%	furrow
Cotton	Muhammad et al., 2011	India	20%	furrow
Lettuce	Sammis, 1980	New Mexico	-	furrow
Lettuce	Hanson et al., 1997	California	-	furrow
Okra	Sivanappan et al., 1987	India	40%	furrow
Onion	Bucks et al., 1981	Arizona	-	furrow
Onion	Halvorson et al., 2008	Colorado	15%	furrow
Peanut	Adamsen, 1989	Virginia	14%	sprinkler
Pepper	Xie et al., 1999	New Mexico	43-66%	furrow
Pepper	Paul et al., 2013	India	28%	flood
Pistacchio	Goldhamer et al., 2002	California	13%	flood
Potato	Sammis, 1980	New Mexico	-	furrow
Potato	DeTar et al., 1996	California	27%	sprinkler
Potato	Erdem et al., 2006	Turkey	-	furrow
Sweet corn	Phene & Beale, 1976	South Carolina	12-14%	furrow, sprinkler
Sweet corn	Wendt et al., 1977	Texas	-	furrow
Sweet corn	Adamsen, 1992	Virginia	-	sprinkler
Tomato	Schweers & Grimes, 1976	California	14%	furrow
Tomato	Rose et al., 1982	California	20%	furrow
Tomato	Pruitt et al., 1984	California	13-19%	furrow
Tomato	Bogle et al., 1989	Texas	22%	furrow
Tomato	Yohannes & Tadesse, 1998	Ethiopia	39-54%	furrow
Tomato	Hanson & May, 2003	California	15-35%	sprinkler
Tomato	Semiz & Yurtseven, 2010	Turkey	14-27%	furrow
Zucchini	Rubeiz et al., 1989	Arizona	13%	furrow

Table 2: Percentage of Irrigated Acres by Irrigation Method in California

	Gravity (%)	Sprinkler (%)	Drip (%)	Other (%)
<b>2001</b>				
Alfalfa	80.3	17.4	0.0	2.2
Almond & Pistacchio	19.2	11.3	69.3	0.2
Beans (dry)	56.9	43.1	0.0	0.0
Corn	87.1	0.8	0.0	12.1
Cotton	93.9	5.1	0.0	1.0
Onion & Garlic	43.7	56.3	0.0	0.0
Tomato (fresh)	61.3	0.0	38.7	0.0
Tomato (process)	67.8	30.2	2.0	0.0
Vineyard	20.8	8.7	70.2	0.2
<b>2010</b>				
Alfalfa	77.1	17.8	2.5	2.6
Almond & Pistacchio	13.4	14.0	71.2	1.4
Beans (dry)	66.5	21.1	12.4	0.1
Corn	78.4	1.0	7.1	13.5
Cotton	73.0	7.3	15.4	4.3
Onion & Garlic	19.1	39.1	41.6	0.3
Tomato (fresh)	43.6	11.0	45.3	0.1
Tomato (process)	33.1	3.7	62.9	0.3
Vineyard	20.3	2.3	75.4	2.0

Source: California Department of Water Resources. Surveys of irrigated agricultural acreage in California by crop and by irrigation method in 2001 and 2010.

Table 3: Yield Effects of Irrigation Technologies (Crop-by-County Panel Data)

	(1)	(2)	(3)
	Yield (log)	Yield (log)	Yield (log)
Drip (% Irg. Acres)	0.2164* (0.1092)	0.2204* (0.1098)	0.2657* (0.1330)
Sprink (% Irg. Acres)	0.2399 (0.2637)	0.2422 (0.2645)	0.3338 (0.2147)
Other (% Irg. Acres)	0.0871 (0.1794)	0.0710 (0.1776)	0.5688 (0.4164)
Share of Harvested Acres		1.1848* (0.7054)	1.3343 (1.9556)
Mean of Dep Variable	1.6126	1.6126	1.6126
Num of Obs.	280	280	280
R squared	0.0507	0.0543	0.6036
Crop-County FE	Yes	Yes	Yes
Crop-Year FE	No	No	Yes
County-Year FE	No	No	Yes

Clustered Standard Errors in Parenthesis. Clusters are at the county level. There are 51 counties in the sample, across 9 crop categories (Alfalfa, Almond and Pistachio, Corn, Cotton, Dry Beans, Onion and Garlic, Fresh Tomato, Process Tomato, and Vineyards) and two years (2001, 2010). Irrigation technologies include Drip, Sprinkler, Gravity, and Other. Gravity is the omitted category.

\* $p < 0.10$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ .



Table 4: Yield Effects of Irrigation Technologies (Monterey County Panel Data)

	(1)	(2)	(3)
	Yield (log)	Yield (log)	Yield (log)
Drip (% Irg. Acres)	0.2563 (0.2641)	0.2921 (0.2626)	0.4790* (0.2716)
Sprink w/Furrow (% Irg. Acres)	-0.2707 (0.2802)	-0.2474 (0.2843)	0.5198 (0.5897)
Share of Harvested Acres		-7.9888** (2.8905)	-6.9550** (3.1691)
Mean of Dep Variable	2.160	2.160	2.160
Num of Obs.	376	376	376
R squared	0.049	0.056	0.120
Crop Fixed Effect	Yes	Yes	Yes
Year Fixed Effects	No	No	Yes

Clustered standard errors in parenthesis. Clusters are at the commodity level.

The sample includes 16 years (1993, 1996-2010) and 24 crops in Monterey County.

Crop categories are Vegetables, Tree, Field, Vines, and Berries. Irrigation technologies include Drip, Sprinkler w/Furrow, and Other. Other is the omitted category.

\* $p < 0.10$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

Table 5: Annual Increase in Californian Farm Income from Drip Irrigation under Various Yield Effects

Yield Effect of Drip Irrigation	Income Effect of Drip Irrigation	Increase in Net Farm Income (millions)
16%	5%	\$187
27%	9%	\$324
48%	16%	\$541

Assumptions: Californian net farm income in crop production is \$7.3 billion. Elasticity of demand for California agriculture is -1.5. Percentage of irrigated crops adopting drip is 60% of high-value crops and 15% of low-value crops. Percentage of agricultural crop value from high-value crops is 86%.