The Farmer and the Data:

How Wireless Technology is Transforming Water Use in Agriculture

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I. Introduction

Since the turn of the century, Americans' access and use of wireless technology has increased rapidly. Over the past ten years, wireless has transformed our society and industries across the economy.[1] In 2015, 98 percent of Americans were able to receive 4G wireless coverage,[2] and mobile data traffic grew by more than half.[3] It's no surprise that farmers are also turning to wireless technologies.

Agriculture is a critical component of the U.S. economy – both in terms of output and in terms of natural resource use. The agricultural sector, however, accounts for a disproportionate share of U.S. natural resource use. In 2013, U.S. farms contributed $166.9 billion to the U.S. gross domestic product ("GDP"), or about one percent of total GDP, and supported many other industries – such as food service and food manufacturing.[4] In contrast, over half of U.S. land is categorized as agricultural land and agriculture accounts for roughly 80 percent of the U.S.'s total consumptive water use.[5] Despite agriculture's heavy reliance on water less than 10 percent of irrigated farms in the U.S. used advanced irrigation management techniques, such as those using wireless technology.[6] Thus, wireless technology has the potential to not only help farmers more efficiently manage water use but to also add substantial value to the agricultural industry. This paper highlights the ways in which wireless technology can be used to more efficiently manage water use in U.S. agricultural production as well as the degree to which these technologies are yet to be adopted by U.S. farmers.

Farmers' access and use of mobile wireless technology has increased rapidly over the last few years. In 2013, 67 percent of U.S. farms had Internet access compared to just 51 percent in 2005, or a roughly 30 percent growth in Internet access.[7] Accompanying that growth in access was an even larger increase in the use of cellular networks to access the Internet. Twenty-four percent of farms with Internet access used wireless as their primary method of accessing the Internet in 2013, compared to just three percent in 2005.[8] In other words, in eight years there was over a 950 percent growth in the use of wireless technology amongst farms in the U.S. as their primary method of accessing the Internet.[9] The use of wireless technology among farmers continues to rise, 29 percent of farms reported wireless as their primary method of accessing the Internet in 2015.[10]

Between 2005 and 2013, wireless technology as a primary method of internet access grew by more than 950 percent across U.S. farms.

The benefits of the adoption and use of wireless technology in U.S. agricultural production are large. Farming is an inherently risky business; farmers must deal with natural disasters, unpredictable variations in rain, and wide fluctuations in the price of commodities.[11] Wireless technology can help mitigate these risks by providing farmers real-time access to weather and market conditions. Indeed, in 2007, researchers claimed new wireless agricultural technologies "show so much promise…that during the coming decade, wireless networks will offer the same type of quantum leap forward for farming that GPS provided during the past decade."[12]

That prediction is coming true. Today, farmers can use local wireless networks to access real-time information on the current conditions of their fields and the status and location of their equipment. Farmers can also use 3G and 4G networks on their smartphones or tablets to access real-time information on agricultural markets and their own farms remotely.

Wireless technologies are also helping solve two water-related challenges for farmers: scarcity and environmental impacts. Over the last few decades, water has become increasingly scarce, especially in Western states.[13] In the next ten years, 40 out of 50 states expect to have some type of water shortage.[14] As water becomes increasingly scarce farmers' irrigation costs are likely to rise – cutting into farmers' profits and the economic vitality of the agricultural industry.

Agricultural water use also has significant negative externalities on the local environment. Over-watering of crops causes nutrient runoff which can lead to "dead zones" in the world's oceans.[15] Second, the diversion of water for agricultural use can threaten environmentally sensitive areas and ecosystems.[16]

Wireless technology helps prevent farmers from both over- and under-watering their crops, helping address both challenges.[17] For example, wireless technology can be installed on soil moisture monitors to allow farmers to instantaneously access information on the actual soil moisture needs of their fields. Farmers can then use wireless technology to switch off their irrigator remotely to adjust to the crops' water needs.

As farmers use inputs, such as water, more efficiently, they are conserving environmental resources. The conservation of water in agricultural production is an important component of the United States Department of Agricultures' ("USDA") larger objective of promoting "sustainable agriculture."[18] Sustainable agriculture helps to ensure that we meet the needs of society today without compromising the welfare of future generations. In addition, by enabling farmers to use water more efficiently wireless technology increases farmers' profits.[19]

While the use of wireless technology by farmers has increased notably, there is still significant room for adoption of the technology in irrigation management. In 2013, nearly 80 percent of farms with irrigated land still used visual inspection of the crop as a method of deciding when to irrigate.[20] In comparison, only 11 percent of farms used a moisture sensing device as a method of deciding when to irrigate in 2013.[21] Since 2003, however, the number of farms using a soil moisture sensing device grew by nearly 50 percent.[22] If the number of farms adopting moisture sensing devices grew at the same rate from 2013 to 2023 then an additional 12,900 farms will have adopted the technology by 2023 – nearly 40,000 U.S. farms total.[23] Indeed, moisture sensing devices were the fastest growing method of irrigation decision-making of any method from 2003 to 2013.[24]

The use of moisture sensing devices grew at a faster rate than any other irrigation decision-making method across U.S. farms from 2003 to 2013.

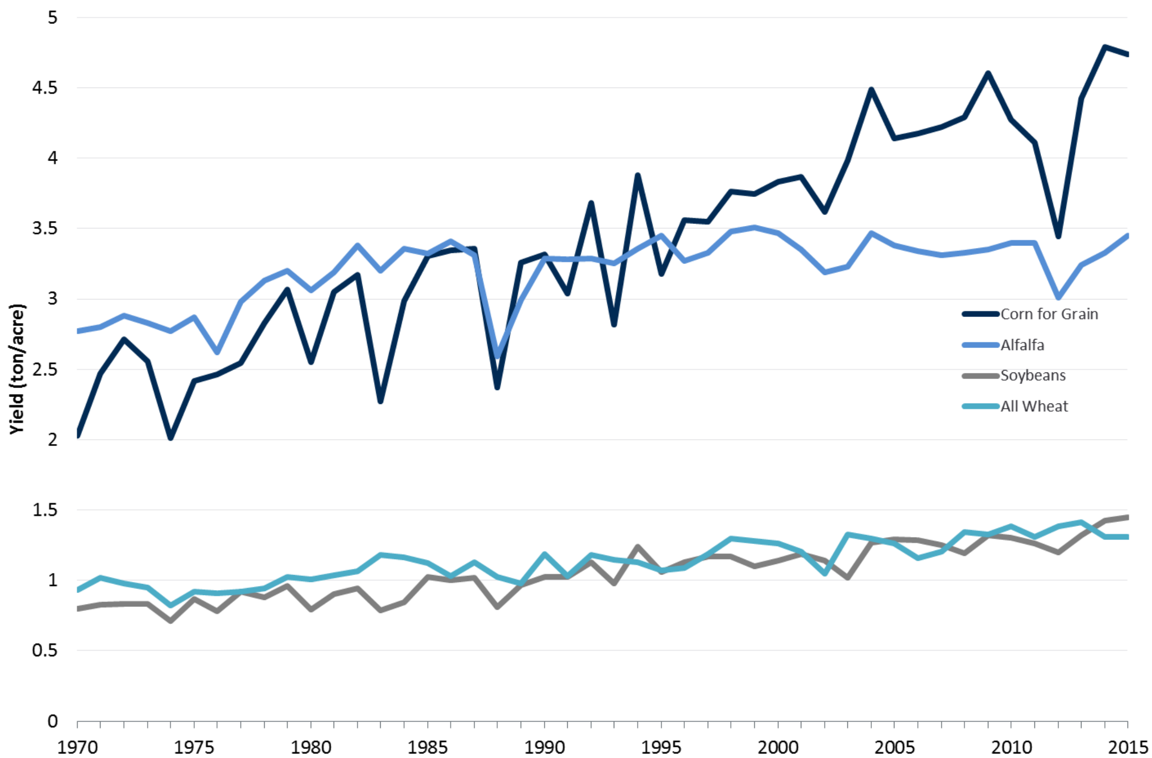
In this paper, we evaluate the ways in which wireless technology has the ability to enhance farmers' water-related decision making abilities in the U.S. We focus on the ways in which wireless technology is being used in irrigation management and the positive externalities this use has on water conservation and water quality. In Section II we provide an overview of irrigation and water use in U.S. agriculture. Section III describes the important role of wireless technology in agriculture, and in Section IV we review case studies from two key agricultural states, California and Minnesota, on the adoption and use of wireless technology in agricultural production. Finally, in Section V we present important lessons learned and conclusions.

II. Overview of Irrigation in U.S. Agricultural Production

The importance of agriculture will continue to increase as economics develop and populations grow. Scientists estimate that, by 2050, crop production will need to double to meet global food demand.[25] Increasing agricultural productivity is a critical component of meeting this growing food demand.

Agricultural production has become more efficient over the last fifty years with farmers able to produce much higher yields on the same amount of hectares.[26] Both partial and total factor productivity have increased in the U.S. over the last fifty years. "Partial factor productivity" measures average output per unit of a single factor, such as crop yield per acre.[27] As shown in Figure 1, field crop yields have increased substantially in the U.S. over the last forty-five years.[28] "Total factor productivity" ("TFP") measures the contribution of all agricultural inputs to production and is a significant driver of agricultural output growth.[29] The USDA estimates that agricultural TFP grew at an annual rate of 1.49 percent between 1948 and 2011.[30]

Figure 1: Top U.S. Field Crop Yields, 1970 – 2015



Sources and Notes: Corn, alfalfa, soybeans, and all wheat crops represented the top four field crops in terms of market value in 2014. Data from NASS, "Statistics by Subject – Crops and Plants," USDA, October 2, 2015, accessed December 6, 2015, http://www.nass.usda.gov/Statistics_by_Subject/?sector=CROPS.

Irrigation is an important driver of yields and TFP growth in U.S. agriculture. Farmers have been able to apply water more uniformly to their crops and to produce crops on previously unsuitable land with the development of irrigation technologies. The USDA estimates that, as of 2007, the average yield per acre of wheat was 2.2 times the amount on irrigated land as compared to non-irrigated land.[31] Corn, which the USDA estimated to have the highest productivity increase, still had a yield that was 1.2 times higher on irrigated land relative to non-irrigated land in 2007.[32]

Consequently, the adoption of irrigation has increased dramatically over the last several decades. In 1974, around when center-pivot irrigation systems first came into widespread use, more than 41 million U.S. acres were irrigated, or four percent of total farmland.[33] By 2012 over 55 million U.S. acres were irrigated, or six percent of total farmland.[34] This increase corresponds to a 35 percent growth rate.[35] Although irrigated land accounts for less than ten percent of farmland, farms with irrigated land accounted for 20 percent of the total market value of all U.S. agricultural products sold in 2012.[36]

A. Irrigation and Water Use

Agriculture accounts for roughly 80 percent of the U.S.'s total consumptive water use and up to 90 percent of total consumptive water use in some of the Western States.[37] In 2013 the USDA estimated that cropland accounted for 95 percent of all irrigated land with corn, soybeans, and alfalfa being the top three crops grown on irrigated land.[38]

Irrigating farms, however, is costly for farmers. Farmers must spend money on irrigation maintenance, labor, and electricity for pumping water. In 2013, farmers spent nearly $2.7 billion on energy expenses for irrigation pumping – or over $17,000 per farm annually.[39] Irrigation pumping costs are estimated to be, on average, $54 per acre for pumping from wells, and in California, the costs can be as high as $127 per acre.[40]

Irrigating farms also contributes to two primary water-related issues: scarcity and environmental externalities. First, water has become increasingly scarce. While Western states have recently experienced severe water shortages, nearly 80 percent of states are expected to face a water shortage in the next ten years.[41] Agriculture has also depleted some of the U.S.'s most important aquifers. The Ogallala Aquifer, which spans eight states from South Dakota to Texas and is one of the world's largest aquifers, has already been completely depleted in some areas.[42]

Second, the over-watering of crops causes nutrients to leach into groundwater, most notably nitrogen from fertilizer, which has a detrimental impact on water quality – both locally and globally. Runoff of nutrients can contaminate surface water.[43] One major issue stemming from water runoff is the creation of "dead zones," such as the famous ones in the Gulf of Mexico and the Chesapeake Bay; dead zones areas arise when nutrient runoff from agricultural and other human activities stimulate overgrowth of algae that consumes oxygen, creating anoxic conditions that can kill all marine life within that zone.[44] These dead zones are detrimental to ecosystems and significantly impact seafood and tourism industries.[45]

B. Overview of Irrigation Technologies

The USDA categorizes irrigation into four main types:[46] (1) gravity irrigation systems;[47] (2) sprinkler irrigation systems;[48] (3) drip irrigation systems;[49] and (4) subirrigation systems.[50]

Sprinkler systems are by far the dominant method of irrigation in the U.S., covering more than 60 percent of irrigated land in 2013.[51] Indeed, when center pivot irrigation systems were introduced in the 1970s they were described as the "most significant mechanical innovation in agriculture since the replacement of draft animals by tractors."[52]

Less than 10 percent of irrigated farms in the U.S. use advanced irrigation management techniques.[53] Instead, farmers decide when to turn on their irrigation systems based on their own knowledge of their farmland, manually checking soil moisture levels, or through an irrigation scheduling Excel workbook. All of these methods are ad hoc and can lead to inefficient water use. In addition, improved water-management practices are still not widespread and can help farmers "maximize the economic efficiency of their irrigation systems."[54]

III. Role of Wireless Technology in Water Management

To help address these two water-related environmental issues (e.g., scarcity and environmental degradation), farmers are turning to wireless technologies. Farmers can set up their own wireless local area networks ("WLANs") that sends data between electronic devices.[55] They can do this by connecting their LAN either to a conventional antenna (such as those used for two-way communications) or to a wireless cellular service. Linking to an antenna presents obstacles with interference and limited connectivity range, but when a WLAN connects to a cellular service, "distance is unlimited" and the reliability of the farm's network is just as good as the cell service around it.[56]

With wireless technology and the creation of WLANs farmers can access information remotely, enabling more efficient and timely decision making. In what follows, we review the ways in which wireless technology is used across the agricultural industry and then discuss more specifically the developments in wireless technology for irrigation management.

A. Breadth of Uses of Wireless Technology in Agriculture

Through better access to both more – and more accurate – information, wireless technology is a key component to helping farmers increase crop productivity. Specifically, wireless technology promotes precision agriculture, or the "application of information technology to farm-level production operations and management decision making."[57] That is, wireless technology allows farmers to collect "big data" to analyze, among other things, their farm specific input levels, soil samples, and yield levels with aggregated farm data on weather, cropping history, and historical yields.[58] The technology used is generally called "telematics."[59] Telematics can help farmers map their field boundaries, track equipment, and communicate across vehicles and other geographic areas.[60]

1. Equipment Management

The initial use of wireless technology in agriculture focused on management of equipment to include a machine's location, fuel consumption, utilization and status. Equipment management remains an important use of wireless in agricultural production. With wireless technology, farmers can manage their equipment from a smartphone or laptop from any remote location; farmers can remotely detect and resolve equipment problems saving them valuable time and resources. Costs are reduced by the more efficient use of equipment, improved productivity, and quicker response time to manage operations.[61]

For example, farmers can remotely track the capacity of their silos and can use the information to move other complementary equipment accordingly, such as grain carts. Farmers can also program and sync tractors for speed and location, which prevents spillage and gains maximum operational time for the equipment.

2. Drones

Unmanned drones are an example of a specific innovation employed to increase productivity and manage crop quality. Today, farmers are frequently using drones over more traditional crop-monitoring methods, such as satellite photography or manned airplanes, which can provide incomplete or delayed information.[62] Relative to manned airplanes, drones are also able to fly much closer to crops, enabling farmers to capture more detailed information, as close as leaf level.[63] Some drones have the additional advantage of being able to fly over a fixed point for a period of time, overcoming the common problem of needing to couple images taken by aircrafts with traditional flight paths.[64] Drones can be equipped with infrared cameras, sensors, and other technologies that collect a variety of relevant data to inform decisions regarding pesticides, herbicides, fertilizer, and irrigation.[65] For example, infrared cameras mounted on drones have been used to measure crop productivity based on visible and infrared radiation as well as to characterize the health of individual plants.[66]

Drone use is expected to continue to grow in agriculture. The Association for Unmanned Vehicle Systems International, a trade group representing producers and users of drones, predicts that 80 percent of the future commercial market for drones will be comprised of agricultural drones.[67]

Improved computer processing in smartphone technology, including gyroscopes, altimeters, and compasses, has made affordable domestic drone use possible and increasingly popular.[68]

3. Data Management, Interpretation, and Accessibility

Agricultural wireless technologies have advanced such that some systems not only provide farmers with richer information, but also make recommendations based on the data they gather. As one Iowa State University professor stated, a wireless connection "can make the difference between actually taking advantage of what your data can tell you rather than simply producing colorful maps each year."[69]

Advanced wireless sensor networks can gather data on parameters such as temperature, humidity, barometric pressure, soil moisture and acidity, and carbon dioxide levels, which can in turn be used to program networks controlling water pressure, heating and cooling, as well as the dispersal of fertilizer and pesticide.[70] Continuously operating reference station ("CORS") is a survey-grade GPS receiver at a known geographic location that continuously collects 3D positioning data.[71] These data can be used to support real-time kinematic ("RTK") applications, which provide continuous correction data to GPS receivers and can provide valuable information for numerous functions, such as installing tile line and managing drainage, and mapping field variations for VRI through high-fidelity elevation data.[72] Some companies have developed data-driven planting services that capitalize on synergies between data and equipment management. Service-providers analyze historical farming data with algorithms and human specialists, then send farmers a computer file containing equipment programming based on recommendations from their analysis.[73]

B. Specific Uses of Wireless Technology in Irrigation Management

Wireless technology has proven to be particularly beneficial to agriculture for irrigation management and water conservation by reducing the labor intensity of farming and creating pathways for more precise information about growing conditions.

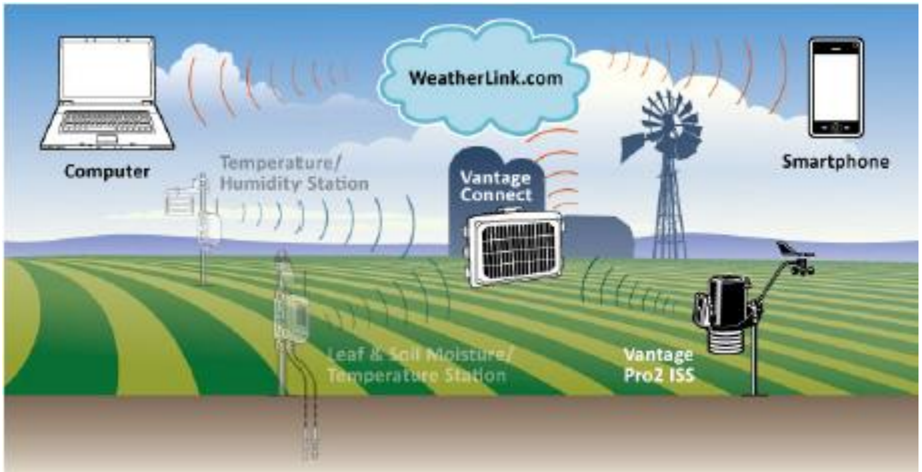
For example, wireless irrigation systems such as remote pivot controls and variable rate irrigation ("VRI") reduce the amount of labor required on farms while streamlining the irrigation process. Remote pivot controls give farmers the ability to direct pivot irrigation systems using satellite, cellular networks, or other telemetry systems rather than drive out to the fields and adjust their systems manually.[74] These controls give farmers the ability to start and stop pivots and chemigation,[75] to adjust pivot speeds, as well as to monitor the system's geographic position; they can also alert farmers through email or text message if a pivot shuts off unexpectedly or experiences a technical issue.[76] Finally, farmers can control the hydraulic commands of scraper blades, which improves the grading, ditching, and plane generation for irrigation.[77]

Similarly, VRI allows farmers to prescribe different watering intervals for different zones of their crop fields to improve irrigation efficiency.[78] For example, farmers can program different sections of sprinkler pipe to pulse off at prescribed intervals rather than watering crops continuously, which conserves water and prevents nitrogen loss from leaching.[79] Farmers whose soil conditions vary within fields can use VRI to apply water at different rates based on soil type rather than apply water at a single rate.[80] This heterogeneous water application avoids over-watering some soils while under-watering others.

Farmers can also use a telematics system to improve irrigation by collecting information on soil and plant moisture levels and weather conditions (e.g., temperature, humidity, and wind). One method for collecting such data is soil moisture sensors, which measure changes in soil water content in the root zone of crop fields and wirelessly transmit data to computers or tablets for farmers to review.[81] These systems connect to cellular or satellite modems, with some models taking soil moisture readings as often as every 30 minutes with multiple sensors placed at various depths underground.[82] Some technology firms have also embraced cloud-based data centers as a means of collecting and providing soil sensor data to farmers.[83]

The growth of the wireless agricultural technology industry has opened the door for synergies amongst these systems. For example, using soil moisture probes in conjunction with VRI can give farmers a more complete picture of crops' irrigation needs, preventing overwatering and reducing costs.[84] Other technologies, such as web-based irrigation scheduling systems, help guide the timing and quantity of irrigation through interactive computer models that synthesize data on soil type, local weather conditions, plant growth stage, and daily crop water use.[85] These systems can be particularly helpful when determining the timing of the first irrigation of the season, as often there is the temptation to begin watering crops too early.[86] Figure 2 shows a diagram of how telematics generally works in facilitating irrigation decisions.

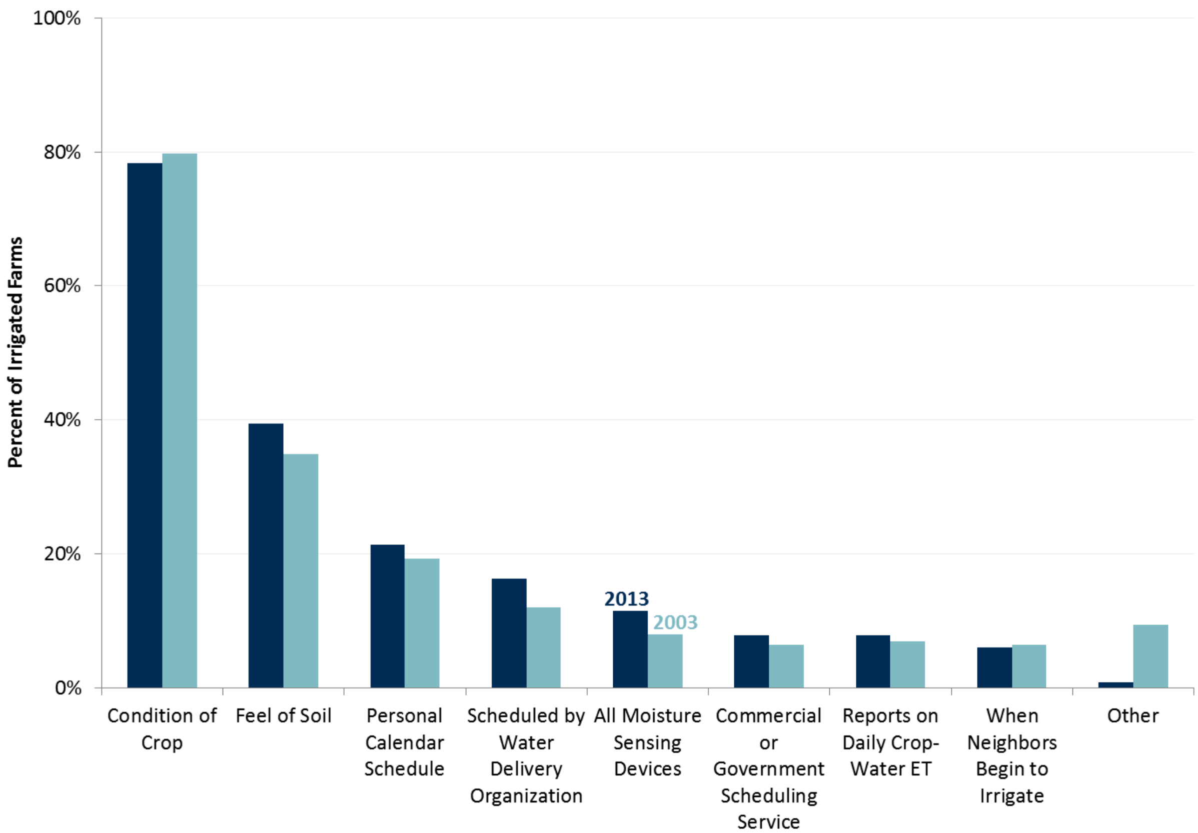
Figure 2: Telematics Irrigation System



Source: "Agricultural Weather Stations for Crop Success," Davis Instruments, accessed December 9, 2015, http://davisnet.com/weather/uses/agriculture-solutions/agricultural-remote-weather-station.asp

Historically, however, farmers have made decisions on when to irrigate their crops based on the visual inspection of the crop or the feel of the soil. Figure 3 shows a breakdown of the methods that farmers used to decide when to irrigate their crops in 2003 and 2013.

Figure 3: Methods Used in Deciding When to Irrigate, 2003 and 2013



Source: USDA, "2003 Farm and Ranch Irrigation Survey," p. 160; USDA, "2013 Farm and Ranch Irrigation Survey," p. 87.

Notes: 229,237 farms were surveyed in 2013 and 220,163 farms were surveyed in 2003. Respondents could choose more than one method. Moisture sensing devices include soil moisture and plant moisture sensing devices. 2013 figures exclude institutional, research, and experimental farms. 2003 figures exclude abnormal and horticultural specialty farms.

As shown in Figure 3, only 11 percent of irrigated farms used either a soil moisture or plant moisture sensing device when deciding when to irrigate in 2013, up from 8 percent in 2003. In 2013, Nebraska saw the highest rate of moisture sensor adoption at 23 percent, while less than 2 percent of irrigated Wyoming farms had adopted the technology.[87] In contrast, almost 80 percent of farmers using irrigation methods nationwide made watering decisions based on the condition of their crops.[88] Table 1 shows that moisture sensing devices were the fastest growing method of irrigation decision-making in the U.S. between 2003 and 2013; computer simulation models were the second-fastest growing method.

Table 1: Growth in Methods Used in Deciding When to Irrigate, 2003 to 2013

Methods Used in Deciding When to Irrigate	2003	2013	2003-2013 Percent Growth
[1]	[2]	[3]	[4]
Any Method	220,163	229,237	4.1%
Condition of Crop	175,560	179,490	2.2%
Feel of the Soil	76,731	90,361	17.8%
Personal Calendar Schedule	42,551	49,048	15.3%
Scheduled by Water Delivery Organization	26,537	37,301	40.6%
All Moisture Sensing Devices	17,645	26,325	49.2%
Commercial or Government Scheduling Service	14,190	17,982	26.7%
Reports on Daily Crop-Water Evapo-Transpiration (ET)	15,323	17,815	16.3%
When Neighbors Begin to Irrigate	14,080	13,717	-2.6%
Computer Simulation Models	1,285	1,915	49.0%

Sources and Notes: Respondents could choose more than one method. 2013 figures exclude institutional, research, and experimental farms and 2003 figures exclude abnormal and horticultural specialty farms. [1]: Moisture sensing devices include soil moisture and plant moisture sensing devices; [2]: USDA, "2003 Farm and Ranch Irrigation Survey," p. 160; [3]: USDA, "2013 Farm and Ranch Irrigation Survey," p. 87; and [4] = ([3] – [2]) / [2].

In 2013, 8,012 farms invested a total of $62 million in computers, control panels, and computer controlled valves for irrigation management[89] – up from only 3,954 farms in 2003 with total investments of $14 million.[90] As the USDA states:

> "Agricultural water conservation is both a farm and basin-level resource conservation issue…The sustainability of irrigated agriculture may depend partly on the willingness and ability of producers to adopt irrigation 'production systems' that more effectively integrate improved water management practices with efficient irrigation application systems."[91]

C. The Development of Wireless Technology Systems for Irrigation Management

As farmers' use of wireless continues to rise their demand for wireless technologies will also grow. Indeed, agriculture is cited as one of the "most fertile laboratories for Internet of Things ("IoT") innovation and large-scale adoption"[92] and as the "last frontier for a lot of different technolgoies."[93] In the third quarter of 2014 alone venture capitalists invested $269 million in agricultural and food startups – a record amount.[94] Traditionally, the agricultural industry has been slow to adopt these technologies but "farmers are increasingly looking to use tech to reduce their use of water and fertilizer to save money."[95]

Table 2 provides a list of companies that we identified as providing telematics service for use in irrigation management. The list demonstrates the range of services available to farmers and the number of different companies offering these services. Moreover, the majority of these services have only started to be offered to farmers in the last six years. The wireless transfer of farm-level data collected with a telematics system can improve a farmer's turnaround time and reduce chances of error. In addition, wireless data collection allows one farmer's data to be analyzed in conjunction with another farmer's data to create more accurate, but still individual-based, recommendations on field management.[96]

Table 2: Companies Providing Telematic Services for Irrigation Management[97]

	Company	System	Year Launched	Communication Method	Data File Transfer
[1]	AGCO	AgCommand Basic Plus	2010	Cellular	No
[2]		AgCommand Advanced	2010	Cellular	No
[3]		FUSE	2013	Cellular, Satellite	Yes
[4]		VarioGuide and Auto-Guide*	2015	Satellite	Yes
[5]	Raven	Slingshot			Yes
[6]	John Deere	JDLink Ultimate	2011	Cellular, Satellite	Yes
[7]		JDLink Connect		Cellular, Satellite	Yes
[8]	Trimble	Connected Farm		Cellular, Radio	Yes
[9]	Case IH	AFS Connect Manager		Cellular	Yes but N/A
[10]		AFS Connect Executive		Cellular	Yes but N/A
[11]	Hortau	WEB-TX 4	2002	Cellular, Cloud	Yes

Notes: Cloud-based refers to the use of the Internet for computing and data storage. Information is then available to users on-demand via computers, tablets, and smartphones. Information not available for empty cells.

These recent initiatives are also frequently being promoted through collaborations across the industry. For example, DuPont Pioneer and AGCO Corporation announced a global collaboration in 2014 that aimed to provide farmers with wireless data transfer technology solutions that allowed "seamless interface of data and farm management information between AGCO equipment and Encirca services."[98] In addition, in 2013 John Deere and Fontanelle Hybrids teamed up to research the impact of moisture probes on a farmer's water use.[99] The study found that using John Deere's Field Connect system could save as much as two inches of water per acre and increase corn yields by as much as five and a half bushels per acre.[100] More recently, John Deere formed a joint venture with DN2K – named SageInsights – that will focus on developing DN2K's Internet-based computing platform, MyAgCentral, to better serve the agricultural industry.[101]

IV. Case Studies

In this section we highlight recent innovations and implementation of wireless technology in California and Minnesota. We selected these two states for case studies because they both rank in the top five in terms of crop production,[102] and they span a range of climates and water practices. As a result, an examination of California and Minnesota provides insight into the use of wireless technology in agriculturally-important states in both the West and the Midwest, two of the United States' principal growing regions.[103] For each state we discuss both the agricultural and environmental challenges faced by the state as well as the creative ways in which wireless technology is being promoted to solve the problem.

A. California

California is the largest agricultural producer in the U.S. and is one of the highest producing agricultural regions in the world; in 2013, California's 44,343 farms contributed nearly $28 billion to the state's GDP, or approximately 1.3 percent of the state's total GDP.[104] In 2013, California produced over one third of the country's vegetables and two thirds of the country's fruits and nuts.[105] In the same year, California accounted for 21.1 percent of U.S. field crop exports, 62.7 percent of fruits and fruit product exports, 100 percent of tree nut exports, and 61 percent of vegetable exports.[106] In 2013 California's top-valued crop was almonds, followed in order by grapes, strawberries, walnuts, and lettuce.[107] California is also the only state in the U.S. that produces a number of crops, including almonds, artichokes, raisins, olives, pistachios, and walnuts.[108]

Supporting such a large agricultural industry requires large amounts of water. On average, agriculture consumes 40 percent of California's available water, and irrigation of California's approximately 9 million acres of irrigated farmland accounts for 80 percent of all human water use in the state.[109] California farmers are among the nation's leaders in the adoption of wireless irrigation technology. Nearly 22 percent utilized soil or plant moisture sensing devices in considering when to irrigate their crops.[110]

Undoubtedly the most significant challenge facing California agriculture is the severe drought currently plaguing the western U.S. At the end of the 2015 "water year," California's spring snowpack contained just 5 percent of a normal year's water level while major reservoirs held 59% of their historical averages.[111] This situation led many farmers to turn to pumping additional groundwater, which has depleted aquifers and caused some parts of the state to sink by as much as 33 centimeters in less than one year.[112]

Water use is further complicated in California by its hierarchical water rights system. Unlike other states, California has a mixed system of riparian and appropriative rights.[113] This water rights system is seen by some as discouraging water conservation, because priority rights holders can experience cuts in their water allocations if they do not utilize their allotments in a given year.[114]

1. Tom Rogers' Almond Ranch in Madera County, CA

Tom Rogers is a California farmer who has turned to wireless technology to solve challenges presented by California's current drought. He owns a 176 acre almond orchard in Madera County, California. Because almond trees are permanent crops and therefore require attention to long-term plant health, maintaining detailed information about individual trees, soil permeability, and microclimates is particularly important to almond farmers.[115] Rogers' ranch utilizes wireless technology in the form of soil and plant moisture monitoring as well as weather information from on-site stations to inform decision-making for both when and how much to irrigate.[116] Soil probes measure soil moisture at the tree root profile at intervals of 15 minutes, showing precisely how water moves through the soil and whether it is being absorbed by tree roots, while weather stations connected by the California Irrigation Management System provide real-time data on temperature, humidity, wind speed, and rainfall, revealing how much water is cycling through the orchard.[117]

Rogers estimates that this system of irrigation scheduling has reduced his orchard's water use by up to 20 percent in some fields and has resulted in higher water-use efficiency overall.[118] These findings are consistent with a previous report published by the Pacific Institute, a global water think tank in California, which found that improved irrigation scheduling has been shown to reduce water use anywhere from 11 to 50 percent.[119]

"In order to know what's going on, you have to monitor," Rogers said of this system. "It's just absolutely imperative that you know where your water is, and if you're actually using it or flushing it through the system."[120] Utilization of wireless technology at this almond ranch has created numerous benefits for the farm beyond more careful water use. Rogers reports higher crop yields compared to neighboring comparable farms, improved plant health, and protection from frost.[121]

2. Camalie Vineyards and "Camalie Networks" in Mount Veeder, CA

Another innovator in California is Mark Holler, who owns the Camalie Vineyard in Northern California and who developed and now sells his own agricultural wireless technology system. Holler's system, called "Camalie Networks," aims to reduce water and energy consumption while increasing crop yield and improving grape quality.[122]

The Camalie Vineyard encompasses several microclimates and soil types, each possessing unique needs at any given time; to better address the specific needs of each part of his vineyard, Holler has employed wireless sensing stations that collect, process, and transmit information on soil moisture, temperature, humidity, water flow, and fermentation rates to his desktop computer.[123] Because the data is sent wirelessly and is readily accessible, Holler can easily monitor his vineyards from miles away, often being alerted to changes in farm operations before anyone else.[124] This information was of particular use to Holler in 2007, when his vineyard experienced an unusually dry spring and summer, receiving only 16 inches of rain compared to 40 inches in 2006; utilizing data on leaf water potential and soil moisture tension for each microclimate, Holler used 149,000 gallons of water during the 14-week irrigation season, a 26 percent reduction from 2006, despite the drought, and doubled the yield of his 4-year-old Cabernet Sauvignon vines from 8 tons to 16 tons.[125] "You better believe I wasn't trucking in any more water than I had to," Holler said of that season. "Knowing the exact soil moisture at 10 locations meant that I did not have to purchase any more water than absolutely necessary."[126] Holler attributes improved water efficiency to the wireless technology as well, reporting that the vineyard was able to grow 3.9 tons of Cabernet Sauvignon grapes per acre in 2007 by irrigating each vine with just 34 gallons of water from June until harvest.[127] Holler has also explored using his wireless nodes and network for his vineyard's fermentation process to measure air temperature, humidity, and pressure inside fermentation tanks.[128]

3. Qualcomm and Verizon

Recently, both Qualcomm and Verizon have piloted efforts in telemetry and data analytics in California agriculture. Verizon has a pilot project with the 1,000-acre Hahn Family Winery. The winery has sensors in the soil near the root zones of its plants to estimate how much water is being delivered to the vines. The winery also has sensors in the canopy of the grapevines that record humidity and temperature in various locations. This system allows the winery to water the plants when they need the water rather than doing so based on time intervals.[129] Since implementing the system, Hahn Family Wines found that they were overwatering in some areas of the vineyard while under-watering in other when they used the fixed amount per week system.[130]

Qualcomm and engineering company CH2 implemented water sensoring on an avocado farm.[131] Avocado production in California is responsible for 83 percent of all avocados produced in the U.S. A mature avocado tree needs 450 gallons of water per week to keep the tree healthy and produce fruit and the price of water has increased by more than 200 percent in the last few years.[132] Qualcomm and CH2 are looking to take existing sensors and make them smarter by bringing smartphone technology to the wireless industry.[133] More specifically, they seek to use Qualcomm's secure networks to give real-time information about how water is being used in transport systems and what the costs of delivery are.[134]

B. Minnesota

In 2012, Minnesota boasted the fourth largest crop output among all states.[135] That year, Minnesota's 74,000 farms generated nearly $14 billion in sales,[136] contributing more than five percent of the state's GDP.[137] Corn, soybeans, and hay are the state's top grossing crops in terms of value of production, accounting for nearly 60 percent of the market value of Minnesota's crops.[138] Approximately 27 million acres[139] (49 percent) of Minnesota's 55.6 million acres of land are used for farm operations.[140]

In 2013, nearly 11 percent of Minnesota's water usage was for irrigation,[141] with 13 percent of farms employing moisture sensing devices in deciding when to irrigate.[142] Approximately 90 percent of the water used in Minnesota's agricultural irrigation is groundwater.[143] Irrigation is the second most common use for groundwater in Minnesota, and is growing far faster than any other use. Between 1988 and 2011, the Minnesota agriculture industry consumed 26 percent of the groundwater pumped in the state.[144]

In contrast to western states that have prior appropriation rights, water is a shared resource in Minnesota. An appropriation permit, for which anyone may apply, is available through the Minnesota Department of Natural Resources ("DNR") and is required for usage of over 10,000 gallons per day or 1 million gallons per year.[145] Agricultural water use is publicly reported through the DNR. Unlike many western states, Minnesota's water challenges are not primarily marked by fears of water shortages or decreasing aquifer levels. Rather, water-related challenges in Minnesota are more frequently related to chemical runoff, particularly nitrate pollution, across the state's many lakes, rivers, and streams.[146] Minnesota may also be at risk of unsustainable groundwater usage,[147] but water contamination remains the focus of public discussion. Nevertheless, efficient water use is a key solution to mitigate this harm.

Extension officers and local soil water conservation districts ("SWCD") promote remote irrigation management systems with the aim of reducing nutrient leaching and fertilizer runoff caused by the over-watering of crops.[148] Joshua Stamper, University of Minnesota Extension Irrigation Specialist, estimates that the use of remote irrigation technologies in Minnesota could save somewhere in the magnitude of 1.5 acre inches of water per year.[149] In the 1990s, portions of

Minnesota began to adopt irrigation scheduling, a targeted watering practice that aims for more efficient crop irrigation and reduced nitrate content of drinking water.[150] Farmers that have not yet adopted the more precise approach tend to water their crops when their neighbors do or when their crops appear stressed.[151]

1. East Otter Tail Soil and Water Conservation District Outreach

In central Minnesota, many farms are embracing the water conservation practices made possible through technology and collaboration with local SWCDs. For an annual payment of $200, SWCD technicians in Otter Tail County will make site visits and use a formula that considers various factors, including solar radiation and air temperature, in order to calculate a farm's level of evapotranspiration and determine if watering is necessary.[152] This information is used in conjunction with measurements made using several weather stations scattered across the region that measure temperature, solar radiation, wind velocity, humidity, and rain, and use cellular modems to transmit data to SWCD offices for analysis.[153]

Another program, the Central Minnesota Ag Weather Network, makes several types of data available through the East Otter Tail SWCD website free of charge.[154] From mid-April through the end of the growing season, hourly and daily weather data are available to farmers in Otter Tail County and several of its neighboring counties.[155] Provided through a partnership between the East Otter Tail SWCD and the Minnesota Department of Agriculture,[156] the Ag Weather Network information tracks rainfall, temperature, humidity, evapotranspiration, and growing degree days.[157] The program is partially designed to promote the efficient use of water for irrigation.[158]

Darren Newville, district manager of the Easter Otter Tail SWCD, has expressed support for the creation of a wireless app that would enable farmers to process and visualize data in order to aid in their irrigation practices.[159] Indeed, the 2011 Forum on Minnesota Irrigated Agriculture noted that a cellphone app to manage its irrigation scheduling is a high priority.[160] The Ag Weather Network currently provides data updates via email[161] and hopes to have a mobile application available to farmers in 2016.[162]

2. Sherburne Soil and Water Conservation District Outreach

In 2014, the Sherburne Soil and Water Conservation District received a $150,000 grant from the Clean Water Fund to use automated soil moisture probes on farms in order to reduce the amount of nitrogen and other nutrients leaching into groundwater.[163] The Sherburne SWCD hopes that by "combining automated soil moisture probes, cell phone technology, and the Internet, this project will provide real time soil moisture conditions to farmers who can use that information to provide improved irrigation scheduling and prevent leaching of nutrients below the crop root zone."[164] To date, their work has focused on determining if this technology can make water use more efficient and if it would reduce the amount of nitrate leaching into the water supply.

Bill Bronder, District Technician for the Sherburne SWCD, notes that both AgSense and John Deer Field Connect technologies have been installed on local farms growing potatoes, corn, and soybeans.[165] These sensors have allowed participating farmers to receive realtime soil moisture data on their cellphones and laptops. The Sherburne SWCD has installed the sensors on local farms each of the past two years, providing five John Deere Field Connect systems and one AgSense system in 2014 and four Field Connects and two AgSense systems in 2015.[166] Thus far, the data from these sensors have been used as a point of comparison for farmers' activities rather than as a determining factor in their farming behavior.[167] As farmers become more comfortable with technologies such as soil moisture sensors, agricultural decisions can be made using the data they provide. As a result, water could be used more efficiently, the leaching of nitrogen and other nutrients could be reduced, and crop yields could potentially be increased.

V. Conclusions and Lessons Learned

Agriculture is a critical component of the U.S. economy – agriculture and agriculture-related industries contributed over four percent of U.S. GDP in 2013 and employed over 17 million people in 2014.[168] The use of wireless technology as a farm's primary method of Internet access grew by over 950 percent between 2003 and 2013.[169] Today, almost 30 percent of U.S. farms with Internet access use wireless as their primary method of accessing the Internet.[170] As the use of wireless technology on farms has grown, the availability and development of wireless technology for agriculture has increased. The use of moisture sensing devices was the fastest growing irrigation decision-making method between 2003 and 2013.[171] Despite this rapid growth, less than 10 percent of irrigated farms use advanced irrigation management techniques.[172]

For agriculture, these new wireless technologies are critical tools for providing farmers with real-time access to information on soil moisture levels, weather, and irrigation equipment. With this information, farmers are able to make more efficient decisions regarding the irrigation of their crops. This increased decision-making power increases farmer profits, conserves water, and improves water quality. Agriculture, and irrigation management in particular, is seen as one of the most fertile areas for the Internet of Things. For example, a Minnesota farmer was recently able to monitor his equipment and crop characteristics during the 2014 harvest nearly 100 miles away while in the hospital undergoing treatment for cancer:

> "I knew [the combine's] speed, the yield and the moisture of the grain. It gave me a lot of ease that I could lay in the hospital and look at the technology on the device and see what was going on at the farm."[173]

Adoption of wireless technologies in irrigation management appears to be increasing rapidly. As highlighted by California and Minnesota, U.S. states are making significant investments in promoting the use of wireless technology in the agricultural sectors. More companies are beginning to pilot and release irrigation management technologies that incorporate the use of cellular communication. As states continue to receive funds to promote wireless technology in agriculture we can expect to see the adoption of these new irrigation management techniques increase dramatically.

Where wireless technology has been adopted for irrigation management farms have realized significant benefits. The uses and benefits of wireless technology for irrigation management vary geographically. Some states, such as California, can rely on wireless technology to manage water use in the face of drought while others, such as Minnesota, can rely on wireless technology to manage water use to avoid nutrient run-off and groundwater contamination. In all cases, better management of irrigation, and the incorporation of wireless technology, is likely to bring significant benefits.

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1 The wireless industry benefits many sectors of the U.S. economy; every dollar in wireless industry revenue supports $1.32 in additional revenue for the U.S. economy and every job in the wireless industry supports over six additional jobs in the U.S. See Coleman Bazelon and Giulia McHenry, "Mobile Broadband Spectrum: A Vital Resource for the American Economy," CTIA, May 11, 2015, pp. 18-21, http://www.brattle.com/system/publications/pdfs/000/005/168/original/Mobile_Broadband_Spectrum_-_A_Valuable_Resource_for_the_American_Economy_Bazelon_McHenry_051115.pdf?1431372403.

2 Office of the Press Secretary, "Fact Sheet: Next Steps in Delivering Fast, Affordable Broadband," The White House, March 23, 2015, accessed April 4, 2016, https://www.whitehouse.gov/the-press-office/2015/03/23/fact-sheet-next-steps-delivering-fast-affordable-broadband.

3 Cisco estimates that mobile data traffic in the U.S. grew by 56% in 2015. Similarly, Ericsson estimates that mobile data traffic on smartphones in North America was up from 483 petabytes (PB) per month in 2014 to 986 PB / month in 2015 and that mobile data traffic on mobile personal computers, routers, and/or tablets was up from 187 PB / month in 2014 to 266 PB / month in 2015. See "VNI Mobile Forecast Highlights, 2015-2020: United States – 2015 Year in Review," Cisco, accessed April 4, 2016, http://www.cisco.com/assets/sol/sp/vni/forecast_highlights_mobile/index.html#~Country; and "Traffic Exploration," Ericsson, accessed April 18, 2016, http://www.ericsson.com/TET/trafficView/loadBasicEditor.ericsson.

4 Agriculture and agriculture-related industries contributed $789 billion to the U.S. GDP in 2013 and provided 17.3 million jobs in 2014. "Ag and Food Sectors and the Economy," USDA Economic Research Service, May 14, 2015, accessed November 25, 2015, http://ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/ag-and-food-sectors-and-the-economy.aspx.

5 Consumptive use estimates measure the amount of water consumed by the crop that is not returned to the water resource system. "Irrigation and Water Use," United States Department of Agriculture ("USDA") Economic Research Service, accessed November 18, 2015, http://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use.aspx; and "Agricultural Production is a Major Use of Land, Accounting for Over Half of the U.S. Land Base," USDA Economic Research Service, accessed April 11, 2016, http://www.ers.usda.gov/data-products/chart-gallery/detail.aspx?chartId=40023&ref=collection&embed=True&widgetId=39734.

6 Glenn D. Schaible and Marcel P. Aillery, *Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands*, Economic Information Bulletin No. 99, USDA Economic Research Service (September 2012): pp. iv, accessed November 25, 2015, http://www.ers.usda.gov/media/884158/eib99.pdf.

7 In 2013 there were 2,094,250 farms in the U.S. compared to 2,092,550 farms in the U.S. in 2005. Calculation: 31.5% = 0.315 = ((0.67 x 2,094,250) – (0.51 x 2,092,550)) / (0.51 x 2,092,550). National Agricultural Statistics Service ("NASS"), "Farm Computer Usage and Ownership," USDA, July 2005, p. 8, accessed November 30, 2015, http://usda.mannlib.cornell.edu/usda/nass/FarmComp//2000s/2005/FarmComp-08-12-2005.pdf; NASS, "Farm Computer Usage and Ownership," USDA, August 2007, p. 21-24, accessed December 22, 2015, http://usda.mannlib.cornell.edu/usda/nass/FarmComp//2000s/2007/FarmComp-08-10-2007.pdf; and NASS, "Farm Computer Usage and Ownership," USDA, August 2015, p. 9 and pp. 25-28, accessed November 30, 2015, http://usda.mannlib.cornell.edu/usda/current/FarmComp/FarmComp-08-19-2015.pdf.

8 NASS, "Farm Computer Usage and Ownership," July 2005, p. 18; and NASS, "Farm Computer Usage and Ownership," August 2015, pp. 22-23.

9 Calculation: 952% = 9.52 = ((0.67 x 2,094,250 x 0.24) – (0.51 x 2,092,550 x 0.03)) ÷ (0.51 x 2,092,550 x 0.03).

10 NASS, "Farm Computer Usage and Ownership," August 2015, pp. 22-23.

11 For example, in July 2015 farmers in Illinois had such flood-damaged crops that they sought a federal disaster declaration. In Illinois' Iroquois County alone flooding drowned approximately 40 percent of crops following record rainfall in June 2015. See Associated Press, "Disaster Declaration Sought to Help Flooded Illinois Farmers," *The Washington Times*, July 22, 2015, accessed December 22, 2015,

http://www.washingtontimes.com/news/2015/jul/22/disaster-declaration-sought-to-help-flooded-illino/.

12 G. Vellidis, V. Garrick, et al., "How Wireless Will Change Agriculture," *Precision Agriculture* 7 (2007): p. 2, accessed November 25, 2015, http://vellidis.org/wp-content/uploads/2013/04/Vellidis.How_.Wireless.Will_.Change.Agriculture.6ECPA.pdf.

13 Western states have faced drought conditions for 11 of the past 14 years that have resulted in severe water shortages. Brian Clark Howard, "Worst Drought in 1,000 Years Predicted for American West," *National Geographic*, February 12, 2015, accessed April 1, 2016, http://news.nationalgeographic.com/news/2015/02/150212-megadrought-southwest-water-climate-environment/ and Ellie Kincaid, "California Isn't the Only State with Water Problems," *Business Insider*, April 21, 2015, accessed December 7, 2015, http://www.businessinsider.com/americas-about-to-hit-a-water-crisis-2015-4.

14 Kincaid, "California Isn't the Only State with Water Problems." For information on individual states' water challenges, see Water Sense, "State Water Facts," United States Environmental Protection Agency, accessed December 7, 2015, http://www3.epa.gov/watersense/our_water/state_facts.html.

15 The second largest dead zone in the world is the Gulf of Mexico dead zone, a 6,474 square mile region that was created and continues to exist due to nitrogen and phosphorus washed into the gulf from sources along the Mississippi River; the dead zone costs the U.S. seafood and tourism industries an estimated $82 million per year, impacting a region that supplies more than 40 percent of the country's seafood. See "2015 Gulf of Mexico Dead Zone 'Above Average'," National Oceanic and Atmospheric Administration ("NOAA"), August 4, 2015, accessed December 7, 2015, http://www.noaanews.noaa.gov/stories2015/080415-gulf-of-mexico-dead-zone-above-average.html.

16 For example, in the Sacramento-San Joaquin River Delta, water exports have resulted in the deterioration of an ecosystem that supports 20 endangered species. See California State Water Project, "Where Rivers Meet – The Sacramento-San Joaquin Delta," California Department of Water Resources, 2015, accessed December 7, 2015, http://www.water.ca.gov/swp/delta.cfm.

17 Over-watering crops can result in nitrogen leaching and runoff, increased weed pressure, and increased potential for crop yield losses due to fungal and bacterial foliar and root rotting diseases. Under-watered crops experience wilting and even potentially the death of a plant. See Suat Irmak, "Plant Growth and Yield as Affected by Wet Soil Conditions Due to Flooding or Over-Irrigation," NebGuide, University of Nebraska-Lincoln Extension, Institute of Agriculture and Natural Resources (April 2014), accessed December 14, 2015, http://extensionpublications.unl.edu/assets/pdf/g1904.pdf and Hal Werner, "Measuring Soil Moisture for Irrigation Water Management," South Dakota State University College of Agriculture & Biological Sciences (April 2002), p. 1, accessed December 1, 2015, http://pubstorage.sdstate.edu/agbio_publications/articles/fs876.pdf.

18 Sustainable agriculture was addressed by the U.S. Congress in the Food, Agriculture, Conservation, and Trade Act of 1990. The term was then defined as "an integrated system of plant and animal production practices having a site-specific application that will, over the long term: (i) Satisfy human food and fiber needs; (ii) Enhance environmental quality and the natural resource base upon which the agricultural economy depends; (iii) Make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; (iv) Sustain the economic viability of farm operations; and (v) Enhance the quality of life for farmers and society as a whole." See "Sustainable Agriculture: Definitions and Terms," USDA, National Agricultural Library, accessed November 18, 2015, http://afsic.nal.usda.gov/sustainable-agriculture-definitions-and-terms-1#toc2.

19 Irrigation management establishes the "proper timing and amount of irrigation for greatest effectiveness. This will minimize yield loss due to crop water stress, maximize yield response to other management practices, and optimize yield per unit of water applied." See Irmak, "Plant Growth and Yield."

20 Moisture sensing devices include soil moisture and plant moisture sensing devices. USDA, "2013 Farm and Ranch Irrigation Survey," 2012 Census of Agriculture, November 2014, p. 87, accessed December 7, 2015, http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris13.pdf.

21 Moisture sensing devices include soil moisture and plant moisture sensing devices. USDA, "2013 Farm and Ranch Irrigation Survey," p. 87.

22 In 2013, 26,325 farms reported using either a soil moisture or plant moisture sensing device ompared to 17,645 farms in 2003. Calculation: 49% = 0.4919 = (26,325 – 17,645) / 17,645. USDA, "2003 Farm and Ranch Irrigation Survey," 2002 Census of Agriculture, November 2004, p. 160, accessed December 7, 2015, http://www.agcensus.usda.gov/Publications/2002/FRIS/fris03.pdf; and USDA, "2013 Farm and Ranch Irrigation Survey," p. 87.

23 Calculation: 39,275 farms = 26,325 farms x (1 + 49.2%).

24 See Table 1.

25 Jonathan Foley, "Feeding Nine Billion," *National Geographic Magazine* (May 2014), accessed December 23, 2015, http://www.nationalgeographic.com/foodfeatures/feeding-9-billion/.

26 This trend has been both within the United States and on a global level. The increase in agricultural productivity by producing a higher yield on the same amount of hectares is referred to as agricultural intensification. Agricultural production increases can also be achieved through agricultural extensification, e.g., the conversion of land to farm land. See David Tilman et al., "Agricultural Sustainability and Intensive Production Practices," *Nature*, August 8, 2012, accessed November 18, 2015, http://www.nature.com/nature/journal/v418/n6898/pdf/nature01014.pdf.

27 Sun Ling Wang, Paul Heisey, David Schimmelpfennig, and Eldon Ball, *Agricultural Productivity in the United States: Measurement, Trends and Drivers*, Economic Research Report 189, USDA Economic Research Service (July 2015), accessed November 25, 2015, http://www.ers.usda.gov/media/1875389/err189.pdf.

28 Figure 1 shows the crop yields for the four field crops with the largest value in 2014. Corn had the largest value with an estimated $52 billion in crop value. Soybeans were second with $40 billion in crop value, wheat was third with almost $12 billion in crop value, and alfalfa was fourth with $10.8 billion in crop value. See NASS, "Crop Values 2014 Summary," USDA, February 2015, accessed December 6, 2015, pp. 9-10, http://usda.mannlib.cornell.edu/usda/current/CropValuSu/CropValuSu-02-24-2015_correction.pdf.

29 Wang, Heisey, Schimmelpfennig, and Ball, *Agricultural Productivity in the United States,* p. 38.

30 Wang, Heisey, Schimmelpfennig, and Ball, *Agricultural Productivity in the United States*, p. 5

31 This ratio is measured as the average crop yield on irrigated land divided by the average crop yield on non-irrigated land. Note that this ratio does not account for any other important differences that may affect crop yield across irrigated and non-irrigated land, such as land quality, local weather patterns, or a farmer's crop management skills. See Wang, Heisey, Schimmelpfennig, and Ball, *Agricultural Productivity in the United States,* p. 52.

32 Wang, Heisey, Schimmelpfennig, and Ball, *Agricultural Productivity in the United States,* p. 26 and 52.

33 In 1974 approximately 1 billion acres of land were categorized as farmland in the U.S. Calculation: 4.1% = 0.041 = 41,243,023 acres of irrigated farmland ÷ 1,017,030,357 acres of farmland. See "1974 Census of Agriculture," U.S. Department of Commerce, Bureau of the Census (Volume 1, Part 51): Table 2, accessed December 4, 2015, http://usda.mannlib.cornell.edu/usda/AgCensusImages/1974/01/51/1974-01-51.pdf.

34 In 2012 approximately 900 million acres of land were categorized as farmland in the U.S. Calculation: 6.1% = 0.061 = 55,822,231 acres of irrigated farmland ÷ 914,527,657 acres of farmland. See "2012 Census of Agriculture," U.S. Department of Commerce, Bureau of the Census (Volume 1, Part 51): p. 17, Table 9, accessed December 4, 2015, http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf; and "1974 Census of Agriculture," Table 2.

35 Calculation: 35% = 0.35 = (55,822,231 - 41,243,023) ÷ 41,243,023.

36 The total market value of agricultural products sold in the U.S. in 2012 was nearly $395 billion. The total market value of agricultural products sold from farms with irrigated land in the U.S. in 2012 was over $150 billion. Calculation: 38.6% = 0.386 = $152,421,721,000 irrigated market value ÷ $394,644,481,000 total market value. See "2012 Census of Agriculture," Department of Commerce, p. 18, Table 11.

37 Consumptive use estimates measure the amount of water consumed by the crop that is not returned to the water resource system. "Irrigation and Water Use," USDA Economic Research Service. For a complete description of water use terms see "Agriculture: A Glossary of Terms, Programs, and Laws, 2005 Edition," Congressional Research Service Report for Congress (June 16, 2005), accessed December 8, 2015, http://digital.library.unt.edu/ark:/67531/metacrs7246/m1/1/high_res_d/97-905_2005Jun16.pdf.

38 In contrast to the U.S. Geological Survey, the USDA reports water as the amount of water applied to the field using an irrigation system. See USDA, "Irrigation: Results from the 2013 Farm and Ranch Irrigation Survey," 2012 Census of Agriculture Highlights, November 2014, accessed December 6, 2015, http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Highlights/Irrigation/Irrigation_Highlights.pdf.

39 The USDA estimates that 154,890 farms pumped water using 603,579 pumps with a total energy expense of $2,669,965,000. Calculation: $17,238 per farm = $2,669,965,000 energy expenses ÷ 154,890 total farms. See USDA, "2013 Farm and Ranch Irrigation Survey," p. 34.

40 USDA, "2013 Farm and Ranch Irrigation Survey," p. 35.

41 Kincaid, "California Isn't the Only State with Water Problems." For information on individual states' water challenges, see Water Sense, "State Water Facts." For example, in California farmers have been forced to pump large amounts of groundwater in order to maintain agricultural production in the face of the drought. Diversions of water resources can also threaten environmentally sensitive areas such as the Sacramento-San Joaquin River Delta, where water exports have resulted in the deterioration of an ecosystem that supports 20 endangered species. See Erika Check Hayden, "California Agriculture Weathers Drought – At a Cost," *Nature*, September 30, 2015, accessed November 18, 2015, http://www.nature.com/news/california-agriculture-weathers-drought-at-a-cost-1.18457 and California State Water Project, "Where Rivers Meet – The Sacramento-San Joaquin Delta."

42 Jane Braxton Little, "The Ogallala Aquifer: Saving a Vital U.S. Water Source," *Scientific American*, March 1, 2009, accessed April 11, 2016, http://www.scientificamerican.com/article/the-ogallala-aquifer/.

[43] Leaching occurs when the amount of water a plant receives exceeds evapotranspiration. Runoff occurs when excess water that was not absorbed by the soil flows downhill and carries with it fertilizer and other nutrients. See "Nitrogen Notes: Number 3," International Plant Nutrition Institute, p. 3, accessed December 22, 2015, http://www.ipni.net/publication/nitrogen-en.nsf/book/FDEE48CFF7600CE585257C13004C7BB0/$FILE/NitrogenNotes-EN-03.pdf and "Application: The Science of Surface Water Runoff," The Shodor Education Foundation, Inc., 1998, accessed December 22, 2015, https://www.shodor.org/master/environmental/water/runoff/RunoffApplication.html.

[44] "2015 Gulf of Mexico Dead Zone 'Above Average'," NOAA.

[45] As noted above, the second largest dead zone in the world is the Gulf of Mexico dead zone. Another major dead zone in the U.S. is located in Chesapeake Bay, which covers approximately 1.37 cubic miles and is fed by excessive nutrient pollution from human wastewater and agricultural activities flowing from the Susquehanna River. The USGS estimated that 58 million pounds of nitrogen reached the Chesapeake Bay between January and May 2015. See "2015 Gulf of Mexico Dead Zone," NOAA; "The Floods' Lingering Effects: New Study Shows Gulf 'Dead Zone' One of the Largest on Record," *The Nature Conservancy,* 2015, accessed December 7, 2015, http://www.nature.org/ourinitiatives/regions/northamerica/areas/gulfofmexico/explore/gulf-of-mexico-dead-zone.xml; and USGS Newsroom, "Scientists Expect Slightly Below Average Chesapeake Bay 'Dead Zone' This Summer," U.S. Geological Survey, June 23, 2015, accessed December 8, 2015, http://www.usgs.gov/newsroom/article.asp?ID=4254&from=rss.

[46] "Western Irrigated Agriculture," USDA Economic Research Service, accessed December 6, 2015, http://www.ers.usda.gov/data-products/western-irrigated-agriculture/summary-of-results.aspx.

[47] Gravity irrigation systems include furrow gravity irrigation and uncontrolled flooding. Furrow systems are the dominant gravity irrigation system and guide water downslope across a field in shallow channels, while uncontrolled flooding relies solely on the natural slope of the land to distribute water across the field. See "Irrigation Systems and Land Treatment Practices," USDA Economic Research Service, October 26, 2004, accessed December 8, 2015, https://wayback.archive-it.org/5923/20120310140351/http:/ers.usda.gov/Briefing/WaterUse/glossary.htm.

[48] Sprinkler irrigation systems include center-pivot and linear-move irrigation systems. Both of these systems are self-propelled and fed by water pumped through a main pipe, but the center-pivot system rotates slowly around a pivot point to irrigate a circular area while linear-move systems follow a straight path across a rectangular field. See "Irrigation Systems and Land Treatment Practices," USDA Economic Research Service.

[49] Drip irrigation systems include subsurface drip and low-flow micro sprinklers. Subsurface drip irrigation lines are installed about one foot below the ground and feature small holes that continuously emit small amounts of water to crops' root zones; low-flow micro sprinklers use a similar system but deliver water through low-volume sprinklers located above the ground's surface to cover a larger area. See Ronald Patterson, Dennis Worwood, and Robert W. Hill, "Small Acreage Low Flow (Micro or Drip) Irrigation System Design and Installation," Utah State University, October 2008, accessed December 8, 2015, p. 2, https://extension.usu.edu/files/publications/publication/AG_Small_Acreage_2008-03pr.pdf.

[50] Subirrigation systems are networks of tubes that deliver water from underground sources to soil within crops' root zones. These systems are dual-purpose in that they provide a mechanism for draining excess water during wet periods as well as a means of pumping water to irrigate crops during dry periods. Because they are closed systems, subirrigation systems can reduce nitrate-nitrogen runoff by as much as 50 percent. See Robert Evans and Wayne Skaggs, "Operating Controlled Drainage and Subirrigation

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