Literature Review of Current & Upcoming Irrigation Technologies and Practices Applicable to Utah

Utah Department of Natural Resources
Division of Water Resources
AWOTF Project 1.1

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List of Abbreviations

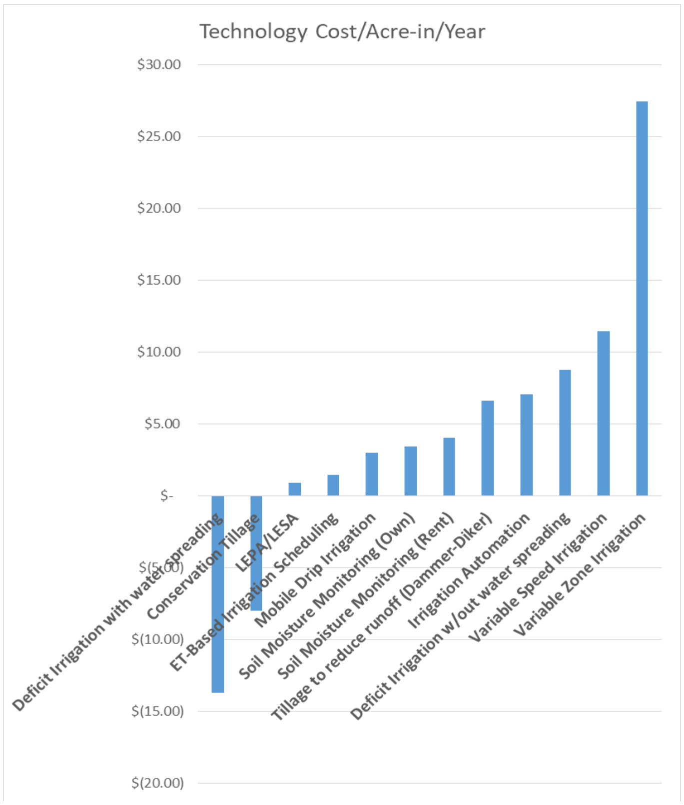
Abbreviation	**Definition**
AW	Available Water
AWOTF	Agricultural Water Optimization Task Force
AZ	Arizona
BPA	Bonneville Power Administration
CDWR	California Department of Water Resources
CHPC	Center for High Performance Computer
CPI	Consumer Price Index
CPN	Campbell Pacific Nuclear
CSFP	Commodity Supplemental Food Program
DNR	Department of Natural Resources
DP	Deep Percolation
EC	Electrical Conductivity
EPA	Environmental Protection Agency
ET	Evapotranspiration
FAL	Federal Agricultural Research Center
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GMS	Granular Matrix Sensors
GPS	Global Positioning System
IRT	Infrared Thermometer Sensors
LEPA	Low Energy Precision Application
LESA	Low Elevation Spray Application
MAD	Management Allowed Depletion
MDI	Mobile Drip Irrigation
MESA	Mid-Elevation Spray Application
NASS	National Agricultural Statistics Service
NDVI	Normalized Difference Vegetation Index
NRCS	Natural Resources Conservation Service
OAWL	Overall Spray Water Losses
PMDI	Precision Mobile Drip Irrigation
RDI	Regulated Deficit Irrigation
RO	Runoff
RUSLE2	Revised Universal Soil Loss Equation, 2nd version
SCADA	Supervisory Control and Data Acquisition
SDI	Subsurface Drip Irrigation
SIS	Scientific Irrigation Scheduling
SWC	Soil Water Content
TMDL	Total Maximum Daily Load

UDAF	Utah Department of Agriculture and Food
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UT	Utah
VRI	Variable Rate Irrigation
WAD	Water Application Depth
WDE	Wind Drift and Evaporation
WUE	Water Use Efficiency

Executive Summary

Irrigation is essential for economical agriculture production in western semi-arid regions such as Utah. The effects of droughts and competition for water due to population growth will mean more effective use of agricultural water supplies will be needed in the future. This document examines the historic, current and upcoming irrigation technologies and practices applicable to the State of Utah. Irrigators in the State continue to make steady improvements towards adopting technologies that enable them to both improve water use efficiency and improve overall crop productivity while protecting the environment. Recent trends show an increase in sprinkler adoption from 53 to 56% between 2013 and 2018 and a subsequent reduction in surface (furrow) irrigation. While Utah's adoption rate is below several western states, given the significant upfront costs associated with center pivot sprinkler systems (USDA NRCS estimate $75-80k resulting in a total annual operating cost of $144/acre), this 3% increase represents a considerable investment by the irrigation community.

Twelve strategies for reducing agriculture water demand were examined. As shown in the figure below, deficit irrigation with water spreading and conservation tillage are the only two options where irrigators would actually make money (negative costs). Each of the other ten options resulted in some additional costs to irrigators. Several low-cost options, such as Low Energy Precision Application (LEPA), ET-based irrigation scheduling, and mobile drip irrigation, have the potential to be adopted in water short areas. Financial incentives for implementing these strategies could be modest.



Knowledge is power and helping growers understand how to get the most out of their limited irrigation water can help them save water, save energy, and make more money for their families and communities. Continued support for irrigation management education and demonstration projects is essential to promote adoption of best management practices.

Finally, many irrigation systems have been designed by the growers or by someone who was not very knowledgeable or was inexperienced. These systems create uniformity and efficiency problems that can persist for 30-40 years. Over designed systems require growers to be better irrigation schedulers to avoid over irrigating. Under-designed irrigation systems are not able to meet crop water demands and result in yield losses. Growers should be encouraged to use certified irrigation designers (CID) who are certified through the irrigation association as someone who knows what they are doing and have education, experience, and continuing education requirements. Commissioning a study to find appropriate irrigation design capacities (gpm/acre) for different crops in different areas of the state will greatly aid these irrigation system designers to create appropriate irrigation systems to the crop and area.

1.0 Introduction

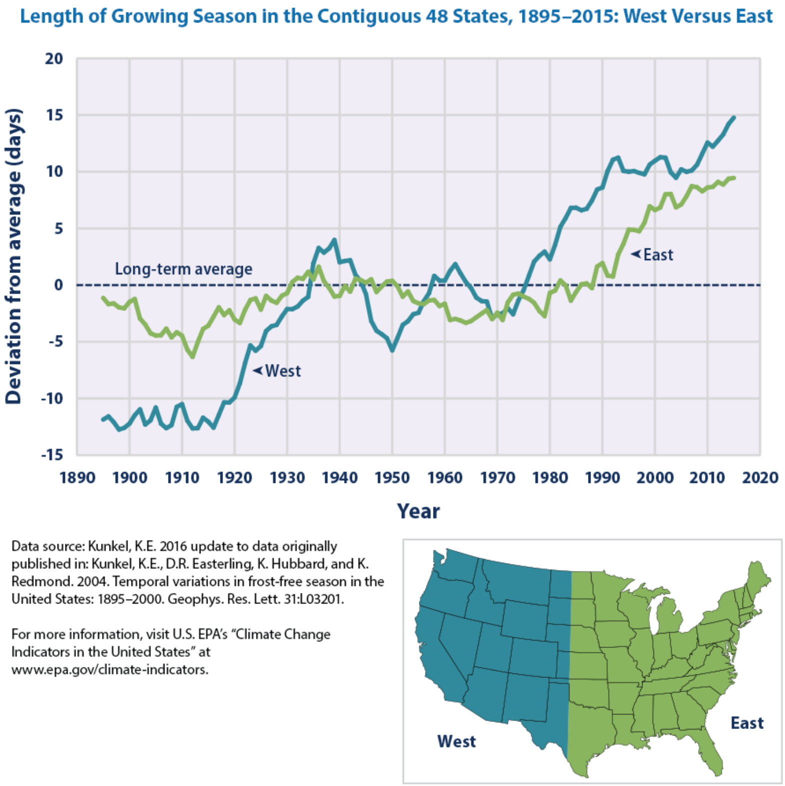
In 2019 the USDA agricultural overview identified 10.7 million acres of farm operations in the State of Utah including both livestock and crops. Of this, approximately 1.2 million acres is devoted to irrigated agriculture (Allen, 2017; USDA, 2020a). According to the U.S. Geological Survey (USGS, 2018) in 2015 the sources of all irrigation water were approximately 82.4% surface water and 17.6% ground water. Furthermore, approximately half of the total acreage (597,000 acres) was irrigated by sprinkler systems. These numbers, however, are not meant to suggest static conditions in the irrigation community. Various economic, regulatory, technology, awareness, and water availability factors act to alter the irrigated landscape. For example, (Pratt et al., 2019) found that despite the expanded urban development of agricultural lands, Utah was seeing an increased number of urban and small farms, which undoubtedly changes the crop selection and water requirements. Moreover, by defining the growing season as the period of time between the last frost of spring and the first frost of fall (Kunkel et al., 2004), they were able to document the increases in growing season length across the contiguous United States including in Utah (see Figure 1). From 1895 to 2016, the State of Utah has seen dramatic increases in the length of its growing season (33.78 days) which again likely affects irrigation demand as well as the potential crop/variety selection. All of these factors mean that as Utah’s population increases and the value of municipal water becomes even greater, renewed pressures on irrigation will lead to calls for better irrigation management practices. In this study, national and international trends in irrigation technologies are examined with the goal of producing more crop per drop while maintaining the economic viability of farming in Utah.

1.1 What makes Utah unique?

From forested mountains to vast desert regions, Utah is geographically diverse and thus it is difficult to talk about averages without understanding the variability that comes with the different landscapes. Total average annual precipitation varies from less than 5 inches in the Great Salt Lake Desert to more than 20 inches in parts of the Wasatch Mountains to even higher snowfalls on several mountain peaks (see Figure 2). Utah is unique in that a large portion of the state does not drain to any ocean. The areas south and east of the Wasatch and Unita Mountains drain into the Colorado River, but the drainages North and West of these mountains terminate in either the Great Salt Lake, Sevier Lake, or several other smaller evaporation basins that have no outlets. These features tend to cause water salinity and soil salinity problems in these evaporation basins that reduces the usefulness of groundwater and increases the irrigation water requirements since some water is necessary for deliberate deep percolation to leach these salts out of the crop root zone. Field run-off and deep percolation water has no-where to go so it stays in the drainage basin. However these water losses to deep percolation in irrigation often have the water quality degraded so much that they are much less useful for irrigation. In other words, irrigation water losses to evaporation or leaching are truly losses in many cases. Even the water in many areas in the south-eastern half of Utah that drains into the Colorado River, travels through highly saline soils such that runoff and deep percolation water from irrigated fields often picks up salts which degrade the water quality for all of the multiple Colorado River water users downstream.

The arable lands in Utah also tend to have very high evapotranspiration rates (ET, or crop water use) and very low precipitation rates. The high ET rates are driven by lots of sunshine in the summers (warm and dry), low humidity, and higher wind speeds than most U.S. states. The nearby mountains are the only reliable source of surface water with snow-melt being the most important source of fresh water in Utah.

Utah is not land-limited, it is water limited. Because of this, agriculture using water efficiently is of more concern than using land efficiently. This has implications for things like center pivots, that do not irrigate field corners well, or deficit irrigation of one crop in order to spread the water to irrigate additional land.



Data source: Kunkel, K.E. 2016 update to data originally published in: Kunkel, K.E., D.R. Easterling, K. Hubbard, and K. Redmond. 2004. Temporal variations in frost-free season in the United States: 1895–2000. Geophys. Res. Lett. 31:L03201.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 1. Growing season changes in the United States (Kunkel et al., 2004).

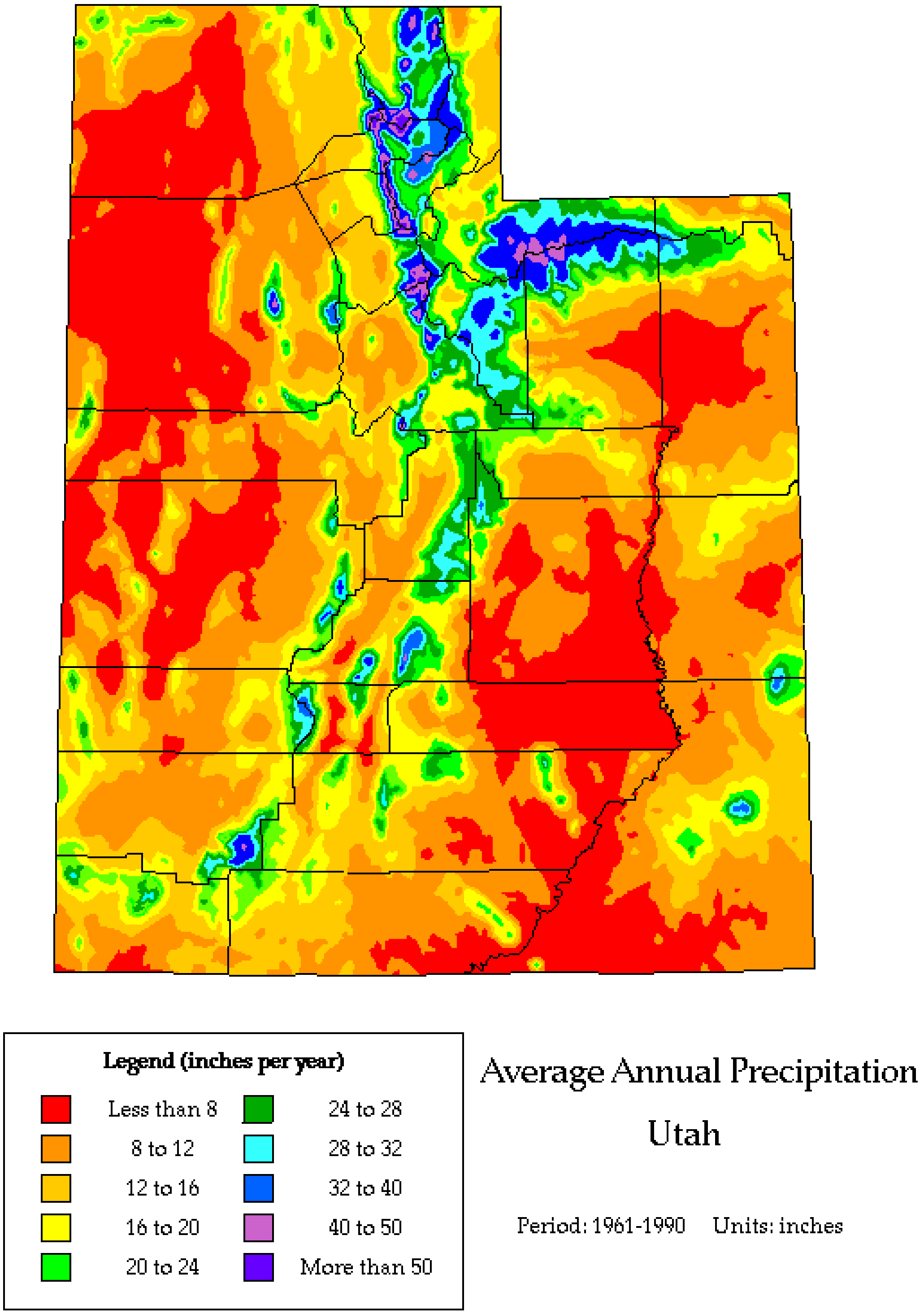


Figure 2. Average annual precipitation in Utah.
(CHPC)

1.2 What this Report Is and Is Not

This report is targeted towards the Utah State Department of Water Resources. The purpose is to educate on the historical, current, and future water technologies that are practical in the state. It is to serve as a guide to help make decisions as to which technologies to promote in Utah. It is to help understand the broader implications and impacts of implementing these technologies, whether these are likely to be implemented, whether they are likely to take root and grow on their own. It is also to help estimate when and how much water might be conserved, and at what cost. And to make recommendations based on this information about potential areas for investment and study to help ensure a strong water situation for Utah's future.

This report is not an explanation of the details of each of these different irrigation technologies or a manual for their use by growers. This is not a description of how to properly implement these different technologies, how to select a manufacturer or vendor for each technology, or to manage them after they have been implemented. That is for more in-depth papers or in-person classes from knowledgeable professionals from either Utah State University extension, conservation districts, irrigation equipment vendors, Utah Department of Agriculture and Food (UDAF), or the USDA Natural Resources Conservation Service (USDA-NRCS), preferably in a concerted and coordinated effort.

1.3 Cost and Efficiency Estimates.

In order to compare the usefulness of the various water conserving or water use optimization technologies it is important to have estimates of how much each of these technologies costs on an ongoing basis and how much water they will save. Most researchers hate to give these numbers because it always "depends" on so many factors that any number that you give will almost always be wrong or change quickly. However, without these kinds of estimates it is very difficult to make decisions. So we have endeavored to put together cost estimates in dollars per acre per year for each of these technologies at the time of this paper's publication, and to use the published literature to get as good an estimate as possible of the potential water savings potential for each of these technologies as a percent. These numbers are then included in the conclusion section to compare costs per acre-in conserved. We realize that many assumptions had to be made that don't apply to all situations. However, we attempted to be as transparent as possible about what our assumptions were and why. If anyone wishes to make changes to the underlying assumptions in order to revise or update the cost estimates for a particular scenario, the spreadsheets will be made available so that one could simply change the values and see how it affects the overall costs.

2.0 Historic Irrigation and Tillage Practices

In this section, we present the literature review of irrigation and tillage practices that have been historically implemented in Utah. Benefits and consequences of the different irrigation/tillage methods and the reasons for people selecting one over another method is briefly explained.

2.1 What irrigation and tillage practices have been implemented in Utah, and to what extent?

2.1.1 Irrigation practices

The basis of civilization was the technical development of agriculture, a foundation allowing human life-styles to evolve from nomadic to sedentary 10,000-years ago during the Neolithic Revolution, also known as The First Agricultural Revolution. Originating from collecting wild grains, agricultural advanced early civilizations, like the ancient Chinese's vast list of processes, methods, and technology that includes the moldboard plow and the seed drill used today. The ancient Egyptians irrigated utilizing the Nile River, and the Sumerians located in the arid region of southern Mesopotamia, required irrigation creativity to hydrate their vast list of crops, including fruits, vegetables, and grains like barley and wheat.

Similar to the hardships faced by the Egyptians and Sumerians farming in arid regions, the early settlers to the arid western North American continent quickly discovered rain was not dependable, and that irrigation was necessary requiring ingenuity and creativity. In fact, Brigham Young understood the arid region of the Great Basin through previous explorers and arrived with full intentions of irrigation development; however, he was not the first to use irrigation in Utah, as Native Americans in Southwestern Utah established an irrigation system of their own long before the pioneers' arrival to water crops of their own (Fuller, 1994)**.**

In July 1847, Utah settlers started their irrigation efforts utilizing a small creek named City Creek. Meandering through the narrow granite canyon in the foothills of Salt Lake City's north-slope, the early settlers constructed Utah's first irrigation infrastructure, a dam, to soften the soil and plant potatoes("Using Water: Irrigation,"). Farmers tapped into the source using irrigation ditches, like the one in Figure 3 found outside Brigham Young's Beehive and Lion houses.

Figure 3. Irrigation ditch outside Brigham Young's Beehive and Lion houses ("Using Water: Irrigation")

Early communities were located where settlers could directly access water sources, like lakes and rivers. The number of farms and farmers increased, requiring others to tap into local man-made irrigation ditches to irrigate their fields. By 1865, pioneers had traversed almost 1,000 miles with irrigation canals, as seen in Figure 4, irrigating 150,000 acres of Utah's cropland. Furrow (or flood) irrigation was the only irrigation practice of the time. Farmers combined furrow irrigation with the conventional tillage practice of ridge-till to grow deep rooted crops, like potatoes (seen in Figure 5).

Figure 4. Pioneers Digging Irrigation Ditch.
(Hooton, 1999)

Figure 5. Furrow Irrigation and Ridge-till.
(Hooton, 1999)

Due to Utah's desert climate, irrigation is necessarily a prominent practice in Utah. Utah irrigation has experienced several phases, the first phase (cooperative: the beginning of 1847 to mid-1880s), the second phase (privatization: 1880-1990), but were only limited to diversion and supply of summer flow to the nearby arid land. During both of these phases, irrigation was nearly 100% surface irrigation using furrow or basin-style irrigation systems.

With the passage of the Federal Reclamation Act on June 17, 1902, the modern era of development of Utah irrigation started, which gave rise to a host of large water storage projects, including the Colorado River Storage Project. These projects provided storage for year-round run-off and regulated several year's water supply, which helped mitigate and compensate for shortages during drought periods. Over time, the growing population and increasing municipal, industrial, and irrigation water demands exceeded even the new storage projects' ability to supply the water needed. Consequently, Utahns began anopting the new pressurized irrigation methods such as sprinkler and drip irrigation, which are mostly used irrigation today. These new practices allowed irrigation of hilly and sloped fields, allowed more frequent irrigation, more uniform irrigation, and reduced deep percolation and field run-off water losses so that growers were able to better meet crop water demands during the hot summer months with the water supplies available. The more frequent and uniform irrigation usually resulted in increased crop yields, especially on lower quality soils (lower water-holding capacity soils) providing an incentive for conversion. These pressurized systems also allowed for greater flexibility for moving and distributing water supplies and allowed the utliziation of groundwater compared to water distribution by gravity flow of water in open ditches and canals.

2.1.2 Tillage practices

Since 1903, Utah focused on improving dry farming methods on a scientific level. With an expanding population, growing agricultural and mining markets in Utah, the local economic demand for exporting crops meant farmers would require additional farmland. This was achievable with the help of the industrial revolution making tractors affordable and the installment of the transcontinental railroad for trade. Also, Utah farms were not limited due to farmable land, land area, or physical ability to farm - even with ox and plow. Before this time, Utah farmers cultivated with a conservative mentality, only growing what was required to support their family selling a fractional amount in local trade for other goods; in other words, Utah farms were small. For Utah farmers, acquiring additional land with adequate soil to meet the increased crop production demand was certainly possible; the only limitation was irrigation. Irrigation canals only carried the water so far. A necessary increase in the number of water storage methods, like: water towers, containers, and dams – along with efficient water usage by irrigation systems became a necessity. Without water storage facilities, additional land supporting quality soil had little to no value. The water demand was satisfied through a novel procedure, which conserved moisture in the soil, exposed moisture, and replenished soil nutrients by the use of tilling. Land lacking irrigation water was tilled, allowing three to four hundred thousand acres of land previously considered incapable of being farmed were brought under cultivation (Zink, 1939). The different tillage practices in Utah pre-dating 1950 are presented in the following historical timeline.

Pre-Industrial Revolution: (1847-1900)

In 1847, when the early pioneers settled in Utah, the tillage technology of the time consisted of a moldboard plow pulled by a horse or ox (see Figure 6). This was a popular tillage method used at the time to ridge-till since most farmers were using flood irrigation. Less than 50-years later, during the turn of the century and industrial revolution, the tractor replaced the horse and plowed due to simplicity rather than necessity. Harvest was focused on community rather than profit, so pioneers grew what was necessary to support their families and distributed locally, thus the horse and plow method was considered adequate. However, as the number of farms grew irrigation and water scarcity started impacting the early Utah agriculturalists, which is relevant today with modern Utah agriculturalists.

Figure 6. Early Mormon pioneer using Horse and Plow to tillage.
(Hooton, 1999)

Post-Industrial Revolution: (1900-1950)

In 1904, tillage investigations in dryland research trials started at the Nephi Station in central Utah. In 1916, an investigation began to determine whether or not plowing in both the fall and spring was advantageous, and if so, which depth combinations would give the best results. The data from this experiment for the period, 1916-1949, are reported as 5-year averages. Plowing 8 inches deep in the fall followed by plowing 3 inches deep in the spring gave significantly higher yields than plowing 3-inches in the fall and 8-inches in the spring or 8 inches in the fall and 8 inches in the spring (Bennett et al., 1954).

Starting in 1930, Utah State University performed a 20-year test at Nephi, Utah. Experimenting with three different plow tillage methods, which include moldboard plow (Figure 7), one-way disk, and disk harrow (Figure 8). Relative wheat yields were used as a basis of comparison. Although the yield differences shown in Table 1 are not drastic, statistical correlation and the general trends were significant. In order from most-to-least productive method is: moldboard plow (most), one-way disk, and the disk harrow (least). The moldboard plow significantly outperformed the field overall. Utah State University found this data to be so significant; they proceeded with the evaluation of more modern tillage implements (Bennett et al., 1954).

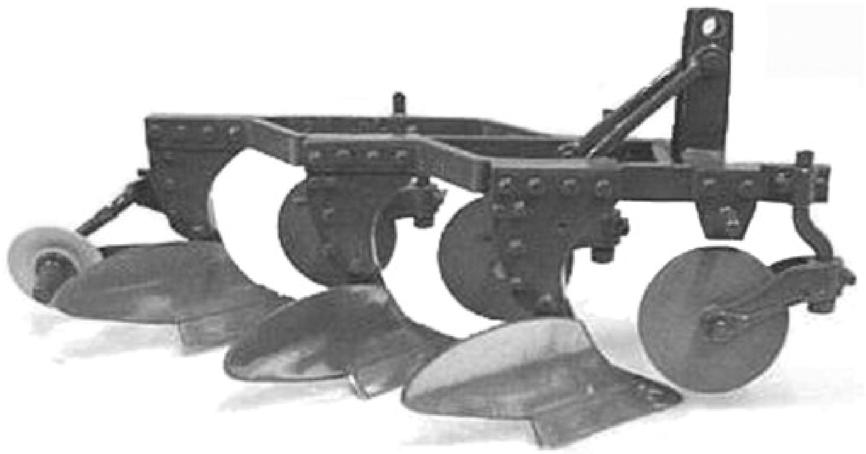


Figure 7. Moldboard Plow

(Carter & McKyes, 2005)

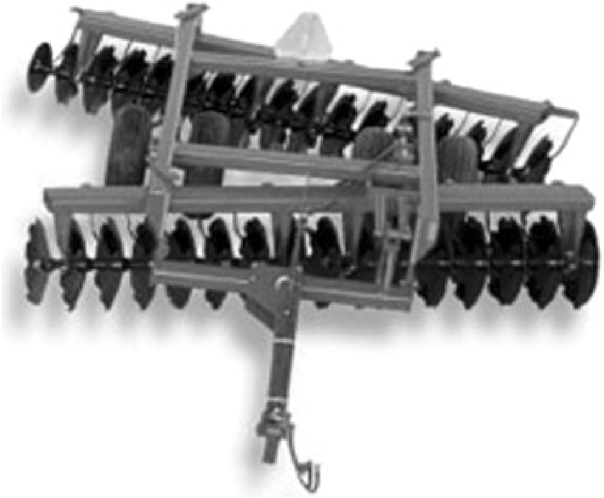


Figure 8. Disk Harrow
(Carter & McKyes, 2005)

Table 1. Comparative winter wheat yields resulting from the use of the moldboard plow, one-way disk and disk harrow.

(Bennett et al., 1954)

	Treatment		
Period	Moldboard plow	One-way disk	Disk harrow
	bushels per acre		
1930-1934	19.0	18.5	17.8
1935-1939	20.5	21.7	21.3
1940-1944	24.3	22.3	19.5
1945-1949	20.8	20.1	18.8
20 year average	21.1	20.6	19.3

Utah State University continued research to investigate the time and depth of plowing, frequency, and manner of cultivation of fallow, and type of plow or tillage implement. During this time, conservation tillage became their main focus and continues today. In 1950, the conservation tillage practices included: no-till, mulch-till, and partial till. Implementations of ridge-till and strip-till were also compared.

2.2 What has influenced change in irrigation and tillage practices in Utah?

2.2.1 Irrigation changes

Utah was growing: population, agricultural industry, and the introduction of mining – the economy was converting from local to national with the installment of the transcontinental railroad. The possibility of exporting crops enticed farmers to change their previous style of growing what was needed to support their family to grow as much as they could by expanding farms. This increased the demand for water (irrigation, municipal, and industrial demand) and exceeded even the new storage project's ability to supply the water needed. The growth of farm size and the increasingly limited water resources motivated farmers to investigate more efficient and sophisticated newer irrigation technologies. Farmers were lured towards more automated technologies requiring less manual work and improving water application uniformity and efficiency simultaneously. In around the 1950s, increased conservation measures were implemented, and new pressurized irrigation methods such as sprinkler and drip irrigation started to replace surface irrigation methods (Bagley & Criddle, 1954). Even the recent data shows that this shift is continuing (see Figure 9 and Figure 10) as sprinkler and drip/micro irrigation has increased from 2013 to 2018. Figure 11 shows the general trend of how surface irrigation is being replaced by the sprinkler irrigation from 2003 to 2018.

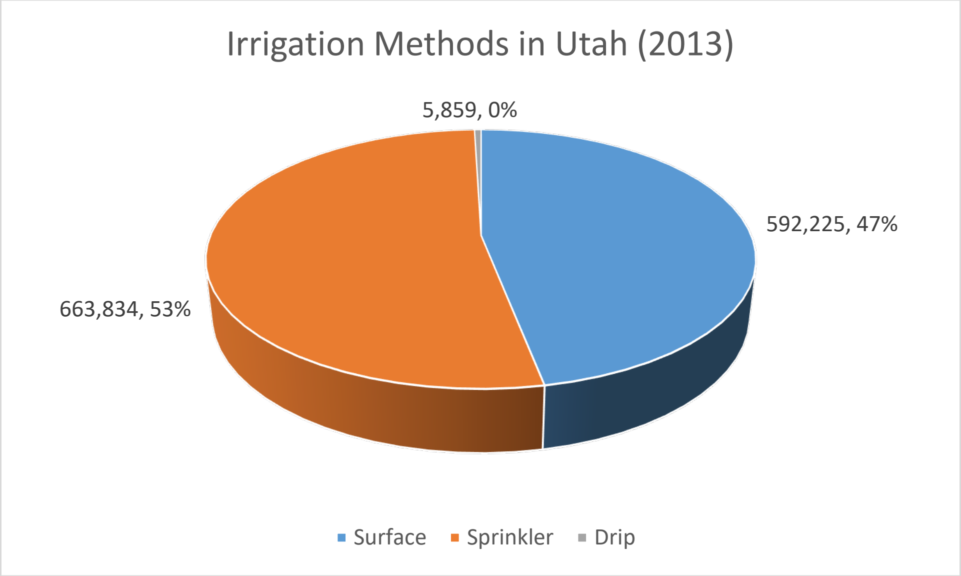


Figure 9. Dominant Irrigation Types in 2013.
(USDA, 2020b)

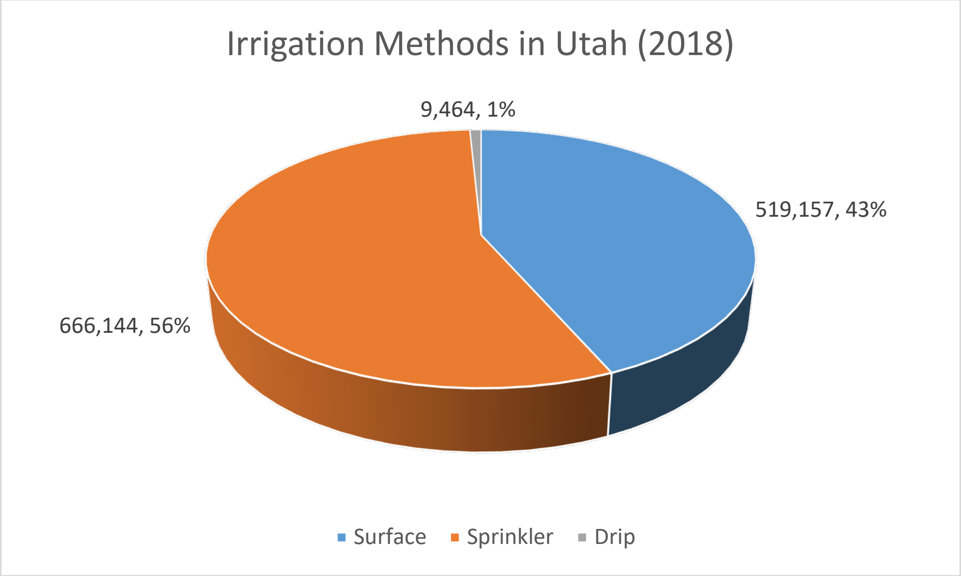


Figure 10. Dominant Irrigation Types in 2018.
(USDA, 2020b)

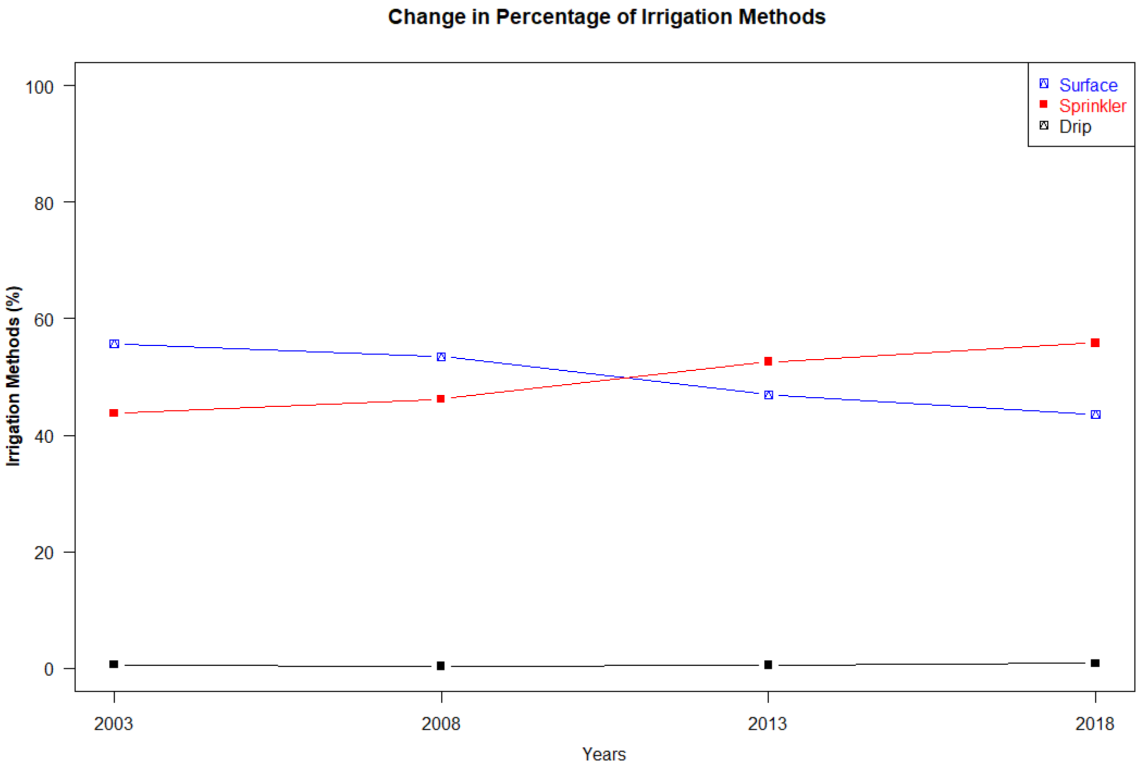


Figure 11. Percentage change in land irrigated by methods of water distribution.

Irrigated acreage totals for Utah have fluctuated from 1967 to 2017. Figure 12 demonstrates that the lowest amount of irrigated cropland was recorded in 1987 and 1992. In 1987, crops were measured to be 23.4% of Utah's agriculture economy. Grain type crops which are non-irrigated made up 14.2 % of Utah's total agriculture economy. With such a large amount of non-irrigated crops harvested that year, less irrigated crops may have been planted, indicating a lower amount of irrigated land (*Utah Agricultural Statistics 1988*, 1988). In 2017, two values were gathered for irrigated cropland. One value is significantly higher at 1,520,000 million acres of irrigated land recorded from the Department of Natural Resources (DNR), and the other from Utah Department of Agriculture and Food (UDAF) recorded 1,097,000 acres of irrigated land. The difference could be how the two administrations classify irrigated land and may indicate that the year-to-year fluctuations may be at least partially due to measurement errors.

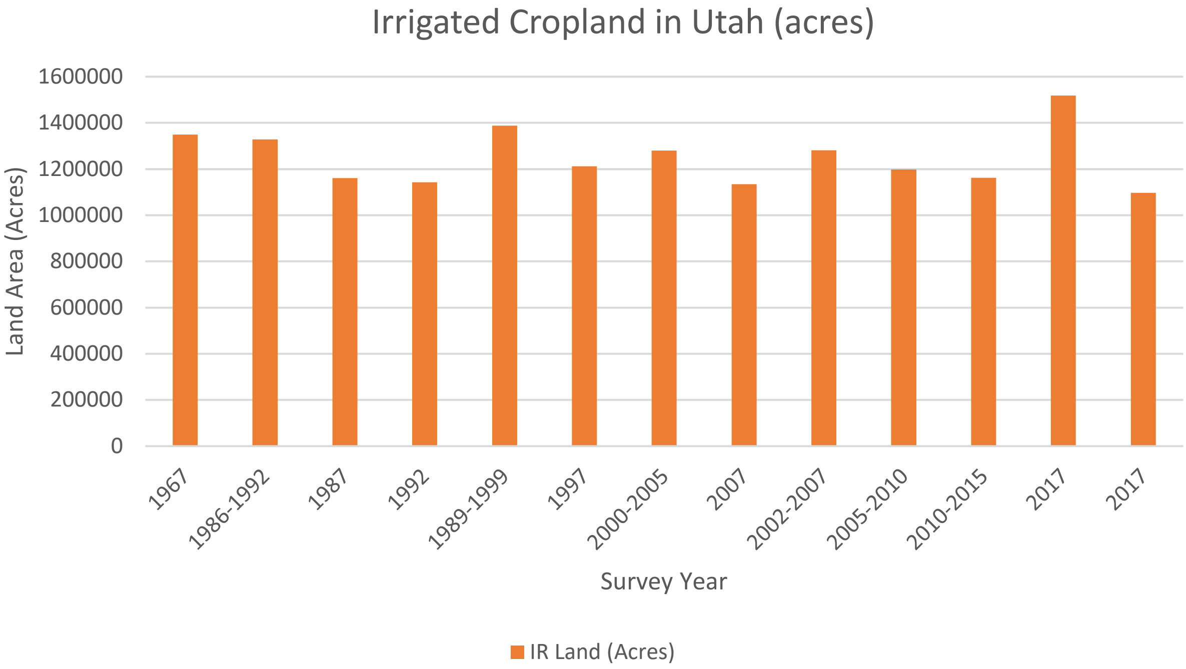


Figure 12. Temporal variations in irrigated cropland in Utah (acres).
(Esri, 2016, 2019a, 2019b, 2019c, 2019d, 2019e)

2.2.2 Tillage changes

Starting in 1901, the Department of Agriculture gave Utah State University a research initiative to study in several counties across the state of Utah. Cultivating adequate land area has never been the issue, even before the industrial revolution before farmers used horses and plows instead of tractors. As the economy changed, trade became critical, and farm sizes increased. Early Utah saw its first significant change due to the economy. Tillage methods remained relatively the same, but the mode in which they were applied, the tractor, was the only major difference. The increase in economy increased farm size and thus enticed farmers to use more sophisticated tillage practices requiring less manual work. using tractors.

2.3 What were the benefits of the irrigation and tillage practices (economic, environmental, labor, and other)?

2.3.1 Benefits of irrigation practices

In examining the history of irrigated agriculture in Utah, it is easy to see that irrigation has significantly improved food production and food security while also helping create economic conditions that have allowed rural communities to prosper. The complex interactions between irrigation, drainage, fertilization, and salinity on crop production have become better understood over time but more work is needed to develop sustainable irrigation practices. The Anasazi Native Americans who lived in the four corners region of southeastern and southcentral Utah between 200-1500 CE, or more generally known as the ancient *Ancestral Puebloans*, were credited as being the first farmers in America by historians (Zimmerman, 2016). The Ancestral Pueblos developed the first irrigation systems in Utah to maintain crops in the hot sun and cultivate their crops, primarily corn, squash and beans. A prominent system of irrigation ditches designed by the Ancestral Pueblos remains in Arizona (Zimmerman, 2016). In 1540, the Spanish expedition lead by Francisco Vazquez de Coronado noted the earliest documented evidence of the Ancestral Puebloans irrigation practices, growing corn, red beans, squash, and cotton (Hess, 1912). A note was made about the natives' abundant harvests and vast irrigation structure, stating “irrigation was doubtless necessary to growing of crops,” also claiming the soil was “sterile.”

In 1847, Utah welcomed Mormon Pioneers with hard, compacted, semi-arid soil unsuitable for growing most crops. Pioneers knew of the semi-arid climate of the Great Basin using reports of government-sponsored explorers (Fuller, 1994). Pioneers never witnessed the practice of irrigation applied, but the stress of immediate necessity discovered an economic and equitable theory to this new sphere of agriculture (Hess, 1912). Innovation and ingenuity were responsible for sustaining living across Utah for both the Native Americans and Pioneers. By diverting water from higher points of the stream into a main canal, water reached fields by irrigation ditches. Later the water flow was controlled with dams and weirs. These helped to improve the soil moisture content and provide drinking water. According to Chapter 27 of H.H. Bancroft’s History of Utah, in 1849, two years after first breaking sod and diverting water for irrigation, farmers produced a rather paltry 130,000 bushels of wheat and other cereals, from 17,000 acres of mostly irrigated land. By comparison, in 1883, the same study reported that 215,000 acres produced 1,600,000 bushels of wheat, 722,000 bushels of oats, 305,000 bushels of barley, 193,000 bushels of corn, 800,000 bushels of potatoes, and 215,000 tons of hay.

Early economic development in Utah was about social wealth rather than financial. At the core of the pioneers' values was *esprit de corps*: fellowship, common loyalty, community, unity, and cooperation – this was possible because they were free from industries of competitive individualism. The discovery of thriving agriculture with artificial watering reinforced this communal ideology, providing a temporary economical solution. The next objective was to develop permanent institutions and building the proposed institutions upon an agricultural economy to provide for the common benefit (Hess, 1912).

Early practices of Utah irrigators offer no signs of doctrine, nor the recognition of the miners' code of water distribution, nor evidence of following after European methods of water government. Sensible only of their economic needs and the ideals of unity and perpetuation resulting from faith and experience. No adverse interests existed within the sphere of their early activities to interfere with or contradict any course of industrial development they might choose to follow. Under these social and economic conditions was formulated the "Old Utah Code" which defined the rights and obligations of the Mormon colonists in the use of flowing waters for irrigation (Hess, 1912).

Knowledge of irrigation practices has grown considerably since the mid-1850's. Fast forward to today's estimated 1.1 million acres of irrigated acreage and per acre yields, it is safe to conclude that evolution in irrigation practices have allowed irrigators to expand irrigated acreage, effectively manage water, and improve crop productivity. IPM data from a 2003 Deer et al. (2006) study reported that irrigated wheat yields in Utah were 87 bushels per acre which is considerably more than the 7.5 bushels per acre when irrigation began in Utah and much better than the 16 bushels per acre for dryland farming reported in this study. While improvements in seed quality, fertilizer management, and other changes in farming practices have undoubtly led to some of this increase, irrigation practices must be credited with the improvement.

2.3.2 Benefits of tillage practices

Conventional Tillage:

The goals of conventional tillage for seed bed preparation are to break up lumps of soil, incorporate and destroy plant debris, expose soil pest to sunlight, and reduce weeds. Conventional tillage increases soil porosity by breaking up the compacted soil particles. Thus allowing air exchange and a soft bed for root growth. The exposure to oxygen hastens the decomposition of the limited soil organic matter releasing those nutrients and making them available for plants growing in the soil, but also lowering the soil organic matter content and evaporating the soil water (Hofmann, 2015).

Conservation Tillage:

In addition to trying to get water to their crops, Utah farmers also face issues with soil erosion. The types of erosion that most affect Utah agriculturalists are water erosion and wind erosion. In this regard, conservation tillage practices involving no-till or reduced tillage help alleviate the negative effects of conventional tillage (Subbulakshmi et al. 2009). The Conservation Compliance Provisions of the 1985 Farm Bill helped established the imputus for conservation tillage practices (Oregon State Extention 2012). No-till reduces water erosion while increasing water retention efficiency by collecting and absorbing rainfall and irrigation water using low-profile natural vegetation covering the soil surface. The low-profile vegetation on the surface also protects the soil from wind erosion. The natural structure, biomatter, and organisms (like worms) beneath the surface enrich the soil and the soil organic matter contents increase over time. They also help move nutrients and allow crop roots to grow deeper via burrows and tunnels created by the worms and decaying roots, which will enable crops to access water deeper in the ground that would otherwise require deep banding (nutrient applications ~6-8 cm below the ground surface on both sides of the row crop). Conservation tillage has also been shown to improve water use efficiency, reduce input costs (nutrients, pesticides, herbicides, and energy), and preserve soil carbon (Busari et al. 2015; Li et al. 2019). Reductions in nutrients, pesticides, and herbicides also help decrease the potential for groundwater pollution.

2.4 What were the consequences and costs associated with these practices (economic, environmental, labor, and others)?

2.4.1 Consequences of irrigation

Early surface irrigation practices involved diverting water from natural sources, like lakes and rivers, and distributing the water by field flooding (overland flow or furrow irrigation). While improving the crop yields dramatically and often allowing for agricultural production in areas that would not economically sustain crops, the increase in water diversion resulted in significantly reduced flows during summer months, threatening aquatic species and contributing to other environmental issues. For example, recent reports from the Great Salt Lake Advisory Council point to reduced inflows caused by both agricultural and municipal diversions as threatening migratory bird habitat, brine shrimp production, recreation, and air quality.

Surface Irrigation

Due to its lower efficiency, surface irrigation requires the diversion of larger amounts of water from waterways. Extensive land preparation is needed requiring more labor for making uniform or level land grades. In addition soils with high infiltration rates (like sands) have a difficulty in obtaining uniform distribution since so much water goes into the soil at the tops of the fields. Moreover, a large amount of land has to be used for irrigation ditches which would otherwise be productive agricultural land. As the water is not directly applied to the crops, there is loss of the water for weed growth. Similarly, the uniform application of fertilizer with surface irrigation is not possible. Monitoring water consumption is almost impossible with surface irrigation.

As discussed later in this report, it should be pointed out that not all of the water that is infiltrated as part of overland flow irrigation is lost to the system. Depending on the specific site conditions, irrigation inefficiencies may result in groundwater recharge or return flows to the stream/river.

Sprinkler Irrigation

Sprinkler irrigation refers to a relatively broad class of pressurized irrigation systems including center pivot, wheel move (side roll), big gun, and linear move tower (Stubbs 2016). As an effort to conserve water, some Utahns started switching from surface irrigation to sprinkler irrigation starting around the 1950s. However, the relatively large initial capital investment made most of the farmers reluctant to switch over initially. Other factors, such as crop type, climate, soil, labor and technology requirements, water availability, and water quality, have also been identified as barriers to implementation (Stubbs 2016). Generally, the lower operational costs of these systems have helped some irrigators transition over time but the initial investment costs can still be prohibitive. In case of large sprinklers like big guns, plant disease or injury and loss of fruits occurred due to the relatively large droplets. Even some of the soil was not suitable for the continuous move system. This method was susceptible to the wind as even a small amount of wind can cause the non-uniform distribution of water. In addition to high initial cost, the cost of repair and maintenance was also higher compared to surface irrigation. There was also a need for a more highly skilled labor to use of this newer technology.

2.4.2 Consequences of tillage practices

Each tillage practice uses a power unit requiring dependency on either animals or machines. Horses and oxen were used before the industrial revolution introduced the modern tractor, but the same principle applies – the farmer cannot till if the horse is malnourished, hurt, or dies; likewise, the farmer is immobilized if the tractor breaks or requires repair. General maintenance is expected, like fuel, oil, and tires. Factors considered before cultivating, include season (rain), topsoil moisture, bottom soil moisture, and till depth.Consequences also include the soil compaction, causing clodding and a hardpan beneath the soil.

Conservation Tillage

Examples of conservation tillage found in Utah are no-till and mulch-till. No-till is a direction agriculturalist using conventional tillage are converting to. Initial consequences for agriculturalists switching to no-till include the average 3-to-5 years of reduced yield while the ground returns to its natural state. In this industry, even temporary reduced income is a considerable risk, but considering this could be 8 or 10 years if not managed correctly, this becomes repulsive to farmers, especially veteran agriculturalists. No-till still requires seed drills and fertilizer. In fact, fertilizer placement is AN ABSOLUTE MUST with No-till. Part of the purpose of conventional till is to disturb unwanted growth, like weeds and parasites. This makes No-till extremely problematic in Utah to plants like jointed goatgrass and perennial weeds (Rasmussen, 2011). Since No-till uses the environment, it's more a fragile system than conventional till. This includes things like, if crop residue isn't incorporated into the soil after harvest, diseases might carry over into the next year's crop. If the agriculturalist properly maintains the system, however, consequences like this are less-likely/preventable.

2.5 How have these irrigation practices performed in terms of irrigation efficiency, water consumption and agricultural productivity?

2.5.1 Efficiency of irrigation

Early Utah irrigation practices include surface irrigation (furrow and controlled flooding) and Sprinkler (Center pivot and Handwheel). A study conducted by (Irmak et al., 2011) at Nebraska found that irrigation efficiency is higher in the sprinkler system of irrigation than conventional surface irrigation. Table 2 shows that the controlled basin flooding has a higher efficiency (60-75%) over conventional furrow irrigation (45-65%). In the case of the sprinkler irrigation system, center-pivot was found to be slightly better over linear move and hand move sprinkler irrigation system.

Table 2. Application efficiency of well-designed irrigation system.

(Irmak et al., 2011)

Sprinkler Irrigation Systems	**Efficiency (%)**
LEPA	80 - 90
Linear move	75 - 85
Center pivot	75 - 85
Traveling gun	65 - 75
Side roll	65 - 85
Hand move	65 - 85
Solid set	70 - 85
Surface Irrigation Systems	
Furrow (surge)	55 - 75
Furrow (with tailwater reuse)	60 - 80
Basin (with or without furrow)	60 - 75
Basin (paddy)	40 - 60
Precision level basin	65 - 80
Microirrigation Systems	
Microspray	85-90
Micro-point source	85-90
Micro-line source	85-90
Surface drip	85-90

2.5.2 Efficiency of Tillage

In 1904, Utah State University started performed tillage investigations concerning the depth of plowing and subsoiling. Winter wheat yields are shown in Table 3. The results prior to 1910 were considered preliminary and were not reported. This was discontinued in 1950 for unknown reasons; however, other similar experiments were introduced to investigate time and depth of plowing, frequency and manner of cultivation of fallow, and type of plow or tillage implement.

Comparing the 5-inch plow depth vs. 8-inch plow depth, the yield for the 8-inch plow depth was higher than the 5-inch plow depth during 30-year of the 39-years and averaged 8 percent higher during these years. This translates to an increase of 1.87 ± 0.69 bushels of wheat, which given the sample size, translates to a significant increase statistically. Comparing the 8-inch plow depth vs. 10-inch plow depth, practically no yield difference was obtained (Bennett et al., 1954).

Fall plowing to a depth of 8-inches gave significantly higher yields than subsoiling 18-inches deep. The difference was 1.35 ± 0.54 bushels. No significant difference was found between 8-inch fall plowing and 15-inch subsoiling (0.8706 + 0.709). From the results of this experiment, it can be concluded that subsoiling does not result in an increase in wheat yields under dryland conditions and that where fall plowing is done, it should be deeper than 5-inches but need not be deeper than 8-inches.

Table 3. Winter wheat yields follow various depth of fall plowing.

(Bennett et al., 1954).

	Treatment				
	Fall plowed			Subsoiled in fall	
Depth:	5 inches	8 inches	10 inches	15 inches	18 inches
Period	bushels per acre				
1910-1914	21.7	22.5	21.8	21.7	20.5
1915-1919	19.8	20.6	21.7	21.7	19.8
1920-1924	23.4	27.5	22.5	25.5	26.2
1925-1929	25.3	29.0	28.9	27.0	28.2
1930-1934	18.1	19.7	18.5	18.8	17.1
1935-1939	21.1	21.9	21.9	20.6	19.7
1940-1944	26.5	26.6	27.5	27.0	27.3
1945-1949	22.3	24.2	24.1	23.4	23.0
Average	22.3	24.2	23.3	23.4	23.0

3.0 Current Irrigation and Tillage Practices

In this section, we describe how current irrigation and tillage practices are being implemented in Utah, their effectiveness, and the reason for people switching from previous technology to a recent one.

3.1 What current irrigation and tillage practices are being implemented in Utah, and to what extent?

3.1.1 Current Irrigation practices

The major irrigated crops in Utah include alfalfa and other hay crops, winter wheat, corn, safflower depicted in Figure 13. To irrigate these crop farms currently, Utahns are using mainly sprinkler, surface, and drip/micro irrigation systems. The pie graph in Figure 10 clearly illustrates that sprinkler and surface irrigation systems are used for the largest areas (measured in acres).

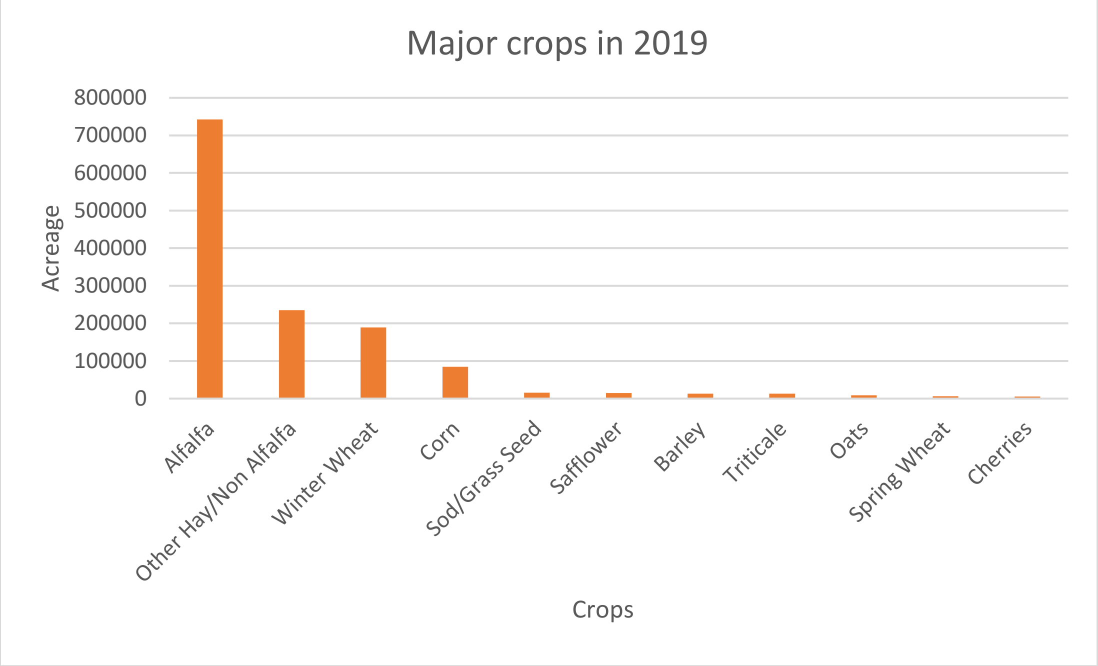


Figure 13. Major crops in Utah (2019).
(USDA & NASS, 2019)

Irrigation in Utah is a critical reason for agricultural success in the state. To aid in the production of crops, multiple variations of surface, drip/micro, and sprinkler irrigation types have been implemented to a specific extent in Utah. The most prominent methods of irrigation based on acreage are center pivot/linear and flood irrigation, which can be seen in Figure 14. Hand/wheel-line sprinkler systems and furrow irrigation are also quite prominent.

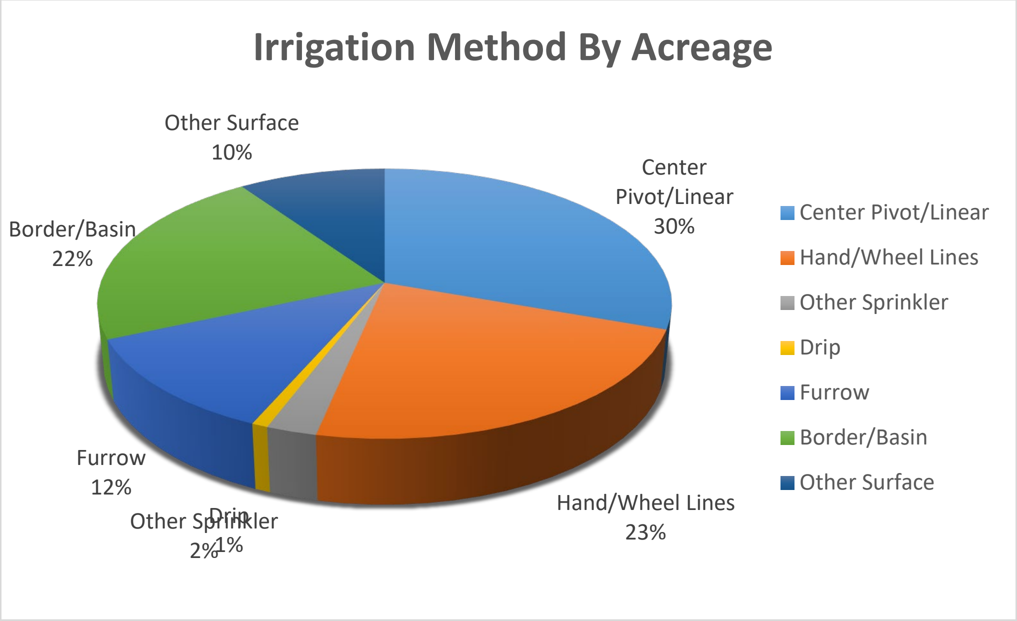


Figure 14. Irrigation methods in Utah by land acreage (2018).
(USDA, 2020b)

The irrigation type utilized on the greatest amount of acreage is sprinkler irrigation (30% as depicted in Figure 14). Figure 15 shows the acreage of land being irrigated by sprinklers for each Utah county. Figure 16 illustrates the different sprinkler methods that are being used in Utah. Prominently center pivot (55%) and linear move systems (41%) dominate the sprinkler acreage.

Like the sprinkler irrigation category except much smaller, the use of drip irrigation is also growing in Utah. Figure 17 shows the percentage distribution of the different methods of drip irrigation practiced throughout the state. Micro sprinklers are highest with 47%, while the subsurface method of drip irrigation is still rarely practiced (Figure 17).

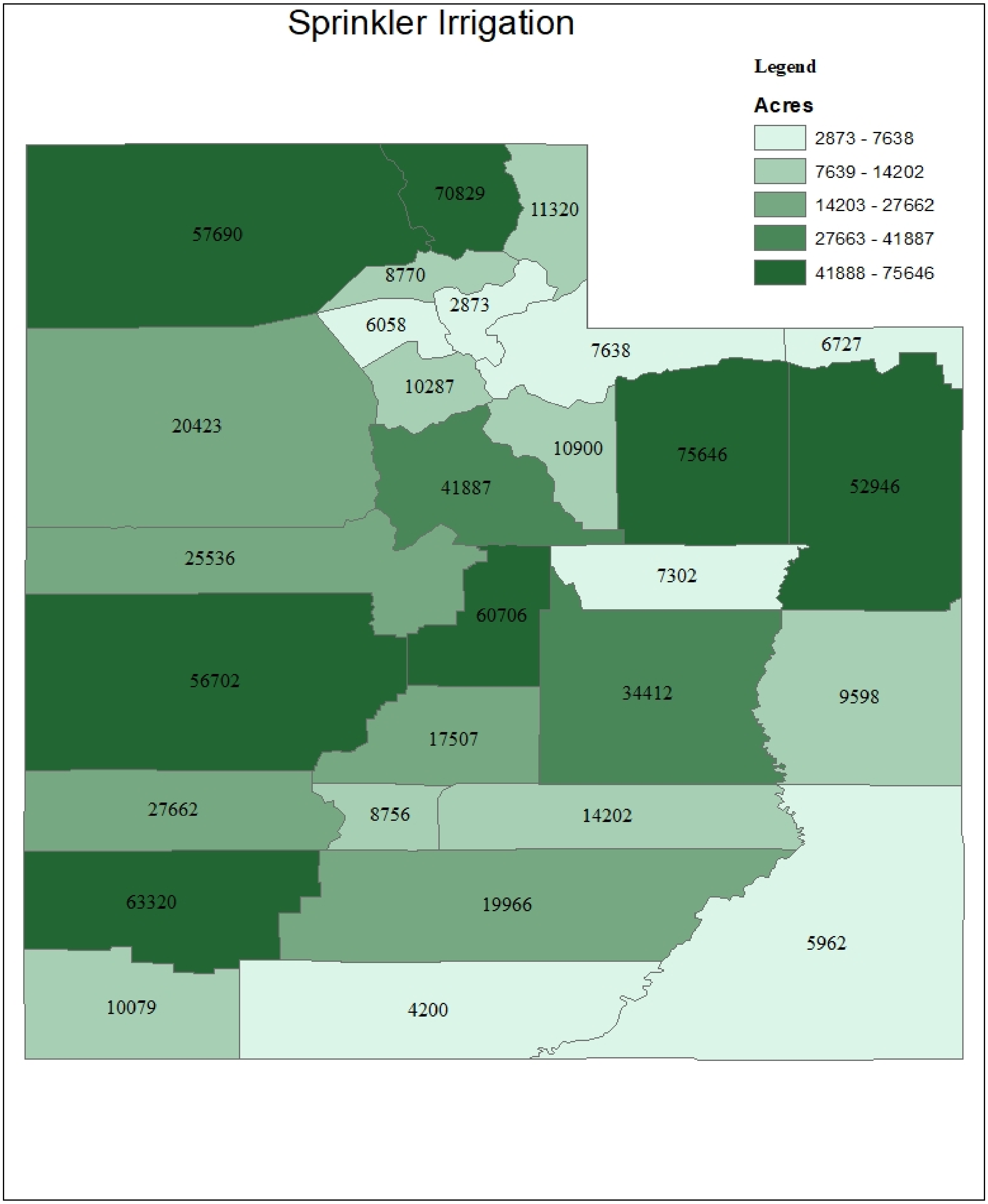


Figure 15. County-wise acreage of sprinkler-irrigated land in Utah (2018).
(USDA, 2020b)

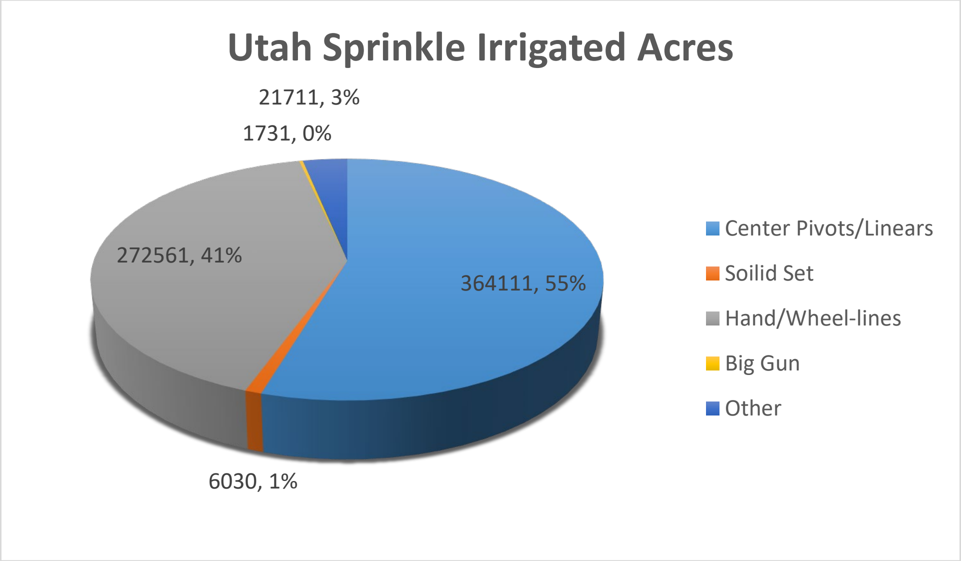


Figure 16. Utah sprinkle-irrigation acres by system type (2018).
(USDA, 2020b)

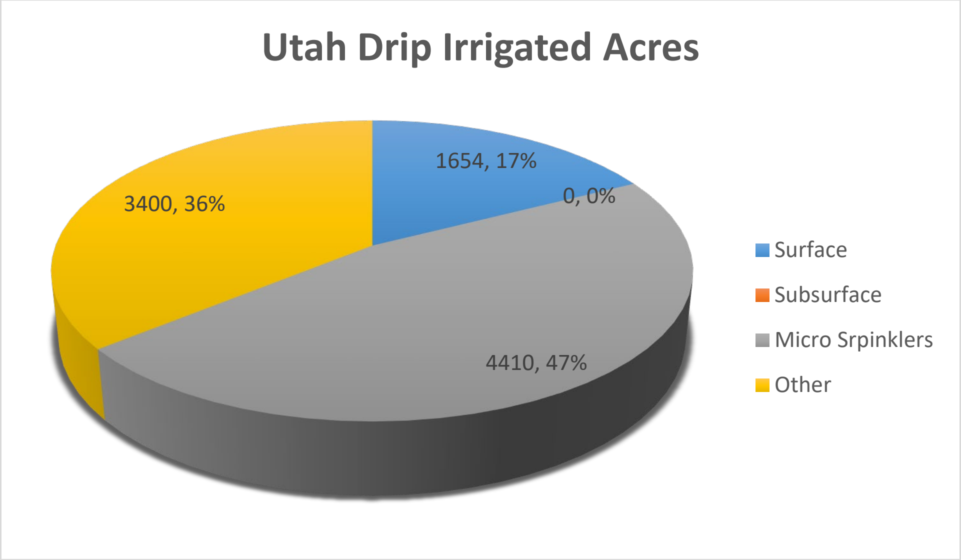


Figure 17. Utah drip-irrigated acres by system type (2018).
(USDA, 2020b)

Irrigation scheduling (deciding when, and how much water to apply) in Utah is still mostly done by the looking at the crop, the look and feel of the soil, or scheduling is simply dictated by when the water is delivered (Figure 18). Irrigating when water stress is observed means that growers will always be watering too late, after yield reductions due to water stress. Irrigating early "just in case" means that many growers will be over-irrigating and losing water to deep percolation. Irrigating only when water is supplied by the irrigation district, or by a personal calendar does not allow the flexibility to respond to the greatly changing water requirements of crops due to the changing weather, crop development, and the season. Doing scientific, or data-based scheduling can decrease water use, increase yields, and save pumping energy costs. There is room for improvement in all western states, and Utah is no exception.

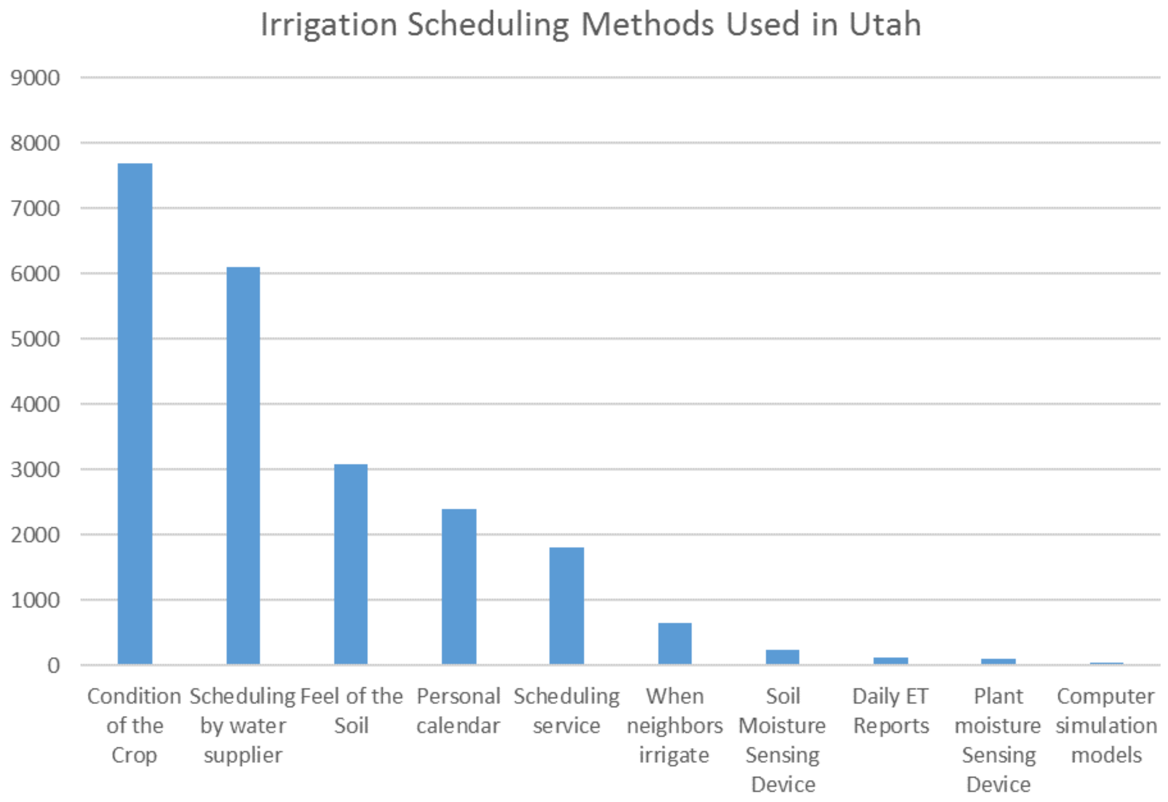


Figure 18. Current irrigation scheduling methods used in Utah.
(USDA, 2020b)

3.1.2 Current Tillage practices

Utah wheat farmers use various tillage practices to grow their crops. Tillage methods range from conventional moldboard plowing, which overturns the soil and leaves little crop residue on the surface of the soil, to conservation methods such as no-till, which disturbs minimal amounts of soil and utilizes (hopefully) healthy crop residue.

Tillage methods which turn the soil over, such as the moldboard plow system and disk plow system, are considered part of the conventional tillage practice. The moldboard plow and disk plow are generally used as the primary tillage after harvest in the late fall. On the other hand, the chisel plow system may be considered either a conventional tillage practice or as a conservation tillage practice based on how the agriculturalist chooses to execute the chisel plow system. Chisel plow methods may be used at any non-harvest time. Apart from minor practical differences between these three systems, their utility is in their mechanical method and utilized for non-chemical fallow (eliminates/minimizes the use of herbicides). Figure 19 shows the different tillage practices in Utah, which clearly illustrates that conventional tillage are the most practiced method used in Utah and Figure 21 show the county-wise bar graph of the number of conservation and conventional tillage practices that are performed in 2017.

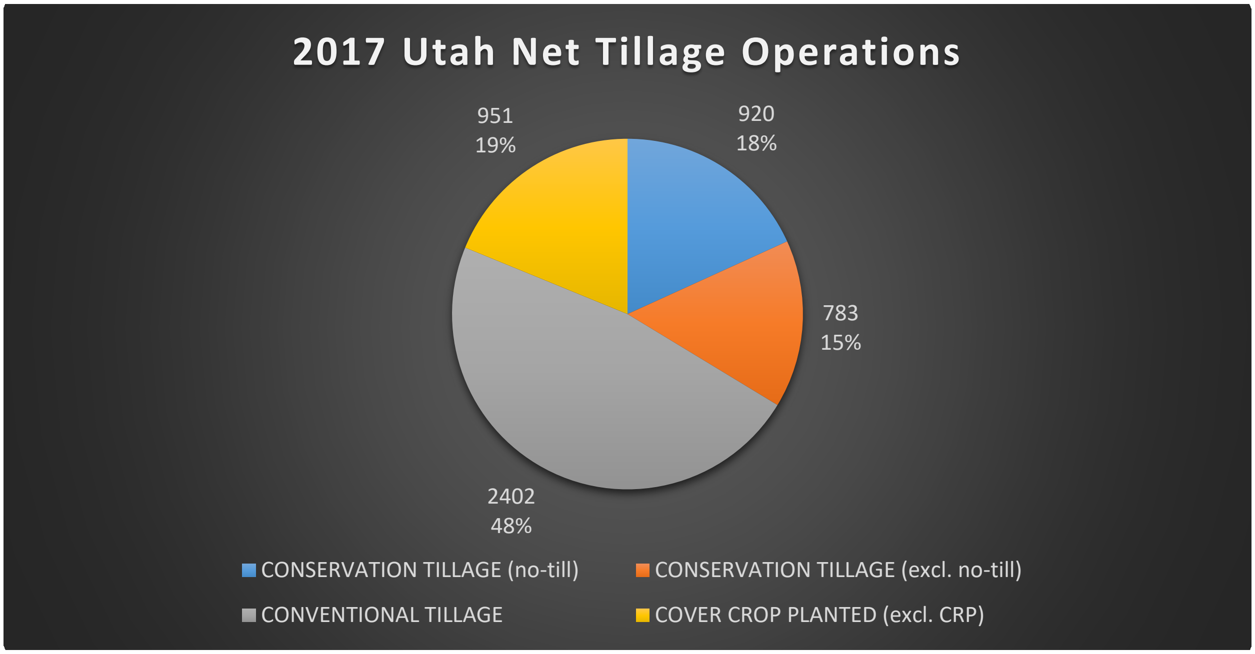


Figure 19. Total Number of Tillage Operations in Utah (2017).
(USDA, 2020b)

Conservation Tillage:

Conservation no-till produces the least soil disturbance of any tillage method, with less than 25% soil disturbance and a RUSLE2 stir value of less than 10. Soil and crop residue (cover crop) is undisturbed except for the crop row where the seed and fertilizer are placed in the ground. They are disturbing less than 25% of the row width. This disturbance includes soil moved in the crop row, dispersed, or splashed (USDA, 2006). Weeds are controlled with herbicides. However, in cases when weeds irreversibly consume the farm full tillage is sometimes the only option, as stated by Phil "No-till Phil" Rasmussen; "No-till doesn't mean never-till" (Rasmussen, 2011). Full benefits of a no-till system can be accomplished after five continuous years of practice. Advantages with this practice include: maximum erosion control, conserves soil moisture, improves organic matter, and the lowest fuel and labor input costs. Challenges with this practice include: limited incorporation potential, may increase dependence on herbicides for weed control, soil warming may be slower in the spring especially on poorly drained soils and heavy residue levels (USDA, 2006).

Conservation strip-till has a soil disturbance of about ~30% and a RUSLE2 stir value between 10 and 15. Considered a form of minimum-till by the NRCS, this system offers the same soil warming benefits of conventional ridge-till and the soil protection of no-till. Strip-till requires multiple passes: the first pass is called the zone-till builder, which tills strips (ridges). The second pass is called the zone-till planter, which plants the seed. Since multiple passes are required, strip-till requires more fuel, contributing to higher emissions than no-till, but less than conventional tillage.

Mulch-till has the highest soil disturbance between 30% and 100% and has a RUSLE2 stir value greater than 15. With mulch-till a chisel plow, disk plow, rotary harrow, turbo-till, or secondary equipment like a field cultivator are used to till prior to planting similar to conventional tillage. However, some crop residue remains on the soil surface. Mulch-till provides moderate protection for the exposed soil from erosion, but also falls victim to water and wind erosion and conserves some soil moisture when residue levels are high. Closely related to conventional tillage, mulch-till has moderate erosion control especially if contour planting is not used, moderate soil moisture loss, medium labor, and fuel costs.

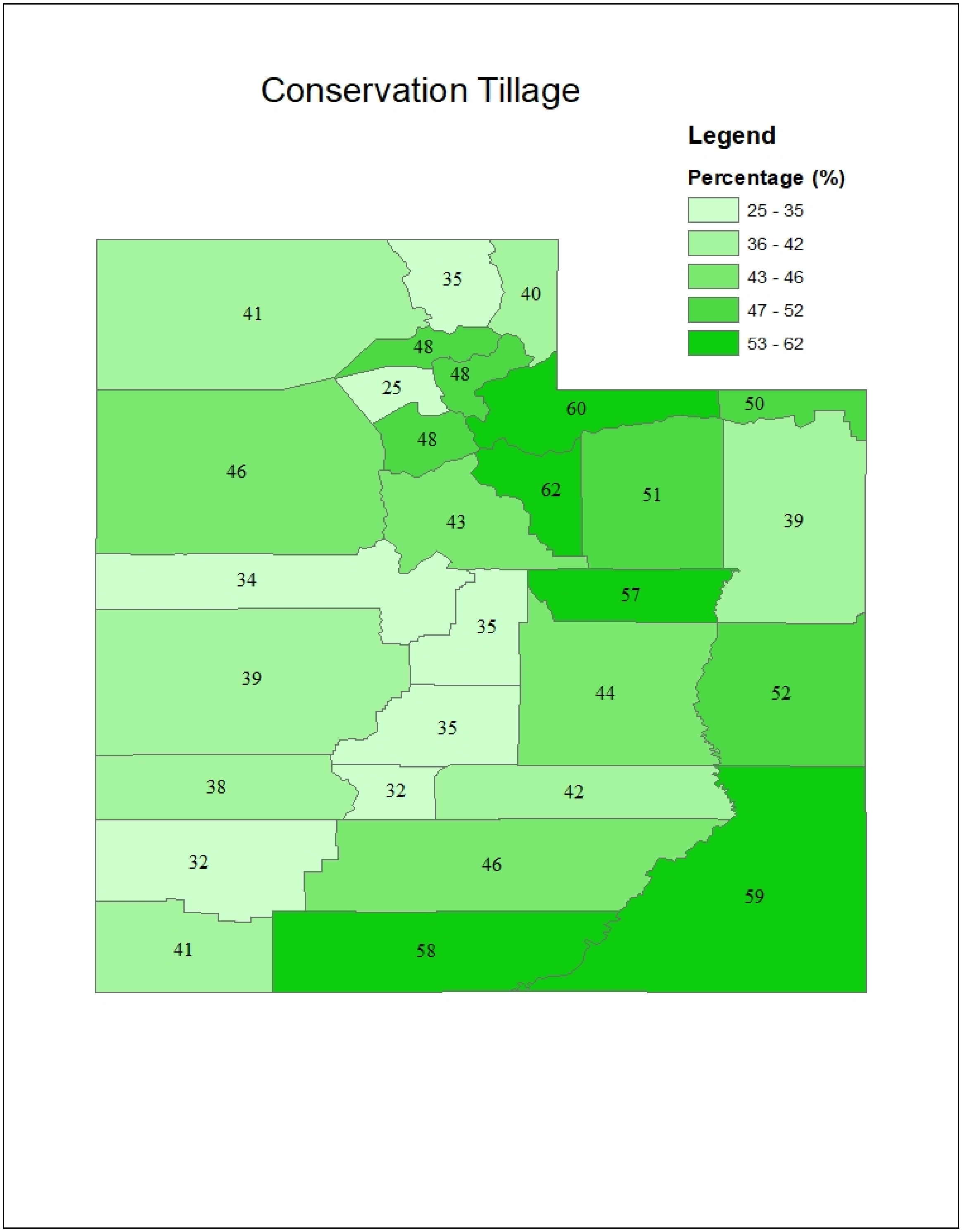


Figure 20. County-wise percentage of conservation tillage operations in Utah (2018). (USDA, 2020b)

Conventional Tillage:

Tillage methods using soil inversions, such as the moldboard plow system and disk plow system, are considered conventional tillage practices. The moldboard plow and disk plow are generally used as primary tillage after harvest during late-Fall. On the other hand, the chisel plow is considered both a conventional tillage practice and conservation tillage practice depending on how the agriculturalist chooses to execute the chisel plow practice. The chisel plow may be used at any non-harvest time. Apart from minor practical differences between these three systems, their utility is in their mechanical method and utilized for non-chemical fallow (eliminates/minimizes the use of herbicides) (Bond, 1992).

The subsoiler goes by several other names, which include: chisel plow, flat lifter, ripper, and v-shape ripper. Intended for deep tillage, the subsoiler consists of as many as 5-7 long, thin blades, called “shanks,” which average depths between 12”-20”, twice that of traditional plows. The subsoiler loosens and breaks-up compacted soil deep below the surface. The ripper reaches deeper than other common traditional plows, like the disc harrow or moldboard plow, to break up deep ground compaction, called hardpan. A subsoiler is used during special cases and not typically used annually. Few agriculturalists own a subsoiler, and instead build their own, borrow, or lease one when needed. Subsoilers are inexpensive and easy to maintain. A tractor with high-horsepower, torque, but most importantly, weight is needed. A deeper shank requires a heavier tractor to increase traction.

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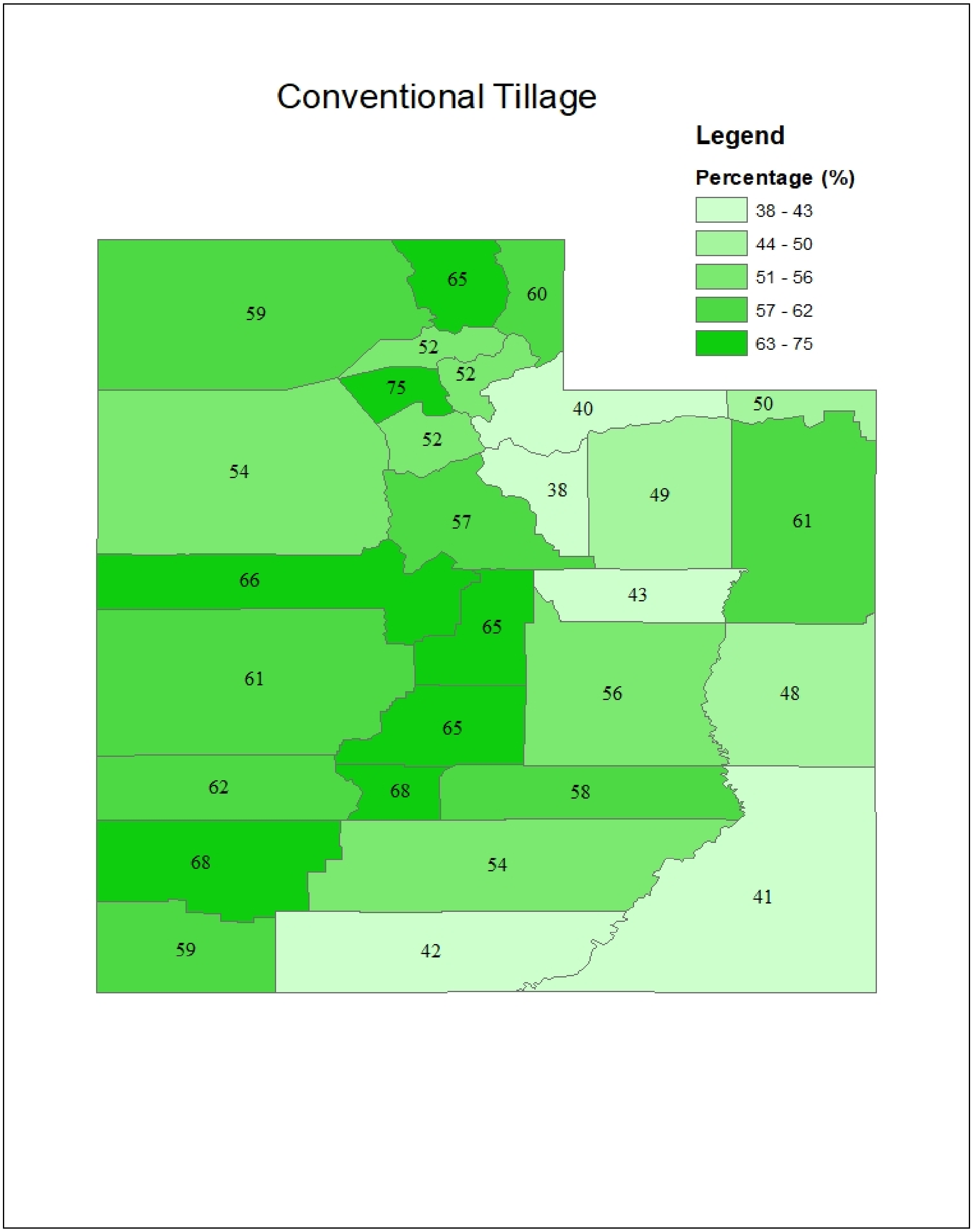

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Figure 21. County-wise percentage of conventional tillage operations in Utah (2018) (USDA, 2020b)

3.2 What has influenced the change from historic irrigation and tillage practices to current practices?

What has influenced the change from historic irrigation practices to current practices?

Current irrigation practices are heavily based on water efficiency and increasing crop production (Mitsuoka). Historic practices were heavily influenced by product demand and urban growth. Utah's population continues to grow in urban areas and a decrease in rural areas. Like everything else, change is primarily driven by economics. The desire to get greater returns. This usually means trying to produce more with less. Less capital investment, and especially lower labor requirements. The main influence of irrigation change comes from the push to grow large amounts of produce with lower and lower land areas every year. This is done by working to improve water use efficiency, which is a measure of crop production per unit of water used. As time progresses, the number of farms in Utah decreases, while the average acreage per farm increases (Mitsuoka).

In general, choosing the right irrigation technology includes the compatibility of the system with other farm operations, economic feasibility, land topography, soil properties, crop characteristics, and social constraints (Walker & Skogerboe, 1987). Many of these push farmers to choose more sophisticated irrigation technologies that are more flexible, have lower labor requirements, and are more efficient. The USDA issued the irrigation guide (USDA, 1997) that provides recommendations and considerations of what kind of irrigation system might be used based on the crops to be grown, topography or physical site conditions, water supply, climate, available energy, chemigation requirements, operation and management skills, environmental concerns, soil, farming equipment, and costs. Moreover, Utah state policy encourages water conservation, efficiency, and elimination of wasteful water practices (Utah, 2020). Thus, water policy, economics, suitability to the farm, and limitation of water are the factors that drove Utah growers to switch to newer irrigation technologies.

What has influenced the change from conventional tillage practices to conservation practices?

Conventional tillage can cause the soil to a clod, creating a brick-like soil structure (see Figure 22). Soil clods make planting seeds into the soil more difficult because it requires planting equipment to break up these clods, which is additional work, fuel expenses, and wear on machinery. The primary driver influencing change from conventional tillage to conservation practices is the reduced labor, tractor wear and tear, and fuel costs associated with conservation tillage. In addition growers are being convinced by the research and by the experiences of their friends and neighbors that are seeing decreased costs, similar or better yields, and an increase in their soil organic matter contents over time. In addition the availability of new tillage and planting machinery that can plant into stubble and create either acceptable or equivalent seed germination rates as conventional tillage is helping promote this technology.

Figure 22. Conventional tillage clods.
(Hansen, 2012)

3.3 What are the leading factors preventing producers from changing irrigation or tillage practices?

3.3.1 What prevents changes in irrigation practices?

The major factors preventing switching to newer irrigation technology are:

1. Economics:

   Every irrigation practices that are being practiced has some machinery and tools. The switch over to newer technology means uselessness of the old equipment. On the other hand, the initial investment cost of newer technology is higher, and which is normally not paid by the more yield, they are getting within the first or second year.

2. Perception of loss of water right:

   The many Western States, including Utah, have a doctrine that uses it or loses it. Currently, if farmers do not use the water right or a portion of it continuously for seven years, then the unused water rights will be forfeited (State of Utah, 2020). Thus, people fear that if they adopt more efficient technology, they may lose part of their valuable water rights.

3. No benefit on saving:

   Even if the state does not remove part of the grower's water right. The current water policy does not allow for water spreading i.e., the water conserved cannot be used to benefit the farmer (State of Utah, 2020). Few Utah citizens are willing to pay additional taxes to benefit the state. Utah farmers are similar and are seldom willing to make personal financial sacrifices for a nebulous public good.

4. Changing practice and techniques:

   Farmers learn their trade through family generations and traditions, along with personal research. Switching over to new practices require new knowledge and skills and experience with how to best use the new methods. That is a big and risky leap of faith for most growers with their livelihoods on the line, especially with the large investments required for new irrigation technologies.

3.3.2 What prevents the switch to conservation tillage practices?

The major leading factors preventing switching to conservation tillage practices are:

1. Initial financial costs transitioning from conventional tillage methods to conservation/no-till methods:

   No- till requires a no-till drill, meaning a whole new machine. The cost associated with transitioning, such as the purchase of no-till drill and at the same time financial burden of the previously purchased tillage machine ($10,000-$20,000) makes farmers reluctant to switch to no- till practices.

2. Changing practice and techniques:

   Farmers learn their trade through family generations and traditions, along with personal research. After perhaps decades of experience using a technique, like conventional tillage, a newer technique seems like a risky, expensive fad with uncertainties.

3. Increased use of herbicides and pesticides:

   Tillage was used to control weeds and prepare seed beds for good seed germination. With conservation tillage weeds have to be controlled by a different method, which is usually using an increased amount and number of herbicides and pesticides compared to conventional tillage. Even with this increased herbicide use, weeds can still be a liability as Phil "No-till Phil" Rasmussen found (Rasmussen, 2011) requiring occasional full tillage.

3.4 How have these irrigation practices performed in terms of irrigation efficiency, water consumption and agricultural productivity?

Irrigation efficiency has improved throughout history, in 1850 it took roughly 2.5 acres of land to produce 100 bushels of corn, now with modern-day irrigation practices 0.6 acres of land is required to produce the same amount of corn (Mitsuoka). A study conducted by (Irmak et al., 2011) at Nebraska found that drip irrigation has higher irrigation efficiency (85-90%), followed by the low energy precision application (LEPA) and lowest being the conventional surface irrigation. From Table 2 we can infer that with the use of surface irrigation technology using best management practices (BMPs) like tailwater reuse, higher irrigation application efficiency of 60-80% can be obtained compared to conventional furrow irrigation (45-65%).

Moreover, no-till acts as a form of natural irrigation efficiency enhancement due to its ability to collect and retain moisture and prevent soil moisture evaporation, while at the same time preventing soil erosion. A layer of natural vegetation covering the surface and increase fiberous soil roots hold the ground together, helping to prevent both wind erosion and water erosion.

3.5 What has been the role of water policy in determining irrigation practices and technologies?

USDA has issued the irrigation guide (USDA, 1997) for selecting from four basic irrigation methods (surface, sprinkler, micro, and subsurface irrigation). While selecting those following factors are given consideration: crops to be grown, topography or physical site conditions, water supply, climate, available energy, chemigation, operation and management skills, environmental concerns, soil, farming equipment, and costs.

In the state of Utah, state policy encourages water conservation, efficiency, and elimination of wasteful water practices (Utah, 2020). Agriculture is required to ensure the optimal use of water to “preserve sustain and improve food production and the productive capacity of agricultural lands.” This was stated in the State Water policy(Utah, 2020) enacted by the 2020 General session. State policy encourages more sustainable practices and encourages accurate water monitoring. Utah’s State Water Policy also states that the implementation of mechanisms that increase the flexibility of water usage should be researched and properly developed (Legislature of Utah, 2020). The State Water Policy plays the role of encouraging agriculture to create better-monitoring systems and to preserve water whilst increasing the production of crops.

Some practices that growers would like to implement, such as using deficit irrigation to conserve water on their fields so that they can use that conserved water to irrigate additional acreage (water spreading), are often prohibited by water policy as the water right is entitled to the property. This is usually because effective water metering is not in place to limit growers using more than their water rights, and land area is the easiest way to limit the expansion of the growers’ water rights. According to an email exchange with James Greer with the Utah Division of Water Rights, while there is no prohibition against using water within water right holder control consistent with the limits of the water right to maximize benefit to the water user, to expand water use beyond the approved place of use or to store unused water in a reservoir would be a modification to the water right and would be required to go through an administrative process of the State Engineer. This provides the State Engineer with an opportunity to review the change proposed and prevent possible impairment to other users. If diversion and depletion is reduced due to a permanent reduction in beneficial use, a portion of your right can move to other uses. If the beneficial use remains the same, the state engineer is unlikely to approve a change to another use. Allowing uses to increase, even when water diverted is used more efficiently has the potential to cause injury or impairment to the rights of others in the system (there will be less water left in the system for other water rights after the use). The State engineer evaluates water uses in terms of potential depletion (water lost for further use) and diversion requirements. Conflicts emerge when water users base their water rights on diversion quantity rather than a right to beneficially use water. *Beneficial use shall be the basis, the measure and the limit of all rights to the use of water in this state* (Utah Code 73-1-3. If a water user can demonstrate that their future use will not divert or deplete more water than their historic uses then the State Engineer will approve the change allowing the water user to spread their water to additional uses.

In states where water-spreading has been allowed, the growers have proven to be very innovative and have greatly increased their overall production, water use efficiency, and income to themselves and consequently to their communities (Yorgey et al., 2018). Many states have also implemented use-it-or-lose-it laws that take water rights away from growers that are not using their water rights (Oregon Water Rights, 2020). These laws were usually implemented to solve paperwork problems (more water rights than there is water), and the resultant unintended consequences are that it can discourage (provides a disincentive for) water conservation and in some cases encourages deliberate inefficient and ineffective use of water in order to preserve the valuable water right (personal communications with growers that would prefer to be off the record).

4.0 Upcoming Irrigation and Tillage Technologies

In this section we describe some relevant upcoming and new irrigation and tillage technologies, whether they will likely have potential for water savings in Utah, an estimate of how much water could be conserved with these technologies, and estimates of the costs of implementing these technologies. The technologies (sections) discussed below are:

1. Irrigation System Conversions (upgrading to more efficient irrigation systems; Section 4.1)
2. Data-Based or Scientific Irrigation Scheduling (Section 4.2)
3. Irrigation Automation (Section 4.3)
4. Variable Rate Irrigation (VRI; Section 4.4)
5. Low Energy Precision Application (LEPA) and Low Elevation Spray Application (LESA) for Center Pivots (Section 4.5)
6. Deficit Irrigation (Section 4.6)
7. Tillage to Reduce Runoff (Section 4.7)
8. Conservation Tillage (Section 4.8)

4.1 Irrigation System Conversions (Upgrading to More Efficient Irrigation Systems)

4.1.1 Discusion of Irrigation Application Efficiency and Water Loss Destinations and How They Affect Long Term Water Availability in Utah

Some irrigation systems are inherently more efficient than others are. How efficiency is defined here is relevant. It is also relevant where the "lost water" goes since this water is sometimes recoverable and sometimes is not recoverable.

4.1.1.1 Defining Irrigation Efficiency

Due to the conservation of mass, water can only change form or location. However, from the viewpoint of the farmer and state we consider irrigation water "lost" in different ways. In an effort to make comparisons between systems and provide useful indices for improvement, we will use irrigation application efficiency (Ea) as the unit for comparing different irrigation systems. It is defined as:

$$Ea = \frac{Water\ Stored\ in\ the\ Root\ Zone}{Water\ that\ Flows\ onto\ the\ Field}$$

This is useful because it allows for comparison between the different irrigation systems regardless of the various final destinations of the "lost" water, whether it be deep percolation, sprinkler wind drift and evaporation, or to field runoff (Figure 23).

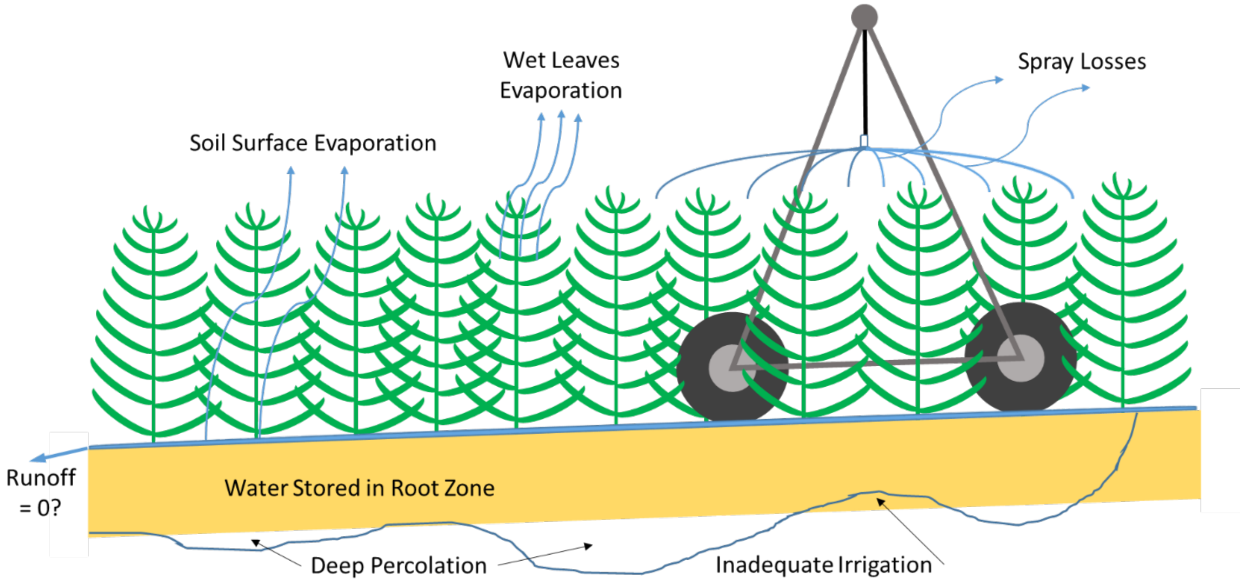


Figure 23. Water losses during irrigation including runoff, deep percolation, spray losses, and evaporation from a wet canopy and wet soil surface. The primary water losses from sprinkler irrigation are wind drift and evaporation (spray) losses and deep percolation due to non-uniform irrigation or imperfect irrigation scheduling.

4.1.1.2 Deep Percolation

Deep percolation occurs when more water infiltrates into the soil than can be held long term in the root zone (the soil water content exceeds field capacity). This excess water moves through the soil profile and out past the bottom of the crop's root zone and this water can no longer be accessed by the crop. Although this water is no longer useful for growing the crop, it moves into the groundwater and may eventually be pumped up from wells for re-use. This water can also come out in river bottoms or in springs and thereafter flow to the ocean. However, in Utah's closed evaporation basins this outflow to the ocean is very limited and in these areas deep percolation water should eventually be available for later use from wells. However, the water quality of deep percolation water losses can be severely degraded (primarily from salinity) by its movement through the soil, subsoil, and the underlying aquifer depending on the local soil and geology. This water quality degredation can limit its ability to be re-used for irrigation. Because of large differences in the underlying geology, and differences in the potential for deep-percolation-water-quality degradation in different areas of Utah, reducing deep percolation water losses may or may not increase long term water availability. Deep percolation is always lost to the farmer and the field crops. However, although the state always loses control of the location and recovery timing of that water, at least a portion of that water is sometimes recoverable.

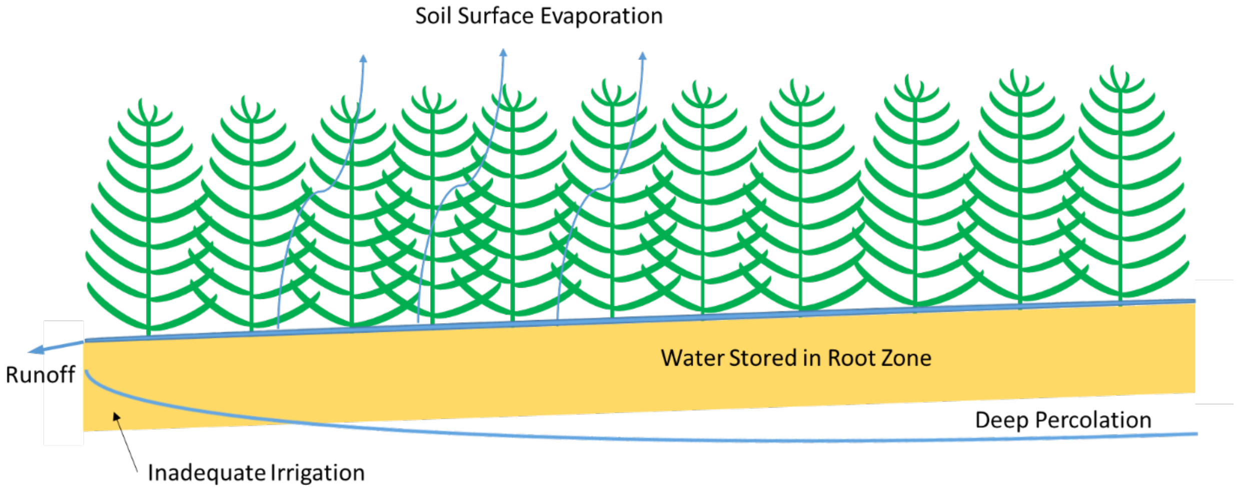


Figure 24. The primary water losses from surface irrigation are deep percolation followed by runoff.

Deep percolation is a very signficant source of water loss in most irrigation systems, but it is especially prevalent in surface irrigation systems (Figure 24). Since deep percolation water losses are is not visible most water managers (on farm and state-wide) don't think about it. In irrigation, deep percolation primarily results from:

- Irrigation mismanagement – Irrigating too soon, or in too great of quantities such that all of the water that is applied cannot be held in the root zone. The excess water “deep percolates” out of the crop’s root zone.
- Imperfect Irrigation System Uniformity – If an irrigation system or method cannot apply the same amount (depth) of water to all areas of a field, then many areas must be over-irrigated (and cause water losses to deep percolation) in order to adequately irrigate the areas with lower application depths. No irrigation system is perfectly uniform and so a certain amount of deep percolation losses are expected. Surface irrigation in particular forces water losses to deep percolation since it takes time for water to move across a field and thus the top part of the field has water infiltrating for many hours before the bottom of the field can receive any water (Figure 23). Water losses to deep percolation in surface irrigation can be as high as 50-70%.

Uniformity is often estimated using infiltration rate curves and saturated time in surface irrigation methods, is tested with catch cans in sprinkler irrigation methods (Figure 25), and estimated using hand measurements of individual emitter flow rates in drip irrigation.

Figure 25. A uniformity evaluation of a center pivot using catch cans.

A common indice for quantifying irrigation uniformity is 'distribution uniformity of the low quarter (DU, or DU_{lq})'. It is calculated as (Figure 26):

$$DU = \frac{AvgLowQuarter}{Avg}$$

where:
AvgLowQuarter is the average of the lowest ¼ of the measured application depths, and
Avg is the overall average measured application depth.

Most growers want to adequately irrigate all areas of the field, and indeed most economic analyses shows that this is the most economical way to irrigate. In order to adequately irrigate the low quarter, the necessary application depth must be divided by the $\mathrm{DU_{lq}}$ of that irrigation system to increase the total application depth. If growers thus increase their application depths to account for poor uniformity then $\mathrm{DU_{lq}}$ is roughly equivalent to irrigation efficiency. For example, if the $\mathrm{DU_{lq}}$ is 0.5 and the grower attemps to adequately irrigate the low quarter, then they would need to apply twice as much water to ensure that the low quarter got fully irrigated.

Poor irrigation system DUs can be partially compensated for by moving irrigation systems where the variability helps fill in the low spots, and by soil's ability to move water laterally, and by roots' ability to grow towards water (Mohamed et al., 2019).

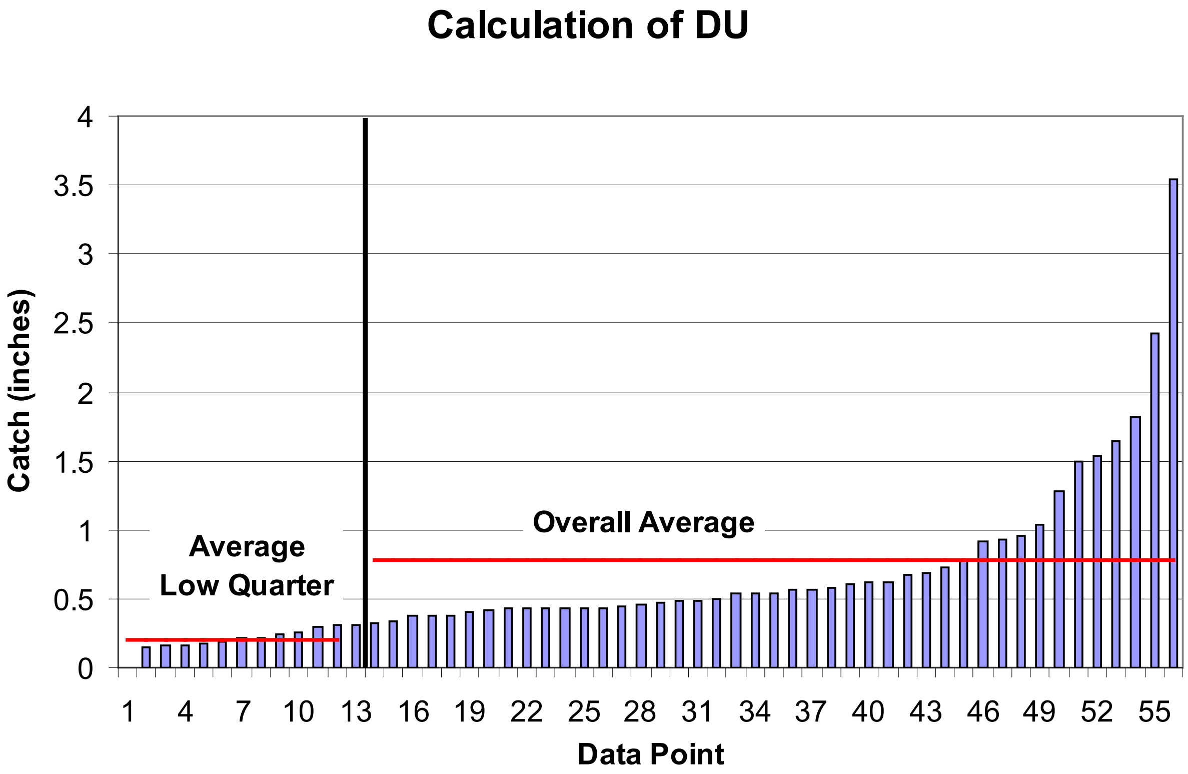


Figure 26. The application depths of an irrigation system uniformity test. The measured application depths are sorted and the average of the low quarter is divided by the overall average. To adequately irrigate all areas of the field, additional water must be applied everywhere in order to adequately irrigate the low quarter.

4.1.1.3 Maintenance to decrease deep percolation.

Improved management and maintenance to limit leaks and ensure good uniformity can greatly decrease water losses to deep percolation. Howard Neibling (Neibling)(University of Idaho) did a full evaluation of 30 hand-line and wheel systems and found a mean of 12% water losses to leaks on Thunderbird wheel-lines, 16% on standard wheel-lines, and mean of 36% losses on hand-line systems. On a typical 40 acre field, and typical application depths, this amounts to 10 to 40 acre-ft of water on that field alone. Most of this water eventually goes to deep percolation. These water losses are not trivial (Figure 27).

Figure 27. A leaking wheel-line connection in Utah. The leak flow rate was over 180% of the flow rate of the sprinkler flow rate above it. Leak water losses go primarily to deep percolation.

4.1.1.4 Runoff

Unlike the other largest losses (evaporation and deep percolation), runoff is very visible and thus most growers, irrigation districts, and law makers are aware of runoff and manage it. Although runoff water quality is often degraded due to running across fields, it is often collected in ponds or drainage ditches and is re-used downstream either for irrigation or for wildlife habitat.

4.1.1.5 Evaporation

Evaporation is when liquid water is converted to water vapor. All evaporation losses can be considered to be total and permanent water losses to Utah since it is unlikely that this water vapor will have the chance to re-condense as rainfall and fall within the state. Reducing these types of water losses will have a significant impact on future total water availability. In irrigation the primary sources of evaporation water losses are:

- Sprinkler discharge (spray) losses to wind drift and evaporation,
- Evaporation from a wet canopy,
- Evaporation from a wet soil surface, and
- Plant transpiration.

Each of these are described and discussed below.

4.1.1.6 Sprinkler Discharge (Spray) Losses to Wind Drift and Evaporation

These are water losses to wind drift and evaporation take place between the time the water leaves the sprinkler nozzle until the time the remaining water hits the soil. These losses are usually measured using catch cans placed at the soil surface. The depth of water that should be collected if all water that left the nozzle made it to the soil surface is compared with the actual depth of water caught. Because most of these losses leave the fields as water vapor, they are not visible and thus “out of sight, out of mind”. Because of this, many water managers don’t consider them. However, these water losses are highly significant! Many different catch can tests from a wide variety of different scientists show that these losses range from close to zero to as high as 40-50% depending on the sprinkler type, height, pressure, and most importantly, the weather. Typical water losses are 35-40% for traveling big guns and pivot end guns, 25-30% for impact sprinklers on hand-lines or wheel lines, 15-20% for typical center pivot mid-elevation spray-application sprinklers, and < 5% for low elevation spray application (LESA) or low energy precision application (LEPA) sprinklers on center pivots (Alam, 1997; Association, 2010; Blaine Hanson, 2004; Brouwer et al., 1989; Charles M. Burt, 1995; C. M. Burt et al., 2000; Irmak et al., 2011; B. Kranz, 2020; T. R. Peters & McMoran., 2009. ; Rogers & Lamm, 1997; Sarwar et al., 2019; Solomon, 1988a, 1988b; Stetson & Mecham, 2011)

4.1.1.7 Evaporation from Wet Canopy

Water evaporation from a wetted canopy are usually a fairly consistent amount. This is because this depends primarily on how much water can be held on a wetted canopy, and thus depends primarily on the canopy size and the percentage of the canopy that is wetted. Many researchers have found that this water loss is about 0.05 inches after each irrigation. These losses are largely avoided in surface, drip (Figure 28), and LEPA, or mobile drip irrigation (MDI) systems because they do not wet the crop canopy. Because these losses occur after every wetting of the canopy, they can be minimized by irrigating less frequently (requires greater depths of water applied per irrigation). However, of course this is limited by the soil’s infiltration rates, and the soil’s water holding capacity (how much space there is in the soil to hold irrigation water). There is a fairly reasonable argument however, that water evaporating from a wetted canopy cools that canopy and thus directly suppresses evapotranspiration because it robs the canopy of the energy required to transpire water from the crop.

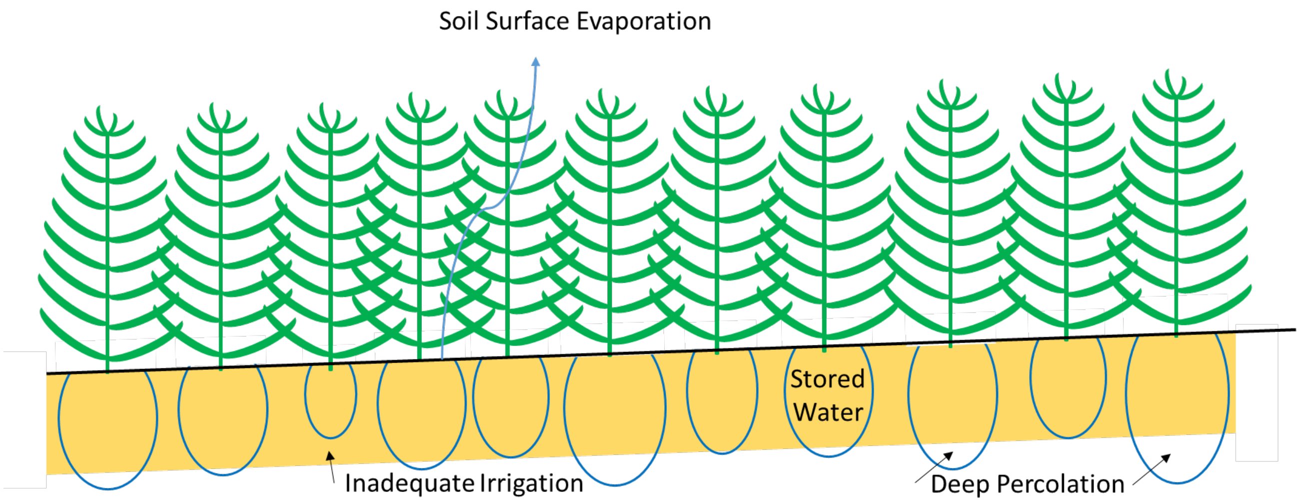


Figure 28. The water losses from drip irrigation are small. Soil surface evaporation is limited due to less soil surface being wetted. The primary water losses from drip irrigation are due to the differences in emitter flow rates resulting in deep percolation in order to adequately irrigate all plants.

4.1.1.8 Evaporation from a Wet Soil Surface

These losses are also usually about 0.05 inches after each irrigation. This can only be avoided by not completely wetting the entire soil surface, which is only possible with drip irrigation (especially subsurface drip irrigation or SDI), furrow irrigation (especially when irrigating every-other furrow), and with LEPA or MDI on center pivots.

4.1.1.9 Transpiration

This is water that is absorbed by the crop roots, travels through the plant stem and is transpired out of the leaves. Transpiration has been shown to be very linearly correlated with crop yield (Doorenbos & Kassam, 1979). Therefore transpiration is the objective of irrigation and it is not desirable to reduce or minimize transpiration. Of course, transpiration leaves the field as water vapor, is truly “consumptive use”, and as such is not considered recoverable in Utah.

4.1.1.10 Consumptive Water Use Timing

Consumptive use is water that is essentially converted to water vapor. Once water is converted to water vapor that water is almost entirely lost to the drainage basin, and likely to the state of Utah. There are minor influences that this water evaporation can have such as slightly decreasing the air temperature and increasing the humidity which may suppress crop evapotranspiration (ET) downwind. However, research is showing that this suppression of ET downwind is minor related to the amount of water consumed by humidifying and lowering the temperature of the air (Molaei and Peters, unpublished).

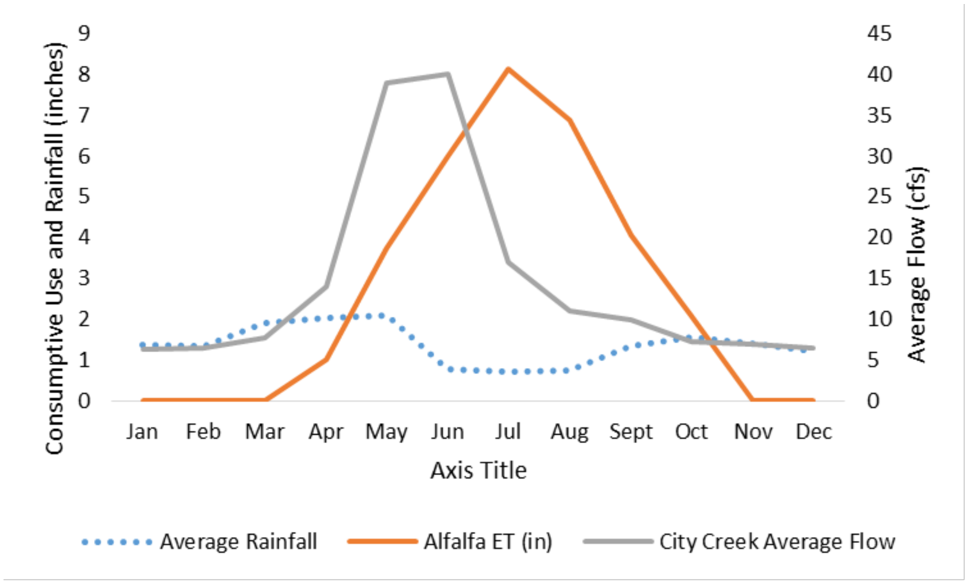


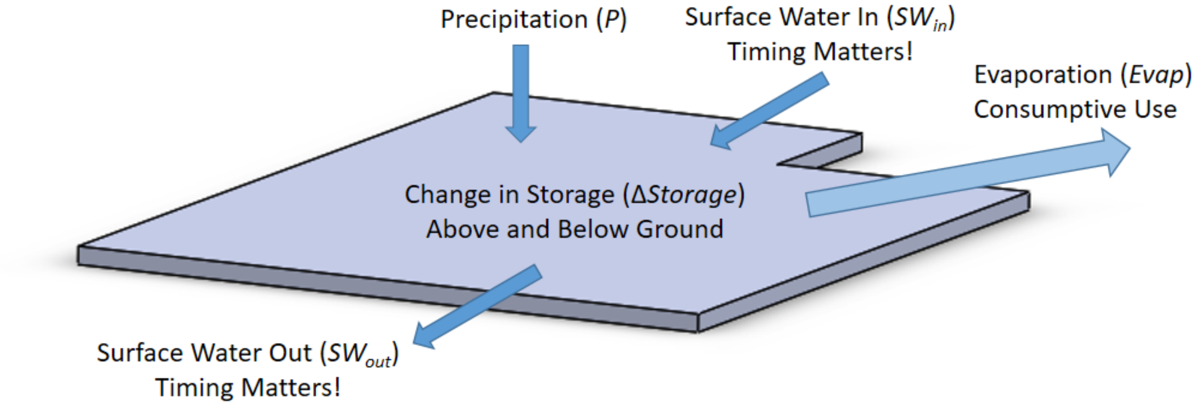
Figure 29. Example of the average consumptive use (ET), and rainfall compared to the stream flow rate in Salt Lake City's City Creek showing the typical disconnect between supply and demand for irrigation water.

The mountain snow melt in Utah mostly runs out of the mountains in the spring, peaking in May and June. However, the consumptive use of water for irrigation peaks in July and August (Figure 29). This disconnect between the timing of the supply and crop water requirements makes groundwater and reservoirs vital in the state to store this spring runoff for summer use. Climate change is predicted to cause the runoff to come earlier and the crop water needs to be greater. This would exacerbate this disconnect between water supply and water requirement timing which will likely necessitate either additional water storage, greater water conservation, or irrigated acreage reductions in the future.

The timing of water needs and the disconnect between the timing of water supply and demand should be kept in mind when evaluating irrigation and tillage technologies for water conservation. Some technologies conserve water mostly in the spring and fall when there is lower needs and greater supplies (such as improved irrigation scheduling and deficit irrigation), while other technologies improve the water availability/productivity during the hot part of the summer when the supplies are most limited and the needs are the greatest (such as LEPA/LESA, MDI, and drip irrigation).

4.1.1.11 The Big Picture

When deciding which irrigation systems to promote, it is important to think of how they affect the water balance to the drainage basin or to the state as a whole. The major methods of water movement into and out of the state with the state-wide water balance is demonstrated in Figure 30 (below). We have no control over precipitation, and only limited control in the surface waters entering and leaving the state as most of those are controlled by treaties. However, Utahans can affect the change in surface and groundwater storage in the state by taking advantage of water from times when the demand is lower, such as in the winter, and they can try to limit evaporation (consumptive use) losses.



$$P + SW_{in} = \Delta Storage + SW_{out} + Evap$$

Figure 30. Considering the long-term water balance to Utah as a whole; the things we have the most control over with irrigation and tillage are the change in storage and the evaporation losses.

Irrigation system efficiency and estimates of how the final destination of the water losses affects the overall water balance in the state of Utah are shown in Table 4. This information was compiled from a wide variety of publications (Alam, 1997; Association, 2010; Blaine Hanson, 2004; Brouwer et al., 1989; Charles M. Burt, 1995; C. M. Burt et al., 2000; Hanson, 1994; Irmak et al., 2011; Kisekka et al., 2016; B. Kranz, 2020; S.-H. Sadeghi et al., 2015; S. H. Sadeghi et al., 2017; Solomon, 1988a, 1988b; Stetson & Mecham, 2011; Steve R. Melvin & Martin, 2018). Based on this research and similar research reports, attempts were made to allocate the fraction of the water losses that end up as deep percolation, wind drift and evaporation, or field runoff. Using a rough estimate that the 75% of the water lost to deep percolation and field runoff is eventually recoverable, then the fraction of the short term losses (1-Ea/100) that are 'forever' losses, or not recoverable can be estimated. These are shown in Figure 31 as a stacked bar chart where the total height is the short term losses (1-Ea/100), and the mid heights are the 'forever' losses. Figure 32 is the same data sorted by the lowest 'forever' losses.

Table 4. Irrigation system efficiency comparisons and estimates of the affects to the overall water balance in the state of Utah.

Type	Irrigation System	Irrigation Efficiency	Primary Destination of Water Losses	Irrigation Efficiency Range (%)	Fraction Losses to DP	Fraction Losses to WDE	Fraction Losses to RO	Fraction Short Term Losses	Fraction Forever Losses
Drip	Subsurface drip	98	DP	85-100	0.95	0.05	0	0.02	0.006
	Surface Drip	95	DP	80-90	0.95	0.05	0	0.05	0.014
	Mobile Drip Irrigation	96	DP	80-90	0.95	0.05	0	0.04	0.012
Sprinkle	Pivot/Linear LEPA	93	WDE	80-97	0.15	0.85	0	0.07	0.062
	Pivot/Linear LESA	92	WDE	80-97	0.1	0.9	0	0.08	0.074
	Microsprinkler	87.5	WDE	80-90	0.2	0.8	0	0.125	0.106
	Undertree Orchard	84	WDE	75-93	0.1	0.9	0	0.16	0.148
	Pivot/Linear MESA	82.5	WDE	75-90	0.1	0.9	0	0.175	0.162
	Solid Set Sprinklers	75	WDE	70-80	0.1	0.9	0	0.25	0.231
	Hand move	70	WDE	60-90	0.1	0.9	0	0.3	0.278
	Wheel Line	70	WDE	65-85	0.1	0.9	0	0.3	0.278
	Big Gun	60	WDE	50-70	0.1	0.9	0	0.4	0.370
	Pivot/Linear (Top of Pipe)	60	WDE	50-70	0.1	0.9	0	0.4	0.370
Surface	Basin	80	DP, RO	75-90	0.9	0.1	0	0.2	0.065
	Border	77.5	DP, RO	70-85	0.8	0.1	0.1	0.225	0.073
	Graded Furrow	77.5	DP, RO	75-85	0.65	0.1	0.15	0.225	0.068
	Contour Border	77.5	DP, RO	75-80	0.8	0.1	0.1	0.225	0.073
	Furrow	70	DP, RO	60-75	0.7	0.1	0.2	0.3	0.098
	Corrugation	68	DP, RO	65-75	0.8	0.1	0.1	0.32	0.104
	Wild Flood	50	DP, RO	40-60	0.8	0.1	0.1	0.5	0.163

* Irrigation efficiency (E_a, or application efficiency) is defined as the water stored in the root zone divided by the water flowing onto the field. DP is deep percolation, WDE is wind drift and evaporation, and RO is runoff.

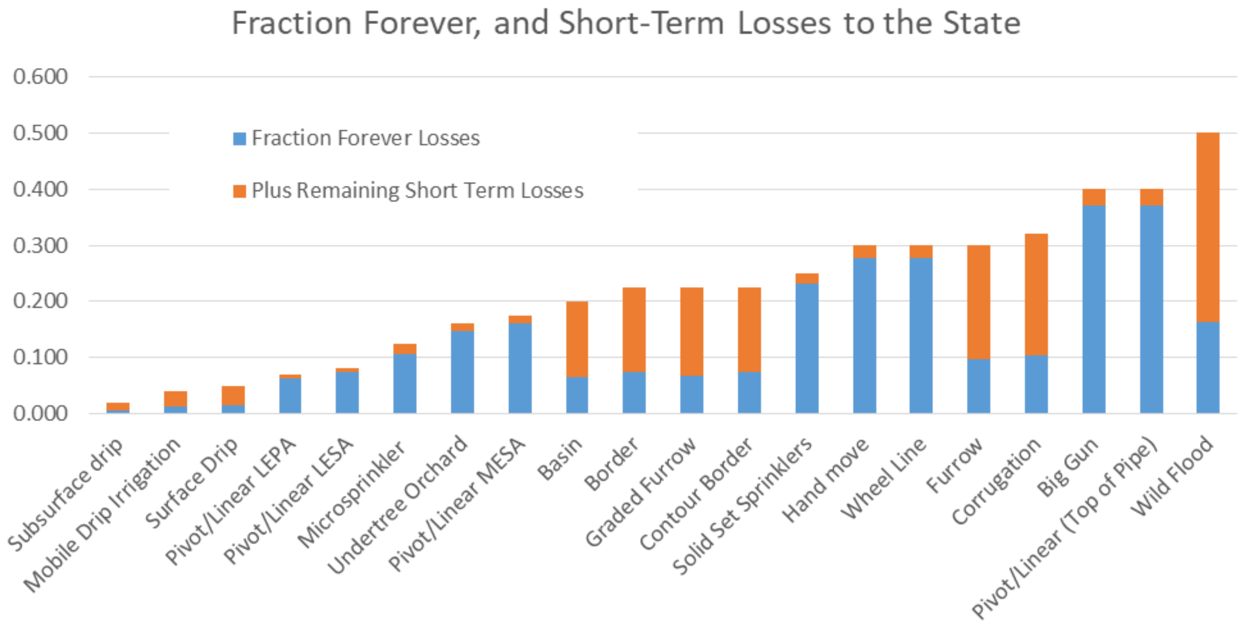


Figure 31. The fraction of the irrigation system losses that are 'forever' losses and short-term losses to the state *sorted by total losses* (1-Ea/100). These assume that 75% of deep percolation and 75% of runoff losses are eventually recoverable.

Figure 32. Water being lost to the wind on a center-pivot irrigation system. Only the droplets are visible. Water losses once converted to water vapor are no longer visible.

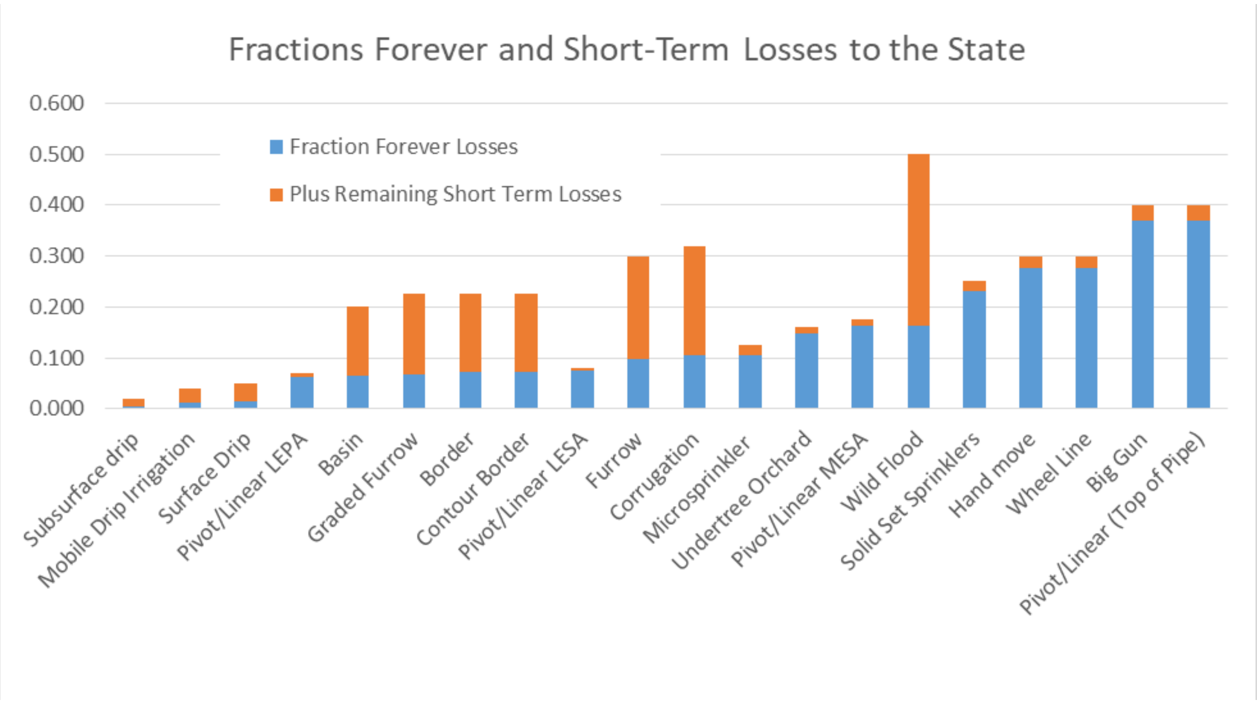


Figure 33. The fraction of the irrigation system losses that are 'forever' losses and short-term losses to the state *sorted by the proportion that are 'forever' losses*. These assume that 75% of deep percolation and 75% of runoff losses are eventually recoverable.

Surface Irrigation Isn't Always Bad

In overall water balance to the state and prioritizing 'forever' losses Figure 33 surface irrigation in not always something to be fought. It is inefficient because we lose track of and control over the water. However, the water is still there, mostly in the groundwater. That is bad for the short term and from a water delivery and supply capacity point-of-view, but can be OK and may be beneficial in the long term. Surface irrigation may be the ideal and most efficient irrigation system for flat, saline, and high-clay-content soils. These surface irrigators can find improvements in their efficiency by using ideal flow rates, run lengths, and irrigation set times, which are key to good surface irrigation system efficiency and uniformity.

Irrigation Systems that Should not be Promoted.

Big guns (Figure 35) typically have a measured irrigation water loss to evaporation of about 40% (permanent losses) and they are associated with poor irrigation uniformity because they are so affected by the wind (T. R. Peters & McMoran., 2009.). Because they require such high pressures, they also are an energy intensive way to irrigate.

End guns on center pivots have been similarly found to have poor irrigation efficiency (around 40% losses), and poor irrigation uniformity. They also require high pressures which translates to higher energy costs. In addition, they are high cost and high maintenance pieces of equipment (personal communication with several irrigation dealers).

Center pivots with high-pressure impact sprinklers mounted on the top of the pipe (Figure 34) also have very high spray losses to wind drift and evaporation (measured in several tests to be around 40%) and require high pressures making them an inefficient way to irrigate in terms of both water and energy. Because they have a large wetted radius these systems are often used on soils with runoff problems due to either the soil or the slope. However, runoff issues can be addressed with tillage methods to increase soil surface storage, and/or with boom-backs to physically spread out the sprinklers on alternate sides of the pivot to allow additional time for water to infiltrate into the soil as the pivot moves by.

Hand lines and wheel lines are more efficient than the above methods, but not by much. The typical measured catch efficiency of these systems is 70-75%, meaning there are 25-30% spray losses to wind drift and evaporation (forever losses). In a large-scale evaluation of 30 different systems of this type Howard Neibling (University of Idaho, unpublished study) found an average of 12% water losses to leaks on Thunderbird wheel-lines, 16% on standard wheel-lines, and mean of 36% losses on hand-line systems, and this was just to leaks or poorly sized nozzles. In addition hand lines and wheel lines require relatively high pressures to operate and therefore use greater amounts of pumping energy (and costs) compared to center pivots, drip, or surface irrigation systems.

Figure 34. A center pivot with high pressure impact sprinklers on the top of the pipe. Around 40% of the water that leaves the nozzles cannot be collected in catch cans at the soil surface.

There are ways to use the above-mentioned irrigation systems efficiently such as only operate under cool, humid, and low wind conditions, but since the weather rarely cooperates and because there is seldom the flexibility to shut down due to non-ideal weather, this is difficult to do in practice. Operating these high-pressure sprinkler systems under windy conditions makes the catch efficiency and irrigation system uniformity drop drastically.

Figure 35. A big gun sprinkler operating on a windy day.

4.1.1.12 Opportunities

Wind not only causes large sprinkler water losses, but it increases the consumptive demand considerably, and makes the irrigation system distribution uniformity to be much worse. Some (not all) irrigators have the flexibility to be able to shut off their irrigation systems under high wind conditions. This should be encouraged wherever possible.

Center pivots should be converted to LEPA, LESA, or MDI as money permits or water shortage pressures motivate. This should be considered especially in arid and windy areas.

Energy Use Benefits

Most technologies that conserve water also conserve energy. This is because energy is required to pressurize and distribute irrigation water. When less water is used, less energy is also used. Many of the more efficient irrigation technologies also require lower pressures, which also means lower energy requirements to pressurize the water.

Conserving Water Doesn't Always Mean More Water Available

Often when farmers upgrade their surface irrigation systems to center pivot irrigation systems they get better yields. This is often because of the center pivot's ability to irrigation more frequently, and because center pivots apply water more uniformly than surface irrigation is able to. Greater yields means greater transpiration because the crops are bigger and healthier. Center pivots also lose more water to evaporation, due to spraying water through the air, and because of more frequent wetting of the canopy, whereas surface irrigation water losses are primarily deep percolation and field runoff. Because of these factors converting farms from surface to center pivots, for example, may not result in more water available for alternative uses.

If conservation practices or more efficient irrigation systems are implemented in areas where the growers usually do not have enough water available for full irrigation (they are already deficit irrigating), then the conserved water will be used for irrigation to reduce the deficit. Again, additional water is not made available, but the growers are more productive.

Efficiency is Limited by Water Delivery

The above efficiency estimates assume an adequate supply and delivery of water, which may not always be available. If a grower is already deficit irrigating, which can be common in Utah, then there will be much lower losses to deep percolation and runoff and therefore water conservation may not be possible. The growers' ability to optimally irrigate also depends on a flexible and preferably on-demand irrigation water delivery systems. It is acknowledged that there are practical, organizational, geographical, financial, and political reasons why these types of water delivery systems may not be available. They require large in-system storage and large delivery capacity systems for the unpredictable on-offs of large flow rates.

4.1.2 Efficiency Gains

Table 5 below can be used to estimate the efficiency gains or sometimes losses by converting from one irrigation system to another. The percent savings or the percent of additional water required when converting *from* one system *to* another system is calculated as $(100/Ea_{from}-100/Ea_{to})/(100/Ea_{from})$ where Ea_{from} is the irrigation efficiency of the system that is being converted from, and Ea_{to} is the irrigation efficiency of the system that is being converted to.

It should be noted that these are approximate estimates of mean irrigation efficiency based on the references above and from irrigation system evaluations. Actual irrigation efficiency can vary substantially depending on the: soil, slope, field size, weather, system pressure, system flow rate, emitter type, application rate, emitter spacing, system maintenance, tillage, crop type and growth stage, time of day or night, and grower practices. However, these tables attempt to capture the inherent abilities or advantages/disadvantages of each system type.

Table 5. Can be used to estimate the percent water savings (positive numbers) or losses (negative numbers) by converting from one technology to another.

			Drip			Sprinkle								Surface							
Type	Irrigation System Convert From ↓ To →	Irrigation Efficiency (%)	Subsurface drip	Mobile Drip Irrigation	Surface Drip	Pivot/Linear LEPA	Pivot/Linear LESA	Microsprinkler	Undertree Orchard	Pivot/Linear MESA	Hand move	Wheel Line	Big Gun	Pivot/Linear (Top of Pipe)	Basin	Border	Graded Furrow	Contour Border	Solid Set Sprinklers	Furrow	Corrugation	Wild Flood
			98	96	95	93	92	87.5	84	82.5	70	70	60	60	80	77.5	77.5	77.5	75	70	68	50
Drip	Subsurface drip	98	**0%**	-2%	-3%	-5%	-7%	-12%	-17%	-19%	-40%	-40%	-63%	-63%	-23%	-26%	-26%	-26%	-31%	-40%	-44%	-96%
Drip	Mobile Drip Irrigation	96	2%	**0%**	-1%	-3%	-4%	-10%	-14%	-16%	-37%	-37%	-60%	-60%	-20%	-24%	-24%	-24%	-28%	-37%	-41%	-92%
Drip	Surface Drip	95	3%	1%	**0%**	-2%	-3%	-9%	-13%	-15%	-36%	-36%	-58%	-58%	-19%	-23%	-23%	-23%	-27%	-36%	-40%	-90%
Sprinkle	Pivot/Linear LEPA	93	5%	3%	2%	**0%**	-1%	-6%	-11%	-13%	-33%	-33%	-55%	-55%	-16%	-20%	-20%	-20%	-24%	-33%	-37%	-86%
Sprinkle	Pivot/Linear LESA	92	6%	4%	3%	1%	**0%**	-5%	-10%	-12%	-31%	-31%	-53%	-53%	-15%	-19%	-19%	-19%	-23%	-31%	-35%	-84%
Sprinkle	Microsprinkler	87.5	11%	9%	8%	6%	5%	**0%**	-4%	-6%	-25%	-25%	-46%	-46%	-9%	-13%	-13%	-13%	-17%	-25%	-29%	-75%
Sprinkle	Undertree Orchard	84	14%	13%	12%	10%	9%	4%	**0%**	-2%	-20%	-20%	-40%	-40%	-5%	-8%	-8%	-8%	-12%	-20%	-24%	-68%
Sprinkle	Pivot/Linear MESA	82.5	16%	14%	13%	11%	10%	6%	2%	**0%**	-18%	-18%	-38%	-38%	-3%	-6%	-6%	-6%	-10%	-18%	-21%	-65%
Sprinkle	Hand move	70	29%	27%	26%	25%	24%	20%	17%	15%	**0%**	0%	-17%	-17%	13%	10%	10%	10%	7%	0%	-3%	-40%
Sprinkle	Wheel Line	70	29%	27%	26%	25%	24%	20%	17%	15%	0%	**0%**	-17%	-17%	13%	10%	10%	10%	7%	0%	-3%	-40%
Sprinkle	Big Gun	60	39%	38%	37%	35%	35%	31%	29%	27%	14%	14%	**0%**	0%	25%	23%	23%	23%	20%	14%	12%	-20%
Sprinkle	Pivot/Linear Top of Pipe	60	39%	38%	37%	35%	35%	31%	29%	27%	14%	14%	0%	**0%**	25%	23%	23%	23%	20%	14%	12%	-20%
Surface	Basin	80	18%	17%	16%	14%	13%	9%	5%	3%	-14%	-14%	-33%	-33%	**0%**	-3%	-3%	-3%	-7%	-14%	-18%	-60%
Surface	Border	77.5	21%	19%	18%	17%	16%	11%	8%	6%	-11%	-11%	-29%	-29%	3%	**0%**	0%	0%	-3%	-11%	-14%	-55%
Surface	Graded Furrow	77.5	21%	19%	18%	17%	16%	11%	8%	6%	-11%	-11%	-29%	-29%	3%	0%	**0%**	0%	-3%	-11%	-14%	-55%
Surface	Contour Border	77.5	21%	19%	18%	17%	16%	11%	8%	6%	-11%	-11%	-29%	-29%	3%	0%	0%	**0%**	-3%	-11%	-14%	-55%
Sprinkle	Solid Set Sprinklers	75	23%	22%	21%	19%	18%	14%	11%	9%	-7%	-7%	-25%	-25%	6%	3%	3%	3%	**0%**	-7%	-10%	-50%
Surface	Furrow	70	29%	27%	26%	25%	24%	20%	17%	15%	0%	0%	-17%	-17%	13%	10%	10%	10%	7%	**0%**	-3%	-40%
Surface	Corrugation	68	31%	29%	28%	27%	26%	22%	19%	18%	3%	3%	-13%	-13%	15%	12%	12%	12%	9%	3%	**0%**	-36%
Surface	Wild Flood	50	49%	48%	47%	46%	46%	43%	40%	39%	29%	29%	17%	17%	38%	35%	35%	35%	33%	29%	26%	**0%**

4.1.3 Costs of Implementation and Annual Maintenance

The costs of converting from one system to another is too large of a task, too variable, and too uncertain to attempt to cover in this report. These costs depend on:

- Field size and shape
- Water source
- Water quality
- Soil type
- Variations in systems, system quality, and system features
- Dealer location, chosen pricing, and training and support.
- Shipping costs,
- Labor availability

4.1.4 Benefits/Drawbacks for grower, environment, labor

Many systems, such as center pivots, have gained traction and are being installed not only because of their relatively good irrigation efficiency and uniformity, but because they reduce labor requirements and management complexity. In general, surface irrigation and hand-lines and wheel-lines are very labor intensive while solid-set systems or any system that is already in place requires significantly less labor.

4.1.5 Summary

- Many irrigation systems are more efficient than others. However it is important to keep in mind where the water "losses" go. Some losses are essentially permanent to the state of Utah and some losses are recoverable and usable at a later time.
- The largest sources of water loss in irrigation, (deep percolation, and wind drift and evaporation of sprinklers) are both not visible and are likely under appreciated.
- Some areas of Utah may be best served by remaining in surface irrigation.
- Irrigation uniformity is very important to on-farm irrigation efficiency but requires improved irrigation system maintenance and management.
- Big-gun sprinklers and pivot end-guns are inefficient with both water and energy, and are associated with poor irrigation uniformly, especially under windy conditions.

4.2 Data-Based Irrigation Scheduling (Soil Moisture Sensors and ET-Based Irrigation Scheduling)

4.2.1 Description

Irrigation scheduling is finding the answers to two basic questions: "When do I turn the water on?" and, "How long do I leave it on?" Improved irrigation scheduling has tremendous public and private benefits. Getting this right is important to avoid water stress for maximum crop yields and maximum beneficial use of the water, and to avoid over-irrigation which most often results in deep percolation, but can also result in field run-off. Benefits of improved irrigation scheduling can include the following:

Benefits to the grower:

- Improved yields,
- Improved quality,
- Lower pumping energy costs,
- Lower irrigation-related labor costs, and
- Decreased loss of expensive fertilizers to runoff or leaching.

Benefits to the environment:

- Less movement of fertilizers and pesticides with the water off of farms fields into streams, water-bodies, and groundwater (non-point source pollution), and
- More undiverted water can remain available in groundwater and in streams for alternative uses including fish and wildlife habitat.

Benefits for energy supply/conservation:

- Decreased irrigation energy pumping costs, and
- Water remains in rivers to drive power-generation turbines at multiple dam sites.

In short, everybody wins with good data-based irrigation scheduling! Data-based irrigation scheduling is also sometimes referred to as scientific irrigation scheduling (SIS). This uses some sort of data to inform irrigation management decisions. There are many publications on how to do this effectively (Crookston, 2011 ; Hillyer, 2010; Ley, 1986; Neibling, 2020; Peacock et al., 2000; Sanden, 2010; Steve Orloff). This can be done using:

- soil moisture sensors,
- weather-based (evapotranspiration or ET) water use models, or
- plant-based measurements.

Most researchers have found that despite many tools being available for irrigation scheduling it is still not widely practiced. This is partially because there is a lot of variability and uncertainty in using most of these methods (Stockle & Hiller, 1994) and they all need to be calibrated to a certain extent due to differences in soil texture, structure, and soil chemistry (Evett et al., 2009). This is true even of ET-based irrigation scheduling as there is still a lot of uncertainty/inaccuracies in the reference ET estimates and in crop coefficients due to crop variety differences, planting densities, climate differences, slopes, management strategies, weed and pest pressure, imperfect weather measurements, etc. Thus all of these methods need to be revised or calibrated to some extent leading to confusion and frustration from growers.

4.2.1.1 Soil Moisture Sensors

The major types of soil moisture sensors (Figure 36) are listed in Table 6 and grouped according to the technology used to measure soil moisture. Although the technologies used by each sensor type are quite different, these sensors can be roughly categorized into two groups: those that measure soil water *content* (how much water is in the soil), and those that measure the soil water *tension* (how hard the dry soil is pulling on the water).

Table 6. Major types of soil moisture sensors and their relative advantages and disadvantages.

	Sensor Type	**Advantages**	**Disadvantages**
Soil Water Content	**Neutron Probe** (Campbell Pacific Nuclear; CPN)	Accurate. Repeatable. Samples a relatively large area. One sensor for all sites & depths.	Government required paperwork and regulations. Can't leave in field. Relatively expensive (about $4,500).
	Time Domain Transmissivity (Acclima, Gro-Point)	Less expensive ($110/sensor). Easy to log data.	Samples small area.
	Capacitance Sensors (Enviroscan, Echo Probes, Acclima, Vernier, etc..)	Easy to set up to log and/or transmit data.	Highly affected by soil conditions immediately next to the sensor. High variability. More expensive ($300 - $1,200/system).
Soil Water Tension	**Tensiometers**	Less expensive ($80/sensor)	Maintenance issues.
	Granular Matrix Sensors (Watermark)	Inexpensive ($40/sensor)	Highly variable output. Less accurate. Sensitive to temperature and soil salinity.

In general, most irrigators and researchers have found that there can be a significant variability (error) in the data from soil moisture sensors due to differences in soil texture, soil structure, and soil chemistry (Evett et al., 2009). Despite this soil moisture sensors can still be used effectively by comparing the dynamics of the measurements over time with the relative position of field capacity, and the point where the plants will begin to experience water stress. In other words, it is possible to consider the measurement as being relative, and self calibrate it using the field and crop conditions. Then the absolute accuracy of the sensor is less important as the sensor is simply compared to field conditions and to itself.

Figure 36. A soil moisture sensor installation in a field with telemetry and a rain gauge to measure applied water.

4.2.1.2 ET-Based (Weather-based) Irrigation Scheduling

This method uses solar radiation, maximum and minimum daily air temperatures, maximum and minimum relative humidity or dew point temperature, and total wind travel from automatic weather stations (Figure 37).

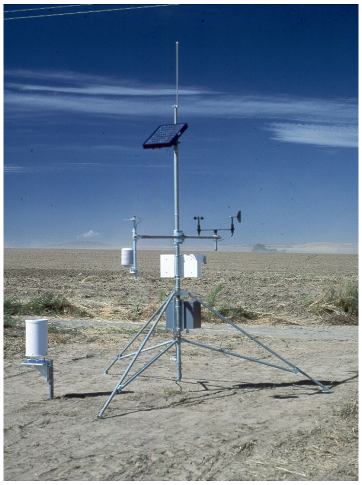


Figure 37. An automatic weather measurement station in agricultural conditions.

This data is used to estimate the evapotranspiration (ET) or water use rate for that time period of a reference crop of clipped grass (ET_o), or alfalfa (ET_r) (Figure 38). This is multiplied by crop coefficients (K_c) that are specific to the reference crop used, the crop, and that crop's growth stage to get an estimate of crop ET (ETc) as:

$$ET_c = K_c \times ET_r$$

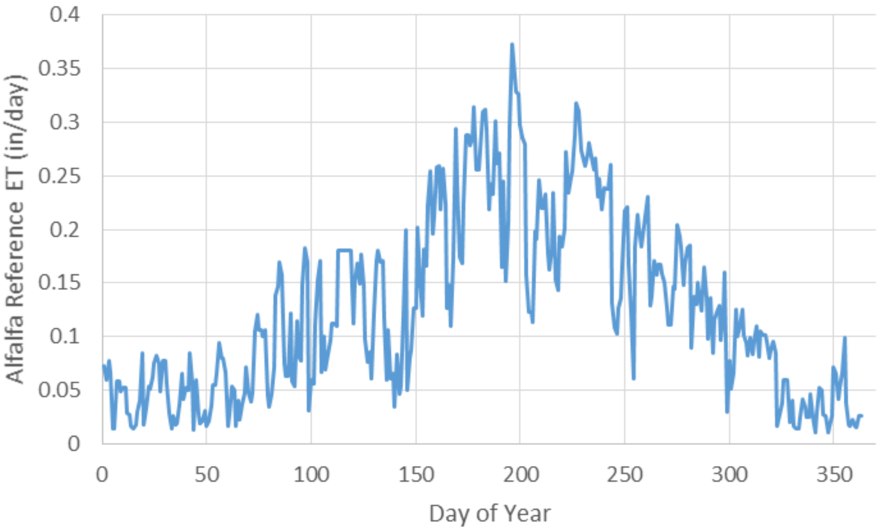


Figure 38. Alfalfa reference ET (ETr) for Beaver, UT in 2019.

A soil water balance is then used to estimate the current soil water content (Figure 39) using the equation:

$$SWC_2 = SWC_1 - ET_c + R + I - DP$$

where all units are in inches and:

SWC_1 is the soil water content at the beginning of the time period,
SWC_2 is the soil water content at the end of the time period,
ET_c is the crop evapotranspiration (ET),
R is the effective rainfall that infiltrates into the soil,
I is the infiltrated irrigation, and
DP is the water loss to deep percolation.

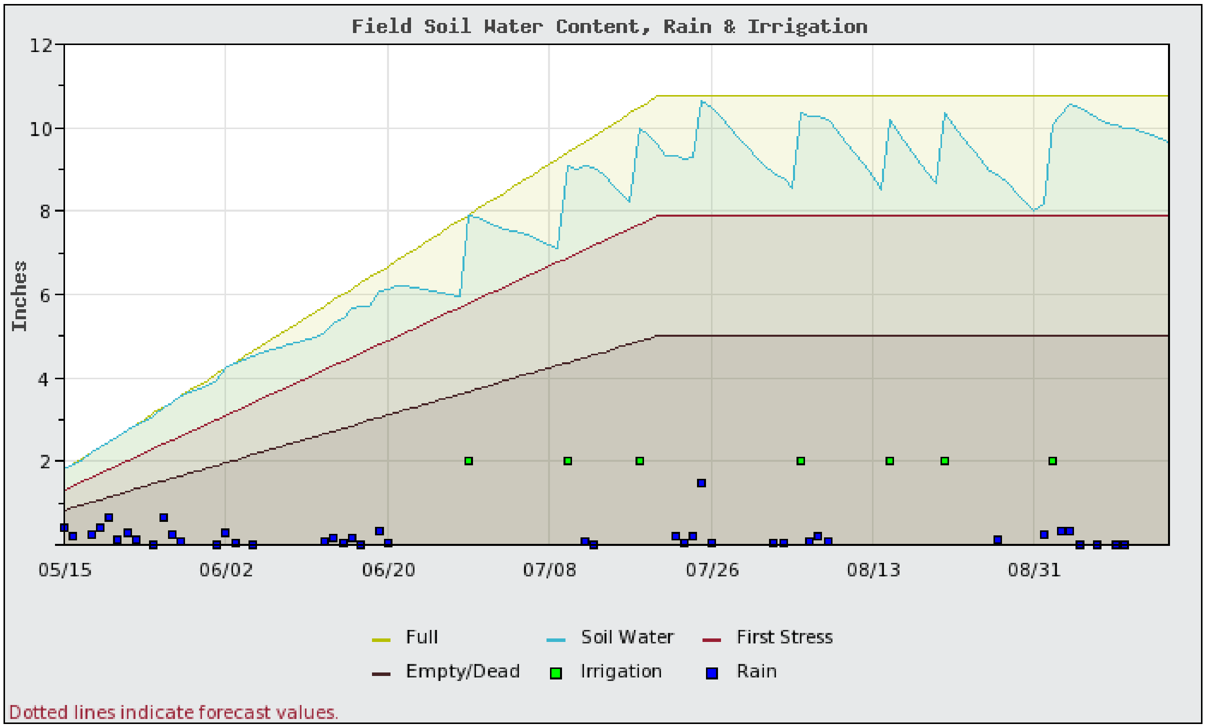
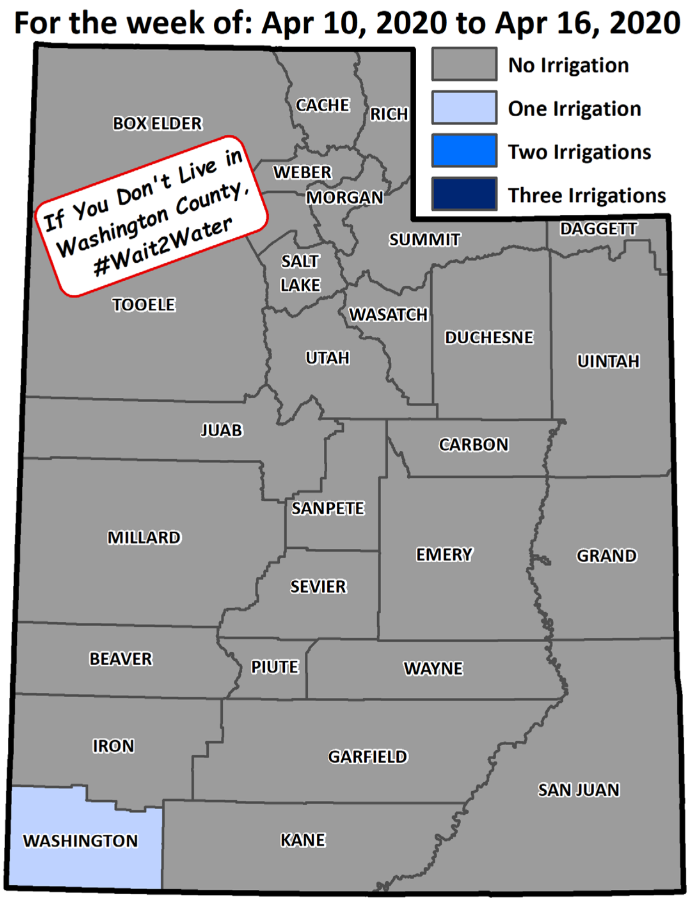


Figure 39. ET-based irrigation scheduling to maintain the soil water content between the full (field capacity) point and the first stress (MAD) lines using Irrigation Scheduler Mobile. This model estimates a linearly growing root zone depth over time.

There are a wide variety of free tools currently available to Utah irrigators to help them with ET-based irrigation scheduling. The following are recommendations for various styles or classes of irrigation scheduling tools:

- Weekly Lawn Watering Guide. General guidelines from the Utah Division of Water Resources Conservation Program (Figure 40) for lawn waters to give rough estimates of when to irrigate.
- Kansched2. A spreadsheet (MS Excel)-based tool that is user-friendly. The user needs to know crop coefficients for Utah-crops and enter the daily reference ET values. ("Kansched for Microsoft Excel,")
- Irrigation Scheduler Mobile (Figure 41). An app or web-page that gives users default crop coefficients, season dates, and soil parameters to get them started and automatically enters

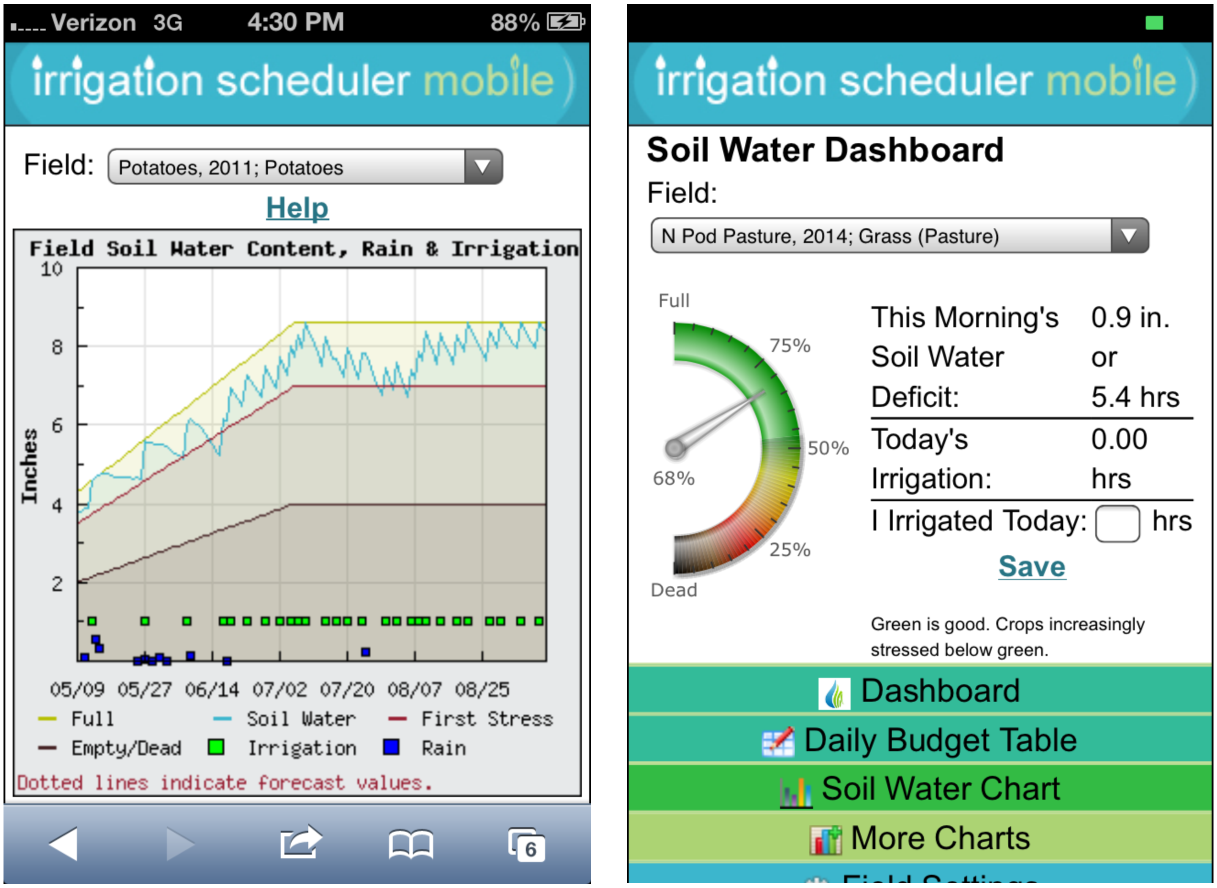
gets and enters the ET and rainfall data from a selected weather station and automatically estimates soil water deficits on a daily basis (S. Hill & Peters).



One Irrigation is equivalent to 20 minutes with pop-up spray heads and 40 minutes with impact rotor sprinklers

Figure 40. Weekly lawn watering guide from the Utah Division of Water Resources Conservation Program.

("Weekly Lawn Watering guide,")



Field: Potatoes, 2011; Potatoes

Soil Water Dashboard

Field: N Pod Pasture, 2014; Grass (Pasture)

This Morning's Soil Water Deficit: 0.9 in. or 5.4 hrs

Today's Irrigation: 0.00 hrs

I Irrigated Today: ☐ hrs

Green is good. Crops increasingly stressed below green.

Figure 41. Soil water chart and soil water dashboard from the Irrigation Scheduler Mobile app.

(S. Hill & Peters)

4.2.2 Efficiency Gains

The widespread water savings that can be expected from improved irrigation management due to accurate soil moisture measurements is difficult to quantify in research trials because it is challenging to define a "control" treatment to compare good irrigation management to. Although perfect irrigation management is easier to determine, what imperfect irrigation management is depends on the behavior, knowledge, skill, work ethic, and conscientiousness of a particular irrigation water manager. And of course these vary widely. To add to this complexity, every growing season in various climate zones is different. In addition, variations in the crop type, crop variety, crop health and vigor, planting density, row spacing, field slopes, planting dates, and harvest dates can change crop water use in time and in space. Because of these things, studies to quantify the water saving-benefits of improved irrigation water management have had highly varied results. Some of the results from these many studies on the water savings of improved methods of irrigation scheduling are shown in Table 7.

Table 7. Relevant research reports showing the measured water savings from data-based or scientific irrigation scheduling.

Citation	Summary of Relevant Findings	Water/ Energy Savings
(King et al., 2001)	With very simple soil water status indicator farmers applied 7% less water on average.	7%
(Hagood et al., 1966)	Most water savings possible early in the season. Soil moisture-based irrigation scheduling saved an average of 2 irrigations over guessing (4 vs 6 irrigations). This is 20-30% savings.	20-30%
Haeri and English, 2003 and 2005	Large scale comparison study of growers both using scientific irrigation scheduling and those not.	9.5-12%
(Henggeler, 2004)	Average irrigation scheduling by soil moisture monitoring or soil moisture is 12% total. More scheduling is done in high rainfall climates than in arid regions for some reason.	12%
(Román et al., 1999)	Used neutron probes and tension-based soil moisture sensors to help with irrigation scheduling. Grain yield was unaffected.	15%
(Steele et al., 2000)	Compared irrigation scheduling methods: Tensiometer and IRT readings, 2 different water balance methods, and CERES-Maize.	30%
(Lamm & Rogers, 2015)	ET-based irrigation scheduling works for growers. Even when irrigation system capacity is less than adequate, irrigation scheduling can save significant amounts of water.	10-30%
(Miller, 1994)	A comparison of the water savings from irrigation scheduling.	20-30%
(Munoz-Carpena & Dukes, 2005)	Describes automatic irrigation scheduling using soil moisture sensors.	up to 70%
(Smajstrla & Locascio, 1996)	Reduced water use by 40-50% without reducing yields.	40-50%
(Muñoz-Carpena et al., 2008)	Using tensiometers and GMS-controlled drip irrigation on tomatoes saved water.	Up to 70%
(Broner, 1993)	"Research in Nebraska, where most water is pumped, shows that irrigation scheduling provides an average 35 percent savings in water and energy. In fuel costs alone, this is a per-season savings of about 550 kwh per acre for a center pivot sprinkler or about 200 kwh per acre for a gated pipe."	35%
(Pereira et al., 2007)	"Foreseen improvements refer to basin inflow discharges, land leveling and irrigation scheduling that could result in water savings of 33% relative to actual demand. These improvements would also reduce percolation and maintain water table depths below 1 m thereby reducing soil salinization."	33%

(Weather- and Soil-Moisture-Based Landscape Irrigation Scheduling Devices, 2012)	"Accurate WeatherSet controllers performed exceptionally relative to other products included in a multiyear study of ET controllers that were installed under funding from California Department of Water Resources (Aquacraft, 2009). The study results indicate a 33-percent average water saving."	33%
(Hunt et al., 2001)	State a 24% water savings on these lawn watering systems.	24%
(Kisekka et al., 2010)	"A study conducted in a carambola orchard in Homestead, Florida, comparing ET controllers to a timer set schedule showed that ET controllers produced an average water savings of 72% without affecting tree growth as measured using physiological response factors."	72%
(Vang et al.)	UC Irrigation studies have shown that irrigation controllers should be adjusted at least monthly for the summer irrigation period. These studies demonstrate that monthly adjustment, versus set-at-the-season-beginning and leave-til-late-fall can produce water savings of up to 40-50%.	40-50%
(Howell, 1996)	An integrated center pivot control system was evaluated for three years on a farm in north central Oregon with over 4,000 ha and 15 center pivots with four pumping stations. In two years of the three-year test the producer participated in a load control program and received a 14% reduction in power costs.	14%
(Vang et al.)	"Irrigation scheduling for flood irrigation systems can save growers 25% or more of a grower's water usage."	25%
Irrigation Scheduling, 2013	"The amount of water saved by implementing advanced irrigation scheduling is difficult to quantify, likely varies from year to year, and is strongly influenced by weather variation, cropping practices, irrigation water quality, and total amount of water used to irrigate. The Pacific Northwest Laboratory (1994) attempted to verify estimates of reduction in the amount of irrigation water pumped in the Grand County Public Utility District resulting from the implementation of irrigation scheduling. The public utility district estimated savings of 0.3 to 0.5 acre-feet per acre (12-20%), but actual savings could not be confirmed or disproved by the Pacific Northwest Laboratory's review."	12-20%

The savings from irrigation scheduling in urban lawn settings tended to be much greater than those in commercial agricultural settings. This makes sense as the economic drivers are much more prevalent in agriculture and the managers are often doing it full time. A conservative 15% water savings from irrigation scheduling was used for economic comparisons with the other irrigation technologies.

4.2.3 Costs of Implementation and Annual Maintenance

The costs of irrigation scheduling are nearly constant regardless of the field size. So the cost-per-acre estimates are very sensitive to field size where the costs are much lower for larger fields. For this study, 120 acres was used (full-sized center pivot) as the field size since these numbers are used for comparison with other technologies and most of the other new irrigation technologies are applicable only to center pivots. For an alternate means of comparison, the total costs per year can be compared instead of the cost per acre per year.

4.2.3.1 Cost Estimates for ET-Based Irrigation Scheduling

Table 8 and Table 9 illustrates the cost estimates for undertaking ET-based irrigation scheduling although care should be exercised to fully understand the notes associated with each cost.

Table 8. Cost estimates for undertaking ET-based irrigation scheduling.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	0	$	6
Equipment Lifespan	30	years	7
Upfront Management Labor	10	hours	8
Upfront Unskilled Labor	2	hours	9
Upfront Management Labor	350	$	10
Upfront Unskilled Labor	30	$	11
Total Labor	380	$	12
Annualized Upfront Labor	$19	$/year	13
Annualized Hardware Costs	$0	$/year	14
Total Annualized Upfront Costs	$19	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	1	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	700	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	700	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	3	hours/year	22
Labor effort hours/year	0	hours/year	23
Ongoing Expenses	0	$/year	24
Total annual management costs	105	$/year	25
Total annual unskilled labor costs	0	$/year	26
Total Annual recurring costs per year	105	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$824	$/year	28
Total Cost per Acre per Year	**$6.87**	**$/acre/year**	29

Table 9. Notes, assumptions and explanations for the cost estimates of using ET-based irrigation scheduling as shown above in Table 8.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumes a fairly large field for equivalent comparison with other technologies.
6	No additional hardware is required. This uses publicly available estimates of daily evapotranspiration (ET).
7	Since there is no hardware required, this is the number of years that the learning will last before needing to be re-done.
8	Time to learn and then to teach to the irrigator.
9	Time to learn to use or respond to management directions.
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.

15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Time to check and update the schedule. Fill in data. Make irrigation management decisions.
17	No additional effort, in fact on average there is usually less labor required because over-irrigation is avoided.
18	No additional expenses as the required tools are free to use.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unkilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Set up the new season's books and to check the calibration (crop coefficients).
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.2.3.2 Cost estimates for Soil Moisture Sensors Owned by the Grower

Cost estimates for using soil moisture sensors to do irrigation scheduling where the grower purchases and owns the sensors is shown in Table 10 and Table 11. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 10. Cost estimates for using soil moisture sensors to do irrigation scheduling.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	3500	$	6
Equipment Lifespan	5	years	7
Upfront Management Labor	50	hours	8
Upfront Unskilled Labor	10	hours	9
Upfront Management Labor	1750	$	10
Upfront Unskilled Labor	150	$	11
Total Labor	1900	$	12

Annualized Upfront Labor	$415	$/year	13
Annualized Hardware Costs	$764	$/year	14
Total Annualized Upfront Costs	$1,179	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	0.5	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	350	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	350	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	4	hours/year	22
Labor effort hours/year	0	hours/year	23
Ongoing Expenses	300	$/year	24
Total annual management costs	140	$/year	25
Total annual unskilled labor costs	0	$/year	26
Total Annual recurring costs per year	440	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$1,969	$/year	28
Total Cost per Acre per Year	**$16.41**	**$/acre/year**	29

Table 11. Notes, assumptions and explanations for the cost estimates of purchasing (to own), installing, and using soil moisture sensors for irrigation scheduling as shown above in Table 10.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumes a fairly large field for equivalent comparison with other technologies.

6	This is the estimated cost of the sensors and the necessary datalogger and telemetry systems.
7	Number of years before hardware has to be replaced and upfront costs are again incurred. Annual maintenance costs are included below.
8	Time required specifying and selecting an appropriate soil moisture sensor system and interacting with dealer. This also includes time learning, installing the sensors, setting it up, and troubleshooting the sensors.
9	Help with installation.
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Checking the data and making decisions.
17	No additional effort, in fact on average there is usually less labor required because over-irrigation is avoided.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unkilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Checking the sensors, winterizing them, setting up the telemetry system for the new season.
23	No additionl labor required.
24	Telemetry (phone plan) subscription services paid to company
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.2.3.3 Cost Estimates for Hiring a Service for Soil Moisture Monitoring

Table 12 and Table 13 depicts the cost estimates for hiring an irrigation advisory service that uses soil moisture sensors. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 12. Cost estimates for hiring an irrigation advisory service that uses soil moisture sensors.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	0	$	6
Equipment Lifespan	7	years	7
Upfront Management Labor	10	hours	8
Upfront Unskilled Labor	0	hours	9
Upfront Management Labor	350	$	10
Upfront Unskilled Labor	0	$	11
Total Labor	350	$	12
Annualized Upfront Labor	$56	$/year	13
Annualized Hardware Costs	$0	$/year	14
Total Annualized Upfront Costs	$56	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	0.5	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	350	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	350	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	2	hours/year	22
Labor effort hours/year	0	hours/year	23
Ongoing Expenses	1850	$/year	24
Total annual management costs	70	$/year	25
Total annual unskilled labor costs	0	$/year	26
Total Annual recurring costs per year	1920	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$2,326	$/year	28
Total Cost per Acre per Year	**$19.38**	**$/acre/year**	29

Table 13. Notes, assumptions and explanations for hiring an irrigation advisory service that uses soil moisture sensors as shown above in Table 12.

Note	Explanation
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumes a fairly large field for equivalent comparison with other technologies.
6	The sensors are not purchased. They are rented.
7	Number of years before the grower needs to re-learn to use the data and/or re-evaluate their decision on who to use for sensors and irrigation service.
8	Interacting with dealer, choosing and purchasing the appropriate sensors and dealer. Learning how to use the data provided.
9	Installed by the company
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Checking the data and making decisions.
17	Managed by the company
18	None.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Time to interact with the dealer, sign a new contract, show them where to install, etc.
23	No additional labor required
24	Annual expenses paid to the company. Includes telemetry costs.

25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.2.3.4. Discussion

These rough estimates (**$6.87/acre/year** for ET-based irrigation scheduling, **$16.41/acre/year** for soil moisture sensors that are owned, and **$19.38/acre/year** to hire a soil moisture sensing service) show that ET-based irrigation scheduling is not without costs. However, these costs quickly become net benefits if the grower is able to realize a yield increase, which often happens. If the grower's gross income per acre is an estimated $720/acre/year (4 tons/acre at $180/ton; NASS, 2019), then they would only need to realize a **1%, 2%, or 3% yield increase to cover the costs** of implementing these three technologies respectively. These yield increases are minor compared to the potential based on the literature reviewed. Yield increases are not guaranteed however, especially if the grower was already deficit irrigating due to inadequate water supplies so these potential benefits were not included in the costs of this technology.

Further, the pumping cost savings from implementing these technologies was not included. Not all growers have the same pumping costs (depending on their water source), but if we assume similar pumping costs as were assume a 35hp pump running 2000 hrs/year (35 hp x 0.745kW/hp x 2000 hrs/season x 0.073/kW-hr) we get $3,807/year of pumping costs for the field size that we used (120 acres). A 15% reduction would be $3,807 x 0.015 = $571/year or %571 / 120 acres = $4.76/acre/year. This would reduce the cost estimates to **$2.11/acre/year**, **$11.65/acre/year**, and **$14.62/acre/year** for ET-based, owned soil moisture sensors, and hired soil moisture sensors respectively. This reduces the necessary yield increase to cover these costs even further.

4.2.4 Benefits/Drawbacks for grower, environment, labor

Despite its benefits, data-based irrigation scheduling continues to be done by only a minority of growers. This is primarily due to the perceived lack of benefit from the education, time, and mental attention that it requires. Like exercise and eating right is for most of us, data-based irrigation management is something that most growers know they should do, understand that it will benefit them, but they do not really want to do it. (R. W. Hill & Allen, 1996) summed it up when they stated that "The irrigation scheduling methods that are most likely to be used and adapted by the farmers must be simple and applicable to a wide range of growing conditions and must require minimal subsequent advisory services."

Another primary obstacle of using soil moisture sensors for growers based on multiple interviews includes interpreting the soil moisture data. They see soil water dynamics but do not always understand how to interpret or react to this information.

For all of the above reasons, hired irrigation advisory services are a good option at least to begin with. Growers learn by hiring an irrigation scheduling service and the benefits (savings) of the service often persist even if the grower no longer hires the consultant.

4.2.5 Summary/Conclusions

- Data-based irrigation scheduling saves water, saves energy, helps the grower get better yields or save on irrigation expenses, and benefits the environment. In short, everybody wins.
- Only a small percentage of farmers are doing irrigation scheduling.
- ET-based irrigation scheduling is inexpensive, requiring only management time and attention.
- Soil-moisture-based irrigation scheduling is more expensive but is a direct measurement, whereas ET-based irrigation scheduling is a model. Using the soil water dynamics and the readings of these sensors relative to the growers experience with the field will be less frustrating.
- The amount of water saved depends on what they were doing before, but averages 10-20%. This is a reduced irrigation losses to deep percolation.
- Yields are either improved, or are unaffected by good irrigation management.
- There are a lot of different methods available for irrigation management, but each of these needs to be calibrated. Because of this is difficult to compare different irrigation scheduling methods to each other.

4.3 Irrigation Automation

4.3.1 Description

Irrigation automation uses the continuous monitoring of either a soil moisture, weather-based ET estimates, or a plant-based water stress measurements and communication systems to automatically make irrigation decisions and turn valves on and off to fully automate the irrigation system. This has been possible for many years and is not overly technologically challenging (Buchleiter, 2007; Michael D. Dukes et al., 2003; Heatherly, 2007; W. Kranz et al., 2010; Lascano & Sojka, 2007; Munoz-Carpena & Dukes, 2005; Nogueira et al., 2003; Osroosh et al., 2016; R.T. Peters, 2018.; R. Troy Peters & Evett, 2008). However this has not been widely adopted or used on a large scale for the following reasons:

- Most companies or consultants are not willing to put together turn-key systems for growers because of liability concerns. If the system glitches, these companies expose themselves to lawsuits for up to 100's of thousands of dollars for lost yield, quality and production expenses (personal communications). Because of this, irrigation advisory services are much more common and likely than full irrigation automation.
- Irrigation systems require very large flow rates. On-demand flow rates of these magnitudes are seldom readily available.

- Every irrigation automation system requires individual engineering, extensive testing, and calibration due to large amounts of uncertainty and variability inherent in soil moisture sensors, ET estimates, and/or valve actuation systems(Osroosh et al., 2016; R.T. Peters, 2018.). These costs put these types of systems out of range for all but the largest growers.

4.3.2 Efficiency Gains

One would expect that the efficiency and energy savings from irrigation automation should be the same as for good irrigation scheduling as described in the sections above for soil-moisture sensors and ET-based irrigation scheduling. Like scientific or good data-based irrigation management, the water savings depends widely depending on the reference condition (some growers were already good, and some were bad) and the particular situation (water supply, soils, crop grown, flexibility of irrigation, etc.). However, (Nogueira et al., 2003) found an 11% water savings on an automatic subsurface drip irrigation control system of sweet corn and peanuts, and (Michael D. Dukes et al., 2003) found a 50% water savings using an automatic irrigation system on bell peppers, but with similar yields. (Munoz-Carpena & Dukes, 2005) found a 70% reduction of irrigation water use with an automated system on vegetables. For our estimates of water savings, we will use a conservative 15% that is the same assumption that we make for data-based irrigation scheduling.

4.3.3 Costs of Implementation and Annual Maintenance

Cost estimates for automating the irrigation scheduling are shown in Table 14 and Table 15. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 14. Cost estimates for automating the irrigation scheduling.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	8000	$	6
Equipment Lifespan	5	years	7
Upfront Management Labor	120	hours	8
Upfront Unskilled Labor	20	hours	9
Upfront Management Labor	4200	$	10
Upfront Unskilled Labor	300	$	11

Total Labor	4500	$	12
Annualized Upfront Labor	$983	$/year	13
Annualized Hardware Costs	$1,747	$/year	14
Total Annualized Upfront Costs	$2,729	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	1	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	700	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	700	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	10	hours/year	22
Labor effort hours/year	0	hours/year	23
Ongoing Expenses	300	$/year	24
Total annual management costs	350	$/year	25
Total annual unskilled labor costs	0	$/year	26
Total Annual recurring costs per year	650	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$4,079	$/year	28
Total Cost per Acre per Year	**$34.00**	**$/acre/year**	29

Again, as was the case previously described, the costs are nearly constant regardless of the field size. Therefore the cost-per-acre estimates are very sensitive to field size where the costs are much lower for larger fields. For this study, 120 acres was used (full-sized center pivot) as the field size since these numbers are used for comparison with other technologies and most of the other new irrigation technologies are applicable only to center pivots. For an alternate means of comparison, the total costs per year can be compared instead of the cost per acre per year.

Table 15. Notes, assumptions and explanations for the cost estimates of irrigation automation as shown above in Table 14.

1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)

3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumed a fairly large field for equivalent comparisons with other technologies.
6	Includes a telemetry system, control valves, sensors to base irrigation signal on,
7	Number of years before hardware has to be replaced and upfront costs are again incurred. Annual maintenance costs are included below.
8	Assume 3 weeks for designing the system, buying the hardware, setting it up, oversee installing the sensors and control valves, and especially calibrating and troubleshooting the system.
9	Help with installing sensors and control valves
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Checking the system and troubleshooting problems since most are custom-jobs and tend to be buggy.
17	Usually done by skilled personnel.
18	Can include weekly subscription, repair parts, vehicle expenses allocated to this project, etc.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Annual system recalibration and troubleshooting and revising the set points for irrigation actuation.
23	Usually done by skilled personnel.
24	Telemetry system costs. Usual phone plans for communicating with sensors and/or actuating valves, although radios can also be used.
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.

28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

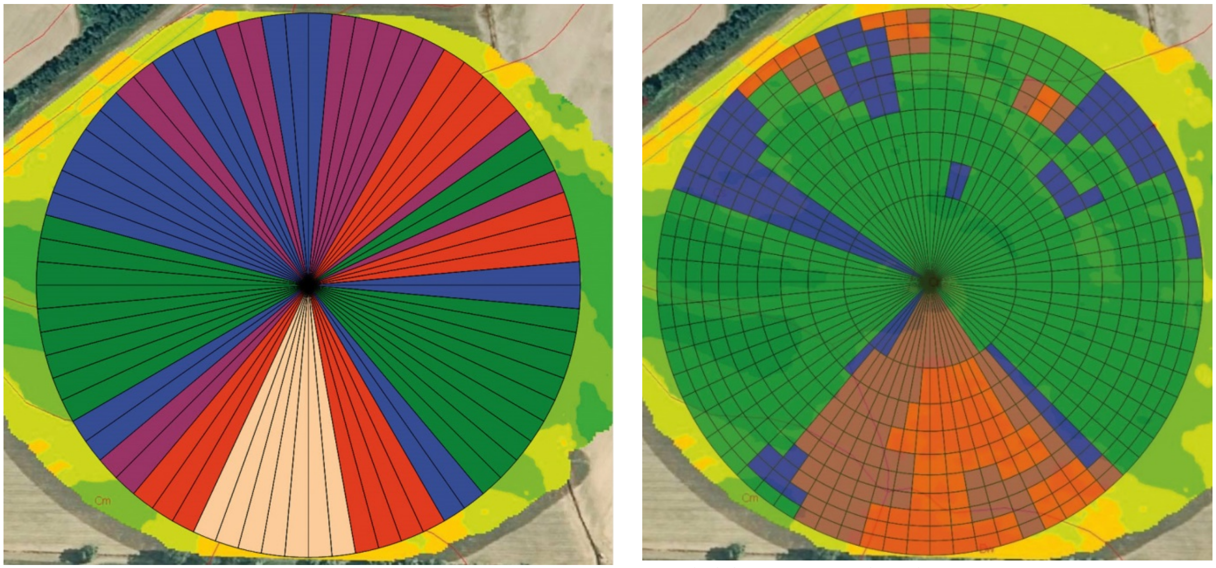
4.3.4 Benefits/Drawbacks for grower, environment, labor

The benefits of irrigation automation are the same as those for good irrigation scheduling. It is possible to get these systems to irrigate the right times to maximize crop yield and/or water use efficiency, depending on the goals or economic drivers for that particular farm. The primary drawbacks are the high costs of setup and custom-building each system, and the potential liability concerns for systems that don't perform perfectly.

4.4 Variable Rate Irrigation (VRI)

4.4.1 Description

Variable rate irrigation (VRI), also sometimes referred to as 'precision' or 'site-specific' irrigation, is the ability of an irrigation system to apply different amounts of water to different areas of the field. Although it is possible to implement VRI on almost any irrigation system, it is most readily applicable to center pivot irrigation (through pivot speed control and pulsing sprinkler banks at different rates) and to drip irrigation (with run-time control to each drip line).



Variable Speed Irrigation. .

Variable Zone Irrigation.

Figure 42. Variable Speed Irrigation (left). The pivot varies travel speed to apply variable amounts of water to defined zones within the field. Colors indicate areas with different amounts of water applied. Images used by permission from pivotirrigation.com.au. Variable Zone Irrigation (right). The pivot varies both travel speed and application rate along the lateral to apply variable amounts of water to defined zones within the field. Colors indicate areas with different amounts of water applied.

Variable Speed Irrigation does not require additional hardware on the pivot. It simply uses a more sophisticated control panel that will slow down or speed up the pivot in different sectors to apply more or less water, respectively, to different areas of the field. Many of the newer pivot control panels already have this ability built into them. After-market solutions from third-party equipment dealers are available. These usually mount on the last tower of the pivot, have an integrated GPS receiver to determine field position, and interrupt and re-send the movement control signal to the last tower to vary the speed of the pivot in different areas of the field. Despite variable speed irrigation's obvious limitations to variations only in pie-shaped wedges Figure 42 (left), variable speed irrigation is fairly low cost ($2,000 - $4,000) since the only modifications to the pivot are to the pivot electronic controls. These costs will likely decrease over time. The overall pivot flow rate remains constant.

Variable Zone Irrigation includes the ability to vary the speed of the center pivot as it moves in a circle *and* vary the application rate of sprinklers along the pivot lateral Figure 42 (right) Variations in the application rate along the lateral works in conjunction with variations in the pivot speed creating the ability to apply a wide variety of irrigation depths to different areas of the field. The application rate along the lateral is usually varied by pulsing sprinklers on and off for various amounts of time. In most cases, zones of sprinklers are controlled independently, in other cases every sprinkler is controlled independently. Because additional hardware (valves) must be mounted on the pivot, as well as more sophisticated control technology, variable zone irrigation is significantly more expensive than variable speed irrigation ($15,000 - $25,000; (C. D. Perry et al., 2007). These costs will also likely decrease over time, although at a somewhat slower rate since the costs are hardware related instead of technology (computer program) related. Variable zone irrigation is much better at responding to the spatial variations in the field. Turning sprinklers on and off varies the overall flow rate to the pivot and therefore a water delivery system that can absorb these variations is necessary.

Most of the papers related to variable rate irrigation (VRI) discuss VRI equipment design and performance. A synopsis of the outcomes of these various papers are that these VRI systems are generally able to apply the targeted amount of water to the different areas of the field as advertised. The separation between these "zones" is of course limited by the overlap (wetted radius) of the sprinklers. They also found that these systems apply water at the various set rates in a relatively uniform manner, or at least as uniform as a normal center pivot or irrigation system. They also found that the higher the application rate, the higher the measured uniformity, and that pulsing (switching the nozzles on and off) did not negatively affect the uniformity (Chávez et al., 2009; M. D. Dukes, 2006; Gossel et al., 2013; Han et al., 2009; Higgins et al., 2016; Hillyer et al., 2013; Kim et al., 2006; J. Li et al., 2015; Moore et al., 2005; O`Shaughnessy et al., 2012; O'Shaughnessy et al., 2011; Calvin Perry & Harrison, 2004; Calvin Perry & Pocknee, 2003 ; C. Perry et al., 2016; C. D. Perry et al., 2007; Sui & Fisher, 2012; Sui & K. Fisher, 2015; Yari et al., 2017).

In an overview/synthesis/discussion paper, (Robert G. Evans et al., 2011) discussed the state of the technology and the state of adoption at the time, which was low. He stated that "the current state of the technology is essentially a solution looking for a problem" but that there was potential to "provide water conservation benefits in cases of over irrigation, under irrigation, runoff, erroneous irrigation scheduling, in-season precipitation harvesting, or inefficiencies associated with particular crop production practices" (S. A. O'Shaughnessy, 2016). also discusses the state of the technology but doesn't present water conservation estimates or results besides stating that these should be possible.

4.4.2 Efficiency Gains

Most research papers on VRI are concerned with the hardware, communication systems, and testing these systems to see how they perform and are unrelated to their ability to save water or pumping energy (M. D. Dukes, 2006; O'Shaughnessy et al., 2012; Higgens et al., 2016). In other words, the control systems and hardware work well and the equipment's ability to apply variable rates across the field is not a barrier to the adoption of VRI.

In summary VRI is possible, and has been studied and tested. They have been shown to be able to apply the targeted amount of water to the targeted areas of the field and to do so with reasonably good uniformity. All three of the major center pivot manufacturers (Valley, Reinke, and Zimmatic) have off-the-shelf VRI packages that can be purchased or retro-fitted onto existing center pivots to make them capable of variable rate irrigation and have been shown to perform well. However, there weren't as many studies on the water-savings capabilities of VRI.

However, we were able to find some research papers that did test the capability of VRI systems to save water. Most of these were simulated studies using computer models. Many of these studies found that VRI does not always save water or conserve power (Barker et al., 2018; Feinerman & Voet, 2000; Haghverdi et al., 2015; Haghverdi et al., 2016; S. O'Shaughnessy et al., 2015; K. C. Stone et al., 2010). Research done in Israel found using computer simulation models that adopting practices to increase infiltration and using irrigation systems with high uniformity increased total yields per unit of applied water, but that the water saving, or yield improvement impacts of VRI were ambiguous (Feinerman & Voet, 2000). They also found that increasing the number of management units in a field did not necessarily result in more optimal water use, and that VRI did not guarantee savings, but in many cases could yield the opposite result.

However, there were quite a few relevant papers that showed significant water savings potential for VRI. Most of the studies that showed clear beneficial results were led by Carolyn Hedley in New Zealand using computer simulation models. They demonstrated that using VRI on center pivot fields with large differences in soil water holding capacities in New Zealand had the potential to save significant amounts of water and reduced deep percolation (C. B. Hedley & Yule, 2009; C. B. Hedley et al., 2009; C. B. B. Hedley, S. ; Ekanayake, J. ; Yule, I. J. ; Carrick, S., 2010) compared to their base line. (C. B. B. Hedley, S. ; Ekanayake, J. ; Yule, I. J. ; Carrick, S., 2010) also found that larger water savings were related to years with rainfall events during the irrigation period. These studies show that large differences in the water holding capacities in the field, and frequent, large rainfall events greatly strengthened the potential savings of VRI. One other computer simulation study that showed the potential water savings from VRI was done in Missouri (T. Nguyen et al., 2015). The final study of the potential overall and large-area water savings possible from VRI was done in the state of Nebraska (Him Lo et al., 2016). The Nebraska study looked at soils statewide and used historical rainfall patterns to estimate the statewide water savings potential from VRI (everybody doing it) to be 1.3%, with 2% of fields being able to save 51mm (2 inches) or more of water per season, and 13% of fields able to conserve 25mm (1 inch) or more in a season. The savings were related to the ability of using VRI to "mine" water from the soils with larger water holding capacities. They state that large in-season rainfall events would allow them to mine the water again and increase the potential savings. Large in-season rainfall events and highly spatially variable soil water holding capacities also lead to the positive simulated water savings results reported from New Zealand, and Missouri.

There were only a few studies that collected actual crop and field data on the water savings of VRI. Most of these were not scientific studies and were popular press articles quoting farmers who stated a water savings without describing their materials-and-methods, didn't use controls, and were not peer reviewed (Hollis, 2019; Martello et al., 2017; Roberson, 2009; Vogt, 2018). There was one peer reviewed field study that did not find significant water savings from VRI (K.-K. Stone et al., 2011), and two field studies that *did* find significant water savings from VRI. (Sui & Yan, 2017) used VRI to apply 25% less water in Mississippi and got slightly increased yields. (McDowell, 2017) found that VRI in New Zealand reduced leaching (different from water savings) by 85%. These results were also in humid and high rainfall areas.

For our estimates for Utah, we used the Nebraska study that showed that 13% of the center pivots in Utah (338,260 acres x 0.16 = 43,974 acres) could save 1 inch of water (3.1%) using a variable zone irrigation system and that a variable speed system would only be able to realize 2/3 of those savings due to geometry limitations.

4.4.2.1 Discussion of Why the Differing Research Results on VRI Make Sense.

The water use of healthy crops with access to sufficient water and nutrients is not significantly affected by the soil they are grown in. Crops grown in sandy soils will not use significantly more or less water than crops grown in silt or clay soils. Because of this, applying different amounts of water to different areas of the field only makes sense if the crops are getting water from another source *besides* the irrigation system, or if the crops are using less water in some areas of the field due to disease or pest pressure. Common misunderstandings and a discussion of these follows.

"I need to use VRI to apply more water to the sandier areas of my field during each irrigation."

Sandy soils do not need more water. They cannot hold the extra water. If they are watered more each time then the additional water applied will be lost to deep percolation. They need to be watered in smaller amounts more frequently compared to silt or clay soils. Because of this, if the entire field is managed as a whole to prevent water stress and water losses to deep percolation in the sandy areas of the field then all other areas of the field will be fine (Figure 43 and Figure 44).

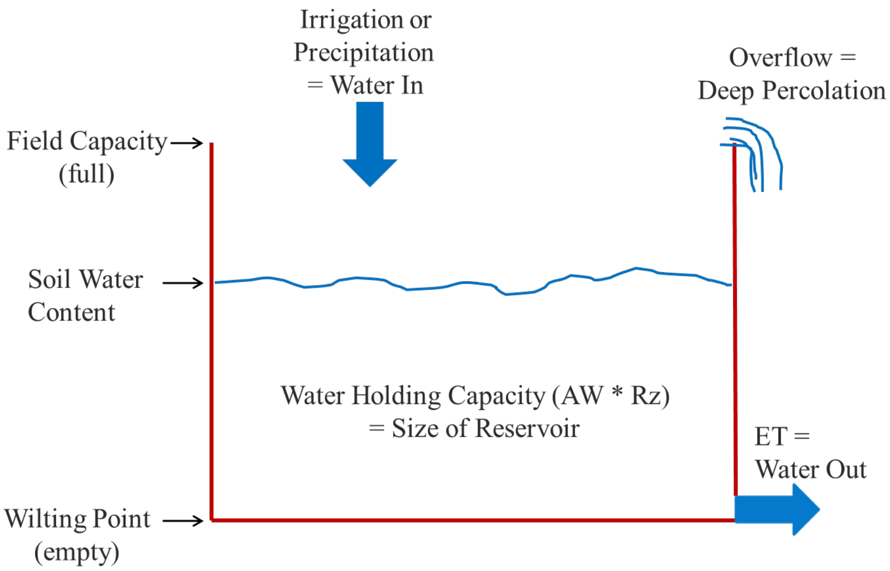


Figure 43. Soil serves as a reservoir for water and nutrients. The size of the reservoir depends on the soil's water holding capacity (how much water it can hold per unit of root depth; AW), and the rooting depth of the soil or crop (Rz). Irrigation or precipitation that infiltrates into the soil when there is space in the soil to hold that water is stored for later use by the crop. If more water is applied to the soil than the soil can hold, then that extra water is lost (leached) out the bottom of the root zone (shown as overflow). Crop water use, or evapotranspiration (ET), is largely independent of the soil type.

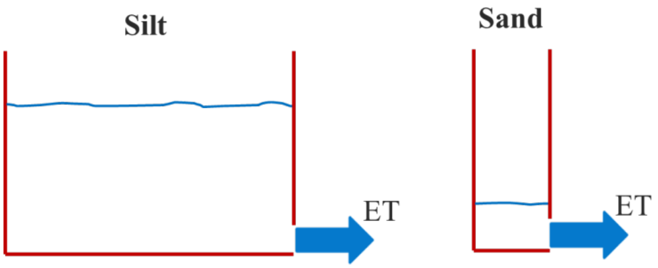


Figure 44. If the same field has areas that are both silt and sand, then if they both started full, then after a given amount of time the sandy areas will be getting dry and exhibiting crop water stress, while the silty areas will appear fine. If the entire field is managed for no stress, or no water losses to deep percolation in the sand (overflow in the diagram), then the silty areas will also be fine. If more water is applied to the sand when refilling the soil, that additional water will be lost to deep percolation. This was shown in simulation studies done using Irrigation Scheduler Mobile
(S. Hill & Peters).

"I have runoff on the steeper slopes. The crop is water stressed in that area of the field so I use VRI to apply more water to those slopes."

If water is already running off of a slope, applying more water will result in *all* of the additional water also running off, possibly causing erosion, and that additional runoff water may pond in the low spots of the field, making the overall irrigation and crop uniformity problems in the field worse. If the water is running off, then less water, not more, needs to be applied to slopes in an irrigation event to ensure that the applied water infiltrates into the soil. But to ensure that these areas of the field don't fall behind the rest of the field and excess water is not applied to other areas, the entire field will need to be irrigated more frequently. Runoff in these steep-sloped areas can also be mitigated by changing the tillage methods, and possibly the crop row orientation. Modifying the sprinkler system so that it applies water at a slower *rate* using boombacks on pivots, or draping every other sprinkler drop around the outside of the pivot truss rods, or using sprinklers with a much larger wetted radius can also help improve infiltration.

Because of these things, *in low rainfall areas, using VRI in response to highly variable soils has little opportunity to increase profitability in comparison to optimally managing the entire field uniformly for the problem soils.*

4.4.2.2 Opportunities to Save Water with VRI Exist, but are Not Common.

Figure 45. Using VRI on fields like these to avoid irrigating the non-cropped surfaces would certainly save water.

Avoid Irrigating Non-Cropped Areas of the Field

VRI can save water, agrochemicals, and reduce maintenance problems by completely shutting the water off in areas of center pivot fields that should not be irrigated (Sadler et al., 2005). These might include rock piles, ponds, or streams, waterways or roads that cross through the field or areas under the irrigation system that are otherwise not farmable (Figure 45). Sometimes pivots overlap. Shutting the water off on one of these pivots in the overlapped areas will reduce overwatering those areas. These constant, unchanging prescriptions where the water is turned off completely will result in the largest water and power savings at the lowest long-term management costs. Consequently most VRI systems being sold are primarily being used in this application (R.

G. Evans, 2012). Avoiding off-target application of agrichemicals or liquid wastes is another large driver for the adoption of VRI in these circumstances.

Areas of the field getting water from other sources

VRI can conserve water by applying less water to areas of the field where the crops are getting water from sources. This may be either a high water table, or an area where water is ponding in the field due to runoff from sub-optimal operation of the pivot, or from water running onto the field from outside sources. Watering these areas less can reduce over-irrigation, saturation of soils, losses of nitrates through leaching, and losses of yield due to waterlogging (Sadler et al., 2005). It may be necessary to modify the VRI prescription (variable irrigation map or plan) throughout the season to irrigate these areas more or less because the alternative sources of water may not be constant or able to keep up with ET throughout the entire season.

Leave room in the soil to capture rainfall

In humid areas where there is significant in-season rainfall, periodically shutting the water off to the areas of the field with larger water-holding capacities will leave space in the soil to capture and hold anticipated rainfall. The sandy areas will still have to be irrigated on a regular basis to avoid stress because of their small water holding capacity; however, the water in the silty or clay soils can be depleted. Then, during significant rainfall events, there will be capacity to hold this rainfall in the silt or clay areas of the field. At these events there will be unavoidable rain water losses to deep percolation in the sandy areas. Doing this accurately requires additional data collection of the soil water content in the different areas of the field, good irrigation scheduling techniques, and in-season modifications to the VRI prescription in response to timing and depth of the precipitation events.

Unfortunately significant in-season rainfall events are not common in Utah and cannot be relied upon to justify this management strategy for VRI to conserve water.

Discussion of Overall Results and Potential for Water Savings with VRI

Most of the studies that show potential water savings with VRI on highly variable soils were done in regions with significant in-season rainfall events. In these cases, the VRI system was used to irrigate the soils as soon as they neared their MAD point (first water stress) which happened very quickly for sandy soils, but could be delayed for the silt and clay soils. This allowed the utilization of this stored soil water in soils with higher water holding capacities and created space in these soils to hold additional water from rainfall events, thereby reducing the total required irrigation water and simultaneously reducing water losses in the sandier soils at rainfall events to deep percolation (leaching).

Since water-out has to equal water-in, in a field with large variation in water holding capacities, if the irrigation system is managed for the smallest water holding capacity soil (sandiest or shallowest) such that there is no water stress or not over-irrigation to cause deep percolation, then the rest of the field will also not have water stress or water losses to deep percolation. Because of this, in arid areas without significant in-season rainfall, the potential for VRI to realize water savings due to variable water holding capacities in limited by the “mining” of the soil water from winter precipitation and a few other special circumstances that will be described briefly below.

4.4.3 Costs of Implementation and Annual Maintenance

Cost estimates of converting a standard center pivot to use **variable speed irrigation** controls are presented in Table 16 and Table 17. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 16. Cost estimates of converting a standard center pivot to use variable speed irrigation controls.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	1800	$	6
Equipment Lifespan	20	years	7
Upfront Management Labor	10	hours	8
Upfront Unskilled Labor	0	hours	9
Upfront Management Labor	350	$	10
Upfront Unskilled Labor	0	$	11
Total Labor	350	$	12
Annualized Upfront Labor	$24	$/year	13
Annualized Hardware Costs	$121	$/year	14
Total Annualized Upfront Costs	$145	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	1	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	700	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	700	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	1	hours/year	22
Labor effort hours/year	0	hours/year	23
Ongoing Expenses	0	$/year	24
Total annual management costs	35	$/year	25
Total annual unskilled labor costs	0	$/year	26
Total Annual recurring costs per year	35	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$880	$/year	28
Total Cost per Acre per Year	**$7.33**	**$/acre/year**	29

Table 17. Notes, assumptions and explanations for the cost estimates of converting a standard center pivot to use variable speed irrigation controls as shown above in Table 16.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumed that this is implemented on a full sized (1/4 mile long, or 1/4 section) center pivot.
6	Assumes that the pivot control panel is replaced with an upgraded control panel that allows variable speed control. Many advanced panels already do this.
7	Number of years before hardware has to be replaced and upfront costs are again incurred. Annual maintenance costs are included below.
8	Time for the manager to specify the new panel, coordinate it's installation, and learn to use the variable speed features.
9	Variable speed irrigation does not require any additional hardware to be installed.
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	This is time required for the manager to monitor and revise the variable speed prescription as needed.
17	This work is done by skilled personnel.
18	Can include weekly subscription, repair parts, vehicle expenses allocated to this project, etc.

19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Analyzing soil and yield data and using that to updating prescription maps.
23	Not different from a standard center pivot.
24	Most repair and updates are not different from a standard center pivot.
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

Table 18 and Table 19 shows the cost estimates for converting a standard full-sized pivot to variable rate irrigation (VRI) with zone-control. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 18. Cost estimates for converting a standard full-sized pivot to variable rate irrigation (VRI) with zone-control.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	20000	$	6
Equipment Lifespan	20	years	7
Upfront Management Labor	40	hours	8
Upfront Unskilled Labor	0	hours	9
Upfront Management Labor	1400	$	10
Upfront Unskilled Labor	0	$	11
Total Labor	1400	$	12
Annualized Upfront Labor	$94	$/year	13
Annualized Hardware Costs	$1,344	$/year	14
Total Annualized Upfront Costs	$1,438	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	1	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	700	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	700	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	15	hours/year	22
Labor effort hours/year	0	hours/year	23
Ongoing Expenses	500	$/year	24
Total annual management costs	525	$/year	25
Total annual unskilled labor costs	0	$/year	26
Total Annual recurring costs per year	1025	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$3,163	$/year	28
Total Cost per Acre per Year	**$26.36**	**$/acre/year**	29

Table 19. Notes, assumptions and explanations for the cost estimates of converting a standard center pivot to use variable zone irrigation controls as shown above in Table 18.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumed that this is implemented on a full sized (1/4 mile long, or 1/4 section) center pivot.
6	Estimates from published papers.

7	Number of years before hardware has to be replaced and upfront costs are again incurred. The annual maintenance costs are included in the annual recurring costs section.
8	Additional effort researching and specifying the system, meeting with dealers, ordering the parts, overseeing installation, learning to use it
9	It is assumed that installation is done by the pivot dealer and is a turn-key system.
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Deciding and modifying prescription maps. Uploading these to the system. Monitoring the system.
17	This work has to be done by skilled personnel.
18	Although telemetry plans for remote monitoring and control are often included, it is assumed that the baseline system for this type of grower already had this installed.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Analyzing soil and yield data and using that to updating prescription maps.
23	Assumes a little more time throughout the season to check nozzles for plugging than MESA. Based on experience with these systems.
24	Annual maintenance costs paid to the pivot dealer to fix breakdowns or issues (assumes grower is not able to fix these on his/her own).
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.4.4 Benefits/Drawbacks for grower, environment, labor

The primary barrier is developing and modifying VRI prescriptions in a way that improves the overall profitability. Prescriptions are the maps, or plans for how the irrigation amounts will be varied in the different areas of the field. These are often developed based on experience, GPS or GIS mapping, and/or GPS-referenced soil sampling. Electrical conductivity (EC) mapping, which is often used to indicate the differences in soil texture or water holding capacity throughout the field, is also widely used. This data collection is often time consuming, expensive, and plagued by high degrees of uncertainty (Higgens et al., 2016) and sources of variability. In addition it must be done by fairly educated and skilled (i.e. expensive to employ) personnel who are often hired consultants. Once the data that characterizes the variations in the field has been collected, it is not always clear how to vary irrigation amounts and timing in response to this data. Additional research is ongoing on how to set up the prescription maps using satellite, thermal sensors, thermal images, multispectral images, soil moisture sensors, and electrical conductivity-based soil maps, the effect of VRI system on the crop yield and water use efficiency (WUE), normalizes difference vegetative index (NDVI) (Booker et al., 2005; Chávez et al., 2009; Koch et al., 2004; X. Li et al., 2017, 2018, 2019; Lo et al., 2017; Mendes et al., 2019; O'Shaughnessy et al., 2012; Sigua et al., 2017; Vories et al., 2017; West & Kovacs, 2017; Zhao et al., 2017).

Further, irrigation decisions must be reevaluated many times over a season. Crop performance relative to other areas of the field, the soil surface conditions that affect infiltration rates, and the various alternative sources of water (size of the pond in your field) *rarely* remain constant throughout a growing season. In addition, using VRI to leave space in soils with larger water holding capacities to take advantage of water from anticipated rainfall events requires in-season modifications to avoid stressing the lower water holding capacity areas and to adjust for the fact that the anticipated rainfall may not materialize. Therefore, it is necessary to modify the prescriptions many times throughout the season. Such modifications can be especially challenging with continuously variable soils. This greatly increases the amount of data collection, analysis, decision-making, and modifications made to the VRI prescriptions throughout the season. This can be time consuming, complex, and therefore expensive in either real costs or opportunity costs.

However, if the specific on-farm conditions allow the use of a consistent VRI over time then significant savings in management time and costs can be achieved and will likely result in considerable water savings. For instance, when there are non-cropped areas which can be left non-irrigated, or if the crops are getting water from a consistently high water table then the VRI prescription need not change over time, and therefore these scenarios have the greatest potential for long-term implementation and measurable water savings.

4.4.5 Summary/Conclusions

- Variable rate irrigation is a mature technology and the machinery and equipment for VRI on center pivots works well.
- The opportunities for significant water savings in arid areas such as Utah due to variable soils are not common.
- Because water out = water in, and crop water use rates don't depend on soil types if the entire field is irrigated for the soil with the lowest water holding capacity (sandy soil) the rest of the field will be fine.

- Research shows that water savings with VRI is possible in areas with highly variable soils and significant in-season rainfall. Otherwise, water savings is limited.
- Using VRI with variable soils requires editing the prescription maps in both space and in time. This is time consuming and complicated (expensive in management or consultant time).
- Since Utah does not have significant in-season rainfall to refill depleted soil water in soils with larger water holding capacities (silts) then the water savings from VRI are minor compared to the high equipment and management costs.
- There are other uses for VRI, such as avoiding irrigating non-cropped areas of a field, but these benefits are not broadly applicable.

4.5 Low Energy Precision Application (LEPA) and Low Elevation Spray Application (LESA) for Center Pivots

4.5.1 Description

Low energy precision application (LEPA) is a modification to the typical sprinkler configuration on center pivots or linear-move machines that minimizes evaporation and wind drift losses by running the water directly onto the soil surface at very low pressure (Figure 49, Figure 50, and Figure 51). Because much less water is lost to wind drift and evaporation, and less of the soil surface is wetted there is less evaporation of water from the soil surface making it much more efficient (Lyle & Bordovsky, 1983). It operates at much lower pressures and consequently saves significant pumping energy. However, because water is applied to the soil in much less time, ponding and runoff can become a greater issue unless the field is tilled and the irrigation system is operated in such a way to limit this runoff. This may include using furrow diking and drag socks to limit the erosion of these dikes (Figure 51), using a dammer/diker to increase the soil surface water storage (Jones & Baumhard, 2003), or speeding up the irrigation system to apply smaller application depths in each pass.

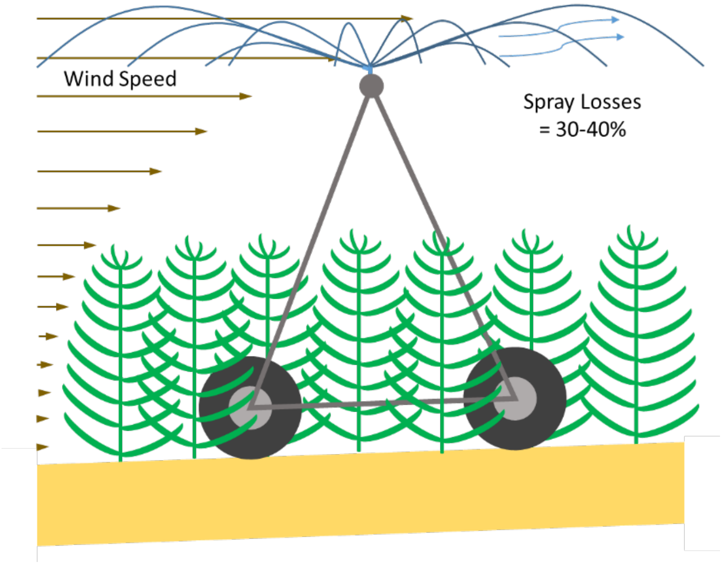


Figure 46. The water losses from sprinklers from traveling big guns, end guns, and impact sprinklers (especially those on top of a pivot) are typically from 30 to 40%. This is due to the higher wind speeds and greater wind mixing at higher heights, the higher sprinkler pressures dispersing the water, and because of longer water travel times through the air.

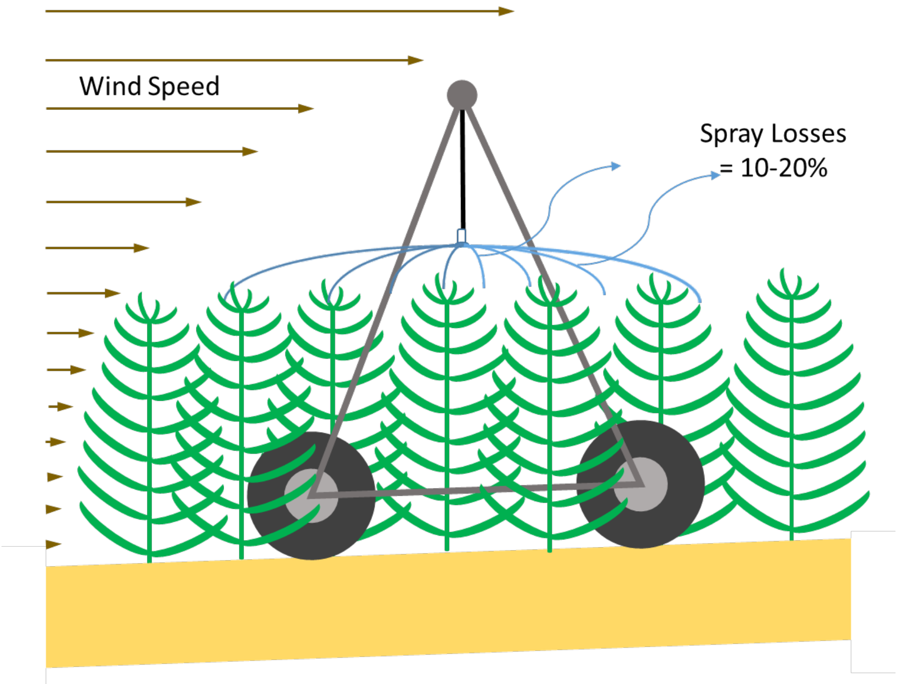


Figure 47. Moving sprinklers closer to the top of the canopy reduces spray losses to wind drift and evaporation. The typical mid-elevation spray application (MESA) sprinkler losses 10-20% of the water to wind drift and evaporation.

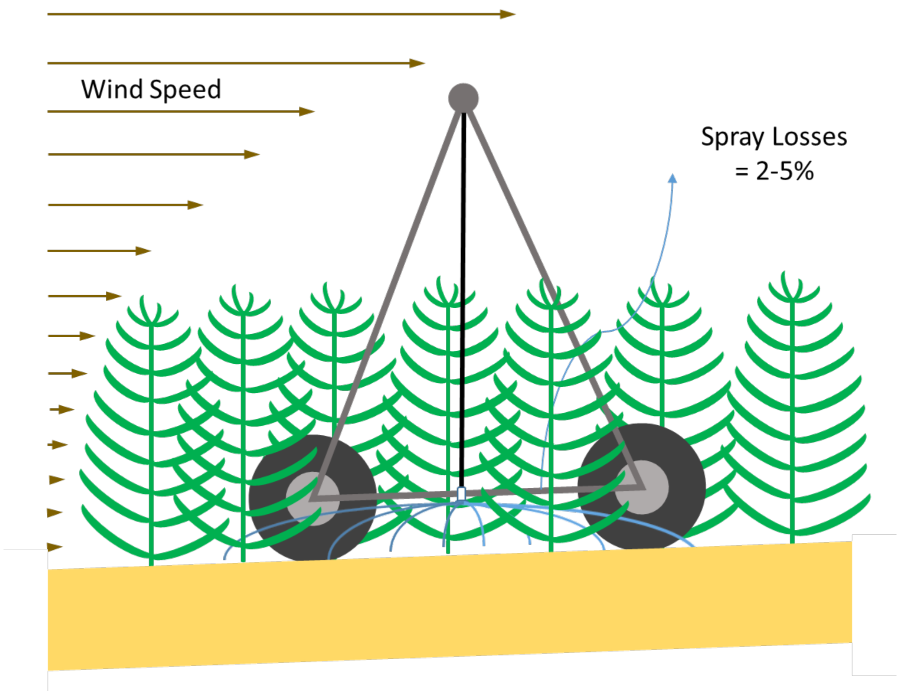


Figure 48. Low elevation spray application (LESA) or low energy precision application (LEPA) sprinklers emit water at low pressures near the soil surface and result in very little spray losses to wind drift and evaporation due to the low wind speed, low atmospheric mixing, higher humidity, low emission pressures, and very small time in the air resulting in very little mixing.

Figure 49. Water losses in the MESA section to the wind are visible, where no water losses can be seen in the LESA section of this pivot.

Low elevation spray application (LESA) is a similar modification to the typical sprinkler head configuration on center pivots or linear-move machines that places the water application very close to the soil surface, but uses a suspended sprinkler or spray head (Figure 48, Figure 52,Figure 53, Figure 54). It also reduces water losses to wind drift and evaporation and is uses less energy since it runs at much lower pressures. However, because the water is spread out in a limited way by the sprinkler head, it applies water more uniformly than LEPA and gives the water more time to infiltrate into the soil. Because of this, it has fewer problems with non-uniformity, crop germination, or with ponding and runoff than LEPA on fields without furrow dikes and therefore can be more flexible with a wide variety of crops, row orientations, and tillage systems.

Figure 50. LEPA on a row crop using drag socks to minimize erosion to the furrow dikes that limit water movement in the furrows.


Figure 51. LEPA on mint. This setup allows conversion back to MESA for better crop germination if desired.


Figure 52. LESA on a center pivot that uses three drops per pivot outlet.

Figure 53. LESA operating in wheat with the sprinkler heads below the top of the canopy.

Figure 54. LESA system using boombacks to spread the water out and increase infiltration on a wheat field near Milton Freewater, Oregon.

4.5.2 Efficiency Gains

In one study using large catch cans dug in such that the tops of the cans were level with the soil surface, they found that **96%** of the water that left the LESA nozzles was collected in the catch cans. By comparison, an average of **81%** of the water that left the MESA nozzles was collected in the catch cans (Mehanna & Peters, 2016). These differences were statistically significant (p <= 0.05) (Figure 55). These differences are likely even higher when the LESA sprinklers operate below the top of a crop canopy. The efficiency measurements for LESA are comparable with those found by other researchers (Fipps & New, 1990; Lyle & Bordovsky, 1983; Rajan et al., 2015; S.-H. Sadeghi et al., 2015; S. H. Sadeghi et al., 2017; Steve R. Melvin & Martin, 2018).

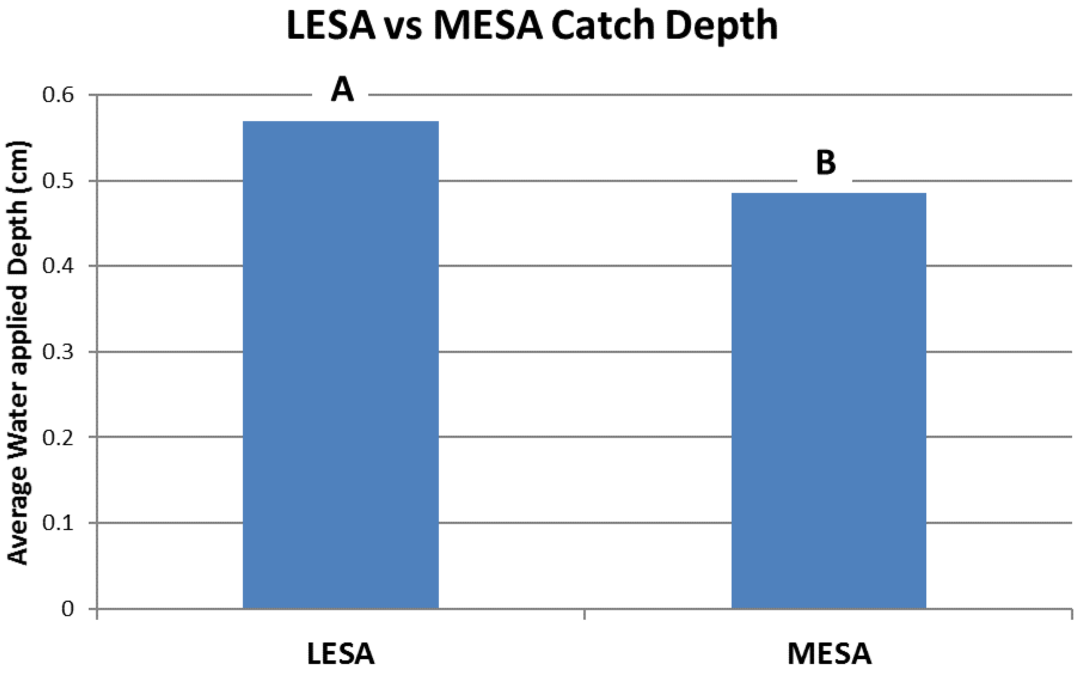


Figure 55. Catch can efficiency comparisons (10 replications) measured an average of 18% more water to the ground with LESA compared to MESA. Differences were statistically significant at the 0.05 level.

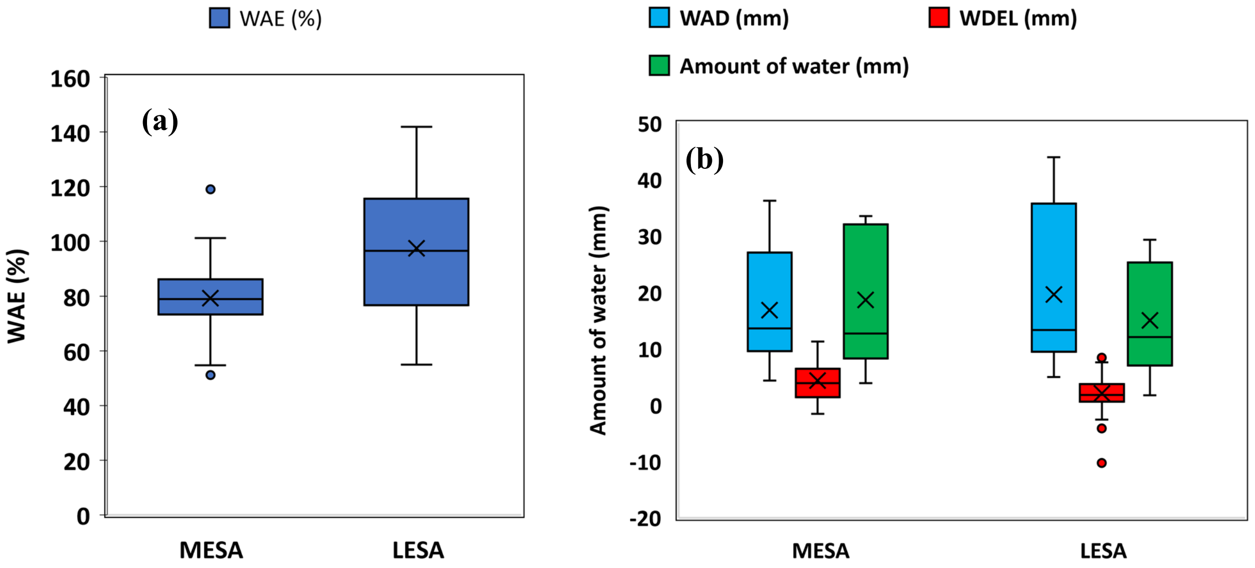


Figure 56. Mean statistics for water application efficienc (WAE, a), water application depth (WAD), and wind drift and evaporation losses (WDEL, b) for sprinkler irrigation systems (i.e. LESA and MESA) measured during a three year period (2015-2017). Where the “x” symbol in the center of the box denotes the mean and the “–“ is the median.

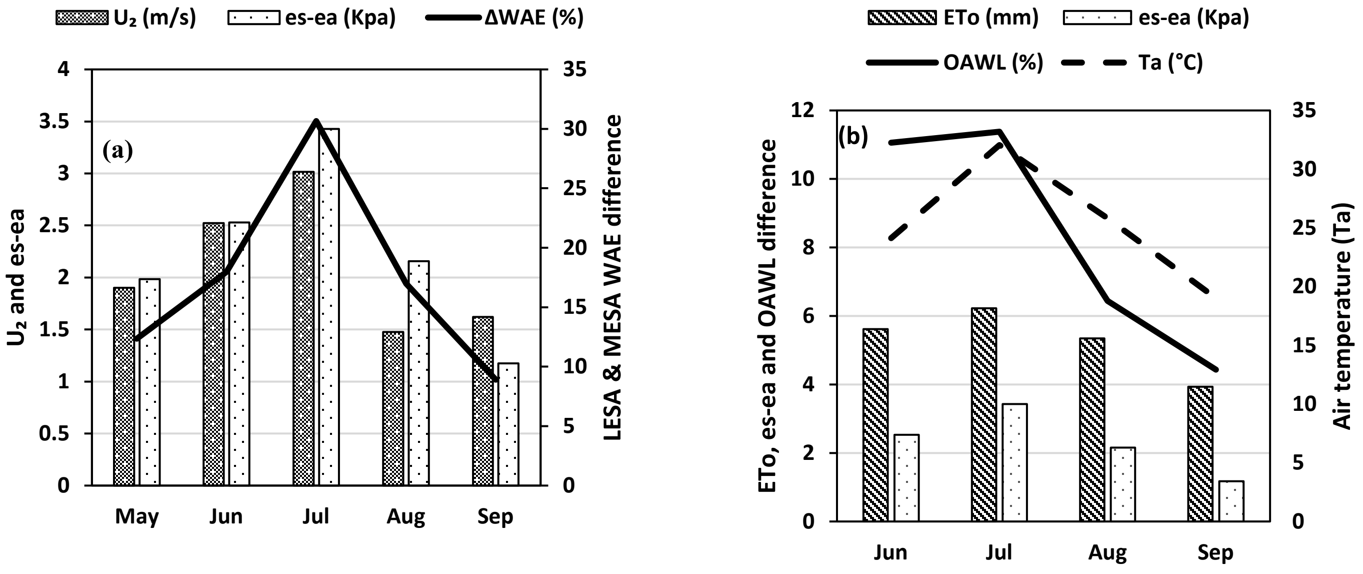


Figure 57. The mean water application efficiency differences (ΔWAE) between LESA and MESA for 2015-2017 on a monthly basis along with monthly average windspeed (U_z) and vapor pressure deficit (air aridity, e_s-e_a)(a). The overall spray water losses (OAWL) differences between LESA and MESA for the study duration (2015-2017) on a monthly basis plotted together with reference evapotranspiration (ET_o), air temperature (T_a), and vapor pressure deficit (e_s-e_a)(b).

4.5.3 Costs of Implementation and Annual Maintenance

When there is not adequate water available there are very strong economic benefits to convert from MESA to LESA (additional yield due to more water in the soil). When there is access to an adequate amount of water and the costs of additional water is negligible, the primary economic benefits of converting to LEPA and LESA are derived from pumping energy savings because the pump requires less power (lower required pressures) and operating time to deliver an equivalent amount of water to the soil. Even if the only return to the growing operation is pumping power savings, it can still be cost effective to convert to LESA (see the cost estimate section below).

Assuming that it is time to replace the pressure regulators and sprinklers of a typical ¼ mile long pivot, a comparison was done of the costs the hardware of converting to LESA vs. replacing the existing MESA sprinklers and regulators on the pivot. The costs to replace MESA drops on a typical 10 ft spacing are compared with a LESA retrofit are shown in Table 20. The costs were annualized at a 4 percent interest rate for the number of years shown for each item.

Table 20. Equipment costs for converting to LESA compared with replacing worn MESA sprinklers.

	LESA Drop			**MESA Drop**			
Equipment Costs		**Years**	**$/Year**		**Years**	**$/Year**	**Notes**
Gooseneck	$ 2.59	10	$0.32	$ 3.55	30	$0.21	LESA $5.17/2 for two drops
Pinch Clamp	$ 0.68	10	$0.08	$ 0.34	10	$0.04	0.34/each
Drop Hose	$ 6.50	10	$0.80	$ 3.90	10	$0.48	0.65/ft x 6 ft.
Truss Rod Hose Sling	$ 2.27	10	$0.28	$ -		$0.00	
Pressure Regulator	$ 9.20	5	$2.07	$ 9.20	5	$2.07	Nelson
Weight	$ 7.46	30	$0.43	$ 7.46	30	$0.43	
nozzle	$ 1.56	5	$0.35	$ 1.56	5	$0.35	Nelson
Nelson R3000 vs D3000 Spray	$ 2.71	10	$0.33	$ 24.24	5	$5.44	Body, plate, and cap
Total/Drop	$ 32.97		$4.67	$ 46.70		$9.02	
Drops/1/4 mile pivot	206			116			1/5 of LESA remains MESA
Total Costs	**$ 7,491**		**$961**	**$ 5,417**		**$1,046**	per 1/4 mile pivot

(4% annual interest rate. LESA: D3000 spray head, 10ft hose. MESA: R3000 sprinkler, 6 ft hose).

In order to achieve the maximum power savings from converting to LESA, the grower will need to use either a variable frequency drive, or a pump will often have to be reworked (the impeller trimmed) so that it will be most efficient at the decreased pressure requirement. These annualized costs at 4% interest rate over a 10 year life span are shown in Table 21 along with the costs of replacing the filter screen to filter out smaller particulates to avoid plugging the smaller nozzles. If the pump already has a variable frequency drive controller, then these additional pump rework costs are unnecessary.

Table 21. Annualized pump rework and replacement filter screen cost estimates.

Pump Rework Costs	**Cost/hp**	**Yrs**	**$/Year**
VFD&Filter or Rework	$ 150		
	$ 3,750	10	**462.341**
Water Filter (Fine Screen)	$ 400	10	**$49.32**
Total			**$ 462.34**

Cost Estimates for Conversion to Low Energy Precision Application (LEPA) and Low Elevation Spray Application (LESA) are shown in Table 22 and Table 23. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 22. Cost Estimates for Conversion to Low Energy Precision Application (LEPA) and Low Elevation Spray Application (LESA).

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	7650	$	6
Equipment Lifespan	10	years	7
Upfront Management Labor	20	hours	8
Upfront Unskilled Labor	192	hours	9
Upfront Management Labor	700	$	10
Upfront Unskilled Labor	2880	$	11
Total Labor	3580	$	12
Annualized Upfront Labor	$420	$/year	13
Annualized Hardware Costs	$897	$/year	14
Total Annualized Upfront Costs	$1,316	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	0	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	0	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	0	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**

Management effort hours/year	0	hours/year	22
Labor effort hours/year	10	hours/year	23
Ongoing Expenses	-858	$/year	24
Total annual management costs	0	$/year	25
Total annual unskilled labor costs	150	$/year	26
Total Annual recurring costs per year	-708	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$608	$/year	28
Total Cost per Acre per Year	**$5.07**	**$/acre/year**	29

Table 23. Notes for the cost estimates of converting a LEPA/LESA systems from MESA as shown above in Table 22.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumed that we are converting a full sized (1/4 mile long, or 1/4 section) center pivot from mid elevation spray application (MESA) sprinklers.
6	Assume 6 total spans of LEPA/LESA (including the overhang) at $650/span. The costs are estimates from conversions done in Washington and Oregon in 2017. The inside spans are assumed to not be converted. This assumes that the conversion is done when the MESA drops would have to be replaced, so this is a *difference* from expenses that had to be incurred anyway. Also includes the cost to rework the pump to take advantage of power savings ($3,750).
7	Number of years before hardware has to be replaced and upfront costs are again incurred. The annual maintenance costs are included in the annual recurring costs section.
8	Additional time specifying the system and overseeing the installation as compared to a normal MESA system.

9	Assumes 8 hrs/day/person x 4 people x 1 day per span * 6 spans = 192 hrs. Data is from experience doing these conversions in 2017-2019. Assumes MESA takes 8 hrs/day/person x 2 people x 0.5 days/span * 6 spans = 48 hrs. Therefore the difference is 192-48 = 144 hrs
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	The weekly management time should not be different from LEPA/LESA as it is for MESA sprinkler systems.
17	The weekly management time should not be different from LEPA/LESA as it is for MESA sprinkler systems.
18	Can include weekly subscription, repair parts, vehicle expenses allocated to this project, etc.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	No different than the reference technology (MESA).
23	Assumes a little more time throughout the season to check nozzles for plugging than MESA. Based on experience with these systems.
24	Assumes$100/yr additional parts/hose repairs compared to MESA. -$958/year due to pumping energy savings over MESA. See other detailed analysis.
25	No different than the reference technology (MESA).
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

Each field will be slightly different depending on the water source, incoming pressures or depth to water table, power costs, and equipment costs. However the power cost savings alone will typically help pay for the conversion from LESA to MESA. However, these benefits are likely small compared to the financial benefits from getting more water to the crop when it needs it. These financial benefits to the grower will be especially apparent when water is limited and the ability to get more water into the soil per gallon of water pumped results in direct yield and crop quality increases.

4.5.4 Benefits/Drawbacks for grower, environment, labor

LEPA/LESA systems have the following benefits and or drawbacks.

- Saves water and energy, and saves the most water and energy at the times of greatest water and energy shortages (hot parts of the summer).
- Reasonably acceptable to growers who can see (reduced water blowing away on the wind) the benefits.
- Improved uniformity right up to the edge of the field.
- Reduced day-night irrigation efficiency swings.
- Reduced wheel tracking issues (pivots getting stuck in the mud).
- Applying the same amount of water in less time due to the decreased wetted radius can increase ponding and runoff (Figure 58 and Figure 59). If a grower is already experiencing problems with ponding and runoff due to tight (high clay content) soils or steep field slopes, then converting to LEPA or LESA is not recommended without using tillage practices that increase the soil surface water storage or improve infiltration.
- Slightly smaller nozzle sizes are used due to less water required per sprinkler drop. This can lead to an increased propensity for sprinkler nozzle plugging with dirty surface water sources. To compensate and prevent plugging, finer filter screens may be required. However, nozzle sizes are larger than many would expect due to the lower operating pressures.
- LESA may cause issues with chemigation uniformity when the sprinklers are below the top of the canopy. Chemigation plates are available that spray water upwards, but studies have not yet been done on how effective these are for pest and disease control when the sprinklers are below the tops of the canopy.

Figure 58. The application rate of LESA and LEPA is much higher than that for MESA. This can lead to increased runoff especially on bare soils, steep slopes, and heavier soils.

Figure 59. Due to its smaller wetted diameter, LESA allows less time for water to infiltrate into the soil. Therefore LEPA or LESA may not be suitable to tight soils or steep slopes where infiltration and runoff can be an issue.

4.5.5 Summary/Conclusions

LESA and LEPA can effectively irrigate a large variety of different crops and saves large amounts of water. The overall season-long measured application efficiency was 97% compared to 80% for MESA. The relative savings varies over the season with the greatest savings occurring during the times of greatest water shortages due and greatest crop water needs. Because of this, large scale conversions to LEPA/LESA will reduce overall system capacity requirements (smaller pipes and pumps) and energy production capacity requirements (fewer power plants). LEPA/LESA is limited by soil infiltration rates and can result in increased ponding and runoff compared to MESA. Therefore in areas where runoff is already a problem it may not be applicable without implementing alternative conservation practices to compensate for this improved propensity for runoff.

4.6 Mobile Drip Irrigation (MDI) for Center Pivots

4.6.1 Description

Mobile drip irrigation (MDI) combines the high efficiency of surface drip irrigation with the flexibility, lower hardware costs, and convenience of center pivot irrigation. In this system, the drip tubing is attached to center pivot irrigation systems to apply water directly to the soil surface as the driplines are dragged across the field and to create a uniform wetting pattern across the entire irrigated area (Figure 60).

Figure 60. Mobile Drip Irrigation (MDI) in an alfalfa field.

MDI consists of heavy wall, in-line drip hoses in place of nozzles or sprinkler heads that are spaced at 20 to 40 inches apart. The sprinklers can also be left in place in addition to the drip line in a dual-purpose setup that allows switching between sprinklers and drip. This spacing is chosen based on the crop, the soil type, and the rooting depth of the crop. The length of the dripline that drags behind the center pivot depends on the flow rate needed and the area that is irrigated during the movement. The length of the dripline increases with distance from the center pivot to apply more water similar to a center-pivot nozzle package.

Netafim (USA., 2020), and Dragon-line("Dragonline,") are some companies that provide commercial MDI components and/or design services. Netafim refers to their product as precision mobile drip irrigation (PMDI) while Dragon-line is a tradename used by that company.

(Rawlins et al., 1974) was the first to develop and test mobile drip irrigation in California. MDI was later studied by additional researchers like (Helweg, 1989; Howell & Phene, 1983; Kanninen, 1983; C. Phene et al., 1982; C. J. Phene et al., 1985). These researchers found that MDI caused a reduction in foliar wetting, salt damage, and spray evaporation. In the past 19 years, MDI has been modified and commercialized. Now MDI is considering to be the most efficient method possible for irrigating with a moving irrigation system like a center pivot, linear move, or boom-cart system.

MDI systems are designed with longer drip lines (with a greater total flow rate due to more emitters) towards the outer end of the pivot and shorter lines towards the center. Installing the MDI system onto the center pivot is not complicated and most growers could do it on their own with a short training (Matt Yost, 2019; Swanson et al., 2016). The required spacing between the driplines depends on the soil type and the crop, but usually needs to be between 20 to 40 inches. Sandier soils and shallow rooted crops require closer drip-line spacing to avoid water stress in between drip lines. Emitters usually have a 1 or 2 gallon per hour flowrate, and are spaced approximately every 6 inches on the driplines (Matt Yost, 2019; "Precision Mobile Drip Irrigation," 2015). Soils with low infiltration rates (clay soils) may need greater distance between the emitters (longer total drip lines) to allow a greater amount of time for the water to infiltrate into the soil as the drip tubing is drug over the soil surface. Shorter spacing between the emitters (shorter total drip lines) can be used on sandier soils. Table 24 provides a comparison of the different center pivot water application technologies. The numbers are approximates and can vary significantly.

Table 24. A comparison of the different center pivot water application technologies.

Pivot Configuration	**Wind Drift and Evaporation Losses**	**Emitter Height From Soil Surface**	**Sprinkler or Drop Spacing**	**Wetted Length (Infiltration Time)**
Impact Sprinklers on Top of Pivot	40%	15 ft	20 ft	50 - 60 ft
Mid Elevation Spray Application (MESA)	20%	5-10 ft	10 ft	30 ft
Low Elevation Spray Application (LESA)	3%	1 - 2 ft	< 5 ft	15 ft
Low Energy Precision Application (LEPA)	0%	0 ft	< 5 ft	1 ft
Mobile Drip Irrigation (MDI)	0%	0 ft	1.5 ft	Up to 65 ft

There are various ways to connect MDI lines to pivots. Which method is ideal depends on the types of crops in the rotation, row spacing, and row orientations (circular planting for row crops vs. planting in straight lines). For shorter crops, a manifold that is 3-4 feet from the ground can be used. The driplines are connected to the manifold that is suspended from, and is fed water from the pivot. Alternatively, this manifold can be attached to the truss rods (Figure 61 MDI installed on a center pivot while retaining the sprinklers for switching between MDI and MESA. The driplines on the outside spans of the pivot are longer since it covers a larger area in the field. Although the crop is wheat, the MDI system is set up for taller crops.

This would be more flexible for taller crops. In some cases, the driplines can be attached directly to the pivot using rigid or flexible drops (Netafim). Sometimes the water is fed through existing sprinkler drops that are left in place and functional to switch back and forth to help with crop germination.

The MDI system needs filtration sufficient for drip irrigation to prevent clogged emitters. The additional filtration can create significant additional costs compared to the mid elevation spray application (MESA; drops spaced about 9-10 feet apart with sprinklers 6 to 10 feet from the soil surface) or low elevation spray application (LESA; drops spaced about 5 feet apart or less with sprinklers 1 to 2 feet from the soil surface). It is recommended to plant the crop in circles and locate a drip line in between every row if possible to ensure equal water to all plants. This avoids dragging the drip tubing over the crop rows and potentially damaging the crops. However, circular planting can add additional cost to MDI management (Schmidt et al., 2016) and planting in straight rows is possible with some crops and MDI attachment configurations.

Figure 61. MDI installed on a center pivot while retaining the sprinklers for switching between MDI and MESA. The driplines on the outside spans of the pivot are longer since it covers a larger area in the field. Although the crop is wheat, the MDI system is set up for taller crops.

4.6.2 Efficiency Gains

MDI is much more efficient than the most common MESA sprinkler configuration on center pivots. The wind-drift and evaporation losses of MESA vary with the weather but can are average about 20% (Sarwar et al., 2019). However, since MDI emitters deliver water directly to the soil surface, wind drift and evaporation losses are near zero. MDI also does not wet the entire soil surface and some areas of the soil remain dry (Figure 62 and Figure 63). This results in a significant decrease in soil surface evaporation losses after the pivot has passed. Because water is distributed by MDI over a longer time period and the soil has more time to absorb the water compared to MESA, and especially compared with LESA and LEPA, the runoff from MDI is significantly decreased. MDI can also help eliminate the overwatering under the inside spans of center pivots and this can save up to 10% of total water distributed to the system (Du, 2011).

A scientific and peer reviewed research study comparing center-pivot sprinkler irrigation to MDI in Germany found a 10-20% (Derbala, 2003), and 25% (Hezarjaribi, 2008) water saving by using MDI. Another study in Kansas comparing LESA with MDI showed that the soil evaporation component of evapotranspiration from MDI was 35% lower than the in-canopy LESA nozzles (Kisekka et al., 2016, 2017). This is because MDI does not completely wet the entire surface of the soil. There were some trial reports presented by Jones in 2015 that found a 31% water savings of MDI trials in Colorado in 2014, and another trial that showed 50% more available soil moisture for crops in trials in Kansas in 2013. In an alfalfa field in Oregon that compared MESA system with MDI, the resulting soil moisture graphs showed that the available moisture at 38 inches under MDI was significantly greater than for MESA.

Figure 62. Shows how driplines move through the crop and how less surface area is wetted compared to sprinklers on MESA systems.

There are also large energy savings from MDI. Because more water reaches the soil surface per gallon pumped, the pivot and pumps can be shut off more often while still getting the same amount of water to the soil. In addition, MDI does not need pressure as high as sprinklers in order to operate at the design flow rate. Lower pressure and run times can result in significant power savings. Depending on the water source, power costs, and pump efficiency, these power savings alone may justify the conversion of a pivot to MDI. Research studies showed that MDI resulted in energy savings of 20-70% (Lamede et al., 2017), 40-50% (Derbala, 2003), 70% (Hezarjaribi, 2008).

Figure 63. MDI doesn't wet the entire soil surface reducing soil evaporation water losses.

4.6.3 Costs of Implementation and Annual Maintenance

The costs of an MDI system have been reported to be between \$150-\$200 per acre (Yost et al., 2019). If converting from low elevation spray application (LESA) to MDI costs have been reported to be \$250-\$280 per acre (O'Shaughnessy & Colaizzi, 2017).

Cost estimates for converting a standard MESA pivot to mobile drip irrigation (MDI) are shown in Table 25 and Table 26. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 25. Cost estimates for converting a standard MESA pivot to mobile drip irrigation (MDI).

General Assumptions	Value	Units	Notes
Management Rate	35	\$/hour	1
Unskilled Labor Rate	15	\$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	Value	Units	Notes
Upfront Total Hardware Costs	12800	\$	6
Equipment Lifespan	10	years	7
Upfront Management Labor	40	hours	8
Upfront Unskilled Labor	240	hours	9
Upfront Management Labor	1400	\$	10
Upfront Unskilled Labor	3600	\$	11
Total Labor	5000	\$	12

Annualized Upfront Labor	$586	$/year	13
Annualized Hardware Costs	$1,501	$/year	14
Total Annualized Upfront Costs	$2,087	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	0	hours/week	16
Labor effort in hours/week	3	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	0	$/year	19
Total weekly unskilled labor costs	900	$/year	20
Total weekly recurring costs per year	900	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	0	hours/year	22
Labor effort hours/year	10	hours/year	23
Ongoing Expenses	-858	$/year	24
Total annual management costs	0	$/year	25
Total annual unskilled labor costs	150	$/year	26
Total Annual recurring costs per year	-708	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$2,279	$/year	28
Total Cost per Acre per Year	**$18.99**	**$/acre/year**	29

Table 26. Notes, assumptions and explanations for the cost estimates of converting a standard MESA center pivot to mobile drip irrigation as shown above in Table 25.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumed that we are converting a full sized (1/4 mile long, or 1/4 section) center pivot.

6	Assumes 6 total spans of MDI (including the overhang) at $800/span. The inside spans are assumed to not be converted. Assumes that the conversion is done when the MESA drops would have to be replaced, so this is a *difference* from expenses that had to be incurred anyway. Also assumes that a new water filtration system is needed $8000.
7	Number of years before hardware has to be replaced and upfront costs are again incurred. The annual maintenance costs are included in the annual recurring costs section.
8	Additional time specifying the system and overseeing the installation as compared to replacing worn sprinklers on a typical MESA system.
9	Assumes 8 hrs/day/person x 4 people x 1.5 day per span * 6 spans = 288 hrs. Data is from grower conversations. Assumes MESA takes 8 hrs/day/person x 2 people x 0.5 days/span * 6 spans = 48 hrs. Therefore the difference is 288-48 = 240 hrs
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	The weekly management time should not be different from MESA sprinkler systems.
17	The weekly labor costs are increased slightly to include untangling drip lines, periodic flushing of the lines, and fixing leakes from rodents or tears.
18	Can include weekly subscription, repair parts, vehicle expenses allocated to this project, etc.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	No different than the reference technology (MESA).
23	Assumes a little more time throughout the season to check nozzles for plugging than MESA.
24	Assumes$100/yr additional parts/hose repairs compared to MESA. -$958/year due to pumping energy savings over MESA. (Peters et al., 2018)
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.6.4 Benefits/Drawbacks for grower, environment, labor

One drawback to more efficient sprinkler configurations on center pivots such as LESA is that they have a small wetted radius and water is often applied faster than the soil can take the water in resulting in ponding and runoff. In addition, the kinetic energy of sprinkler droplets as they hit the soil surface can break up the soil surface structure, create surface sealing and further decrease infiltration and lead to additional runoff problems. MDI applies the water more slowly along the drip tube as it is pulled through the field (Figure 62). Towards the end of a pivot sprinklers apply more water using larger nozzles and create potential runoff issues especially in those areas. However, MDI drip tubing towards the end of the pivot is longer to apply more water making the application rate to the soil the same along the entire length of the pivot. Many growers that have tried MDI have commented on the reduced runoff issues. Some research studies have expressed the reduction in runoff in the field by using MDI (Chu et al., 1992; S. O'Shaughnessy & Colaizzi, 2017).

Because MDI tubing both drags behind the pivot to some degree, and because it applies water directly to the soil, it is easy to keep wheel tracks dry. This greatly reduces frustrating problems with pivots becoming stuck in deep wheel tracks. In all research studies, MDI has resulted in significantly shallower and drier wheel track compared to the MESA, LESA and LEPA (Kisekka et al., 2016, 2017; Matt Yost, 2019; S. O'Shaughnessy & Colaizzi, 2017; Oker et al., 2018; Swanson et al., 2016; USA., 2020).

Figure 64. As a test, even though MDI was available, the span on the left was left running MESA sprinklers. Water ponding in the deep wheel tracks is visible. The wheel tracks in the MDI spans on the right were shallow and dry.

Wet leaves encourage many different diseases including a wide variety of rots, molds, and wilts. MDI does not get the leaves wet and instead the water is applied directly to the soil (Figure 64). This will likely result in decreased plant disease pressure and salt damage to the foliage (Matt Yost, 2019; Rawlins et al., 1974).

4.6.5 Summary/Conclusions

Mobile Drip Irrigation is an irrigation method that many growers could be benefitting from that are not. MDI is able to get 10-25% more water to the soil per gallon of water pumped than traditional MESA sprinklers. MDI has been found to use less water than LESA, and a similar amount of water compared with LEPA. For comparison, LESA has been shown to use about 18% less water than MESA. In addition, there was found to be 35% less evaporation from the soil surface compared with LESA after the water was applied. The primary benefit of MDI is that the water is applied more slowly over time, giving the soil more time to absorb the water. This means that MDI will have less runoff than LESA or especially LEPA. Growers should strongly consider MDI if they do not have enough water, *and* have runoff problems. If they do not have runoff problems then growers will likely be more interested in the lower cost methods of LESA or LEPA.

4.7 Deficit Irrigation

4.7.1 Description

Deficit irrigation is a generic term to describe applying less irrigation water than the plant would use if it was fully irrigated. Deficit irrigation requires very good and informed irrigation water management. Deficits can be applied uniformly throughout the season, or applied only in particular growth stages of the crop (regulated deficit irrigation or RDI). Although every crop responds differently, in general water stress during the vegetative growth stage of grain crops has the smallest impact to the overall yields (Figure 65).

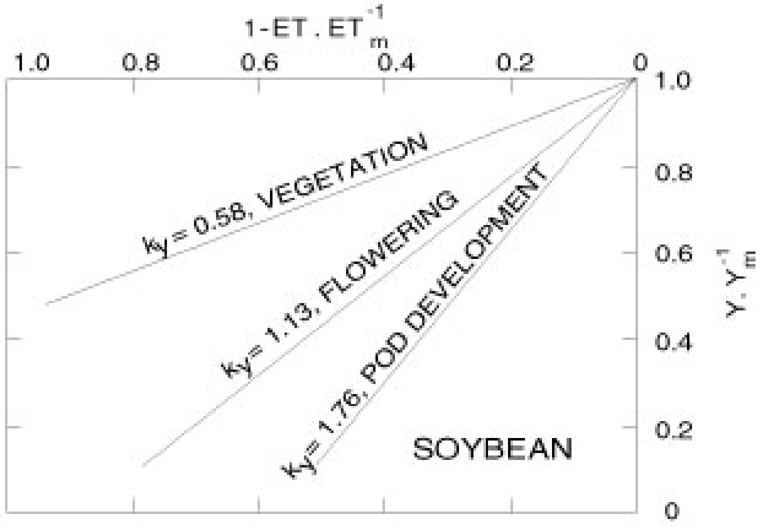


Figure 65. Showing the sensitivity (k_y) of overall yield to water stress in different growth stages (Kaboosi & Kaveh, 2010).

Although crop yield responds fairly linearly with transpiration (Figure 66) crop yield response to the total water applied is not linear (Figure 67). This separation (Figure 68) is because in order to avoid water stress anywhere in the field additional water must be applied to compensate for poor irrigation uniformity. This results in greater water losses to deep percolation creating the separation in those curves. Also, when someone is deliberately deficit irrigating, it often means that the soil surface is drier for a greater proportion of the growing season resulting in reduced evaporation from a wet soil surface.

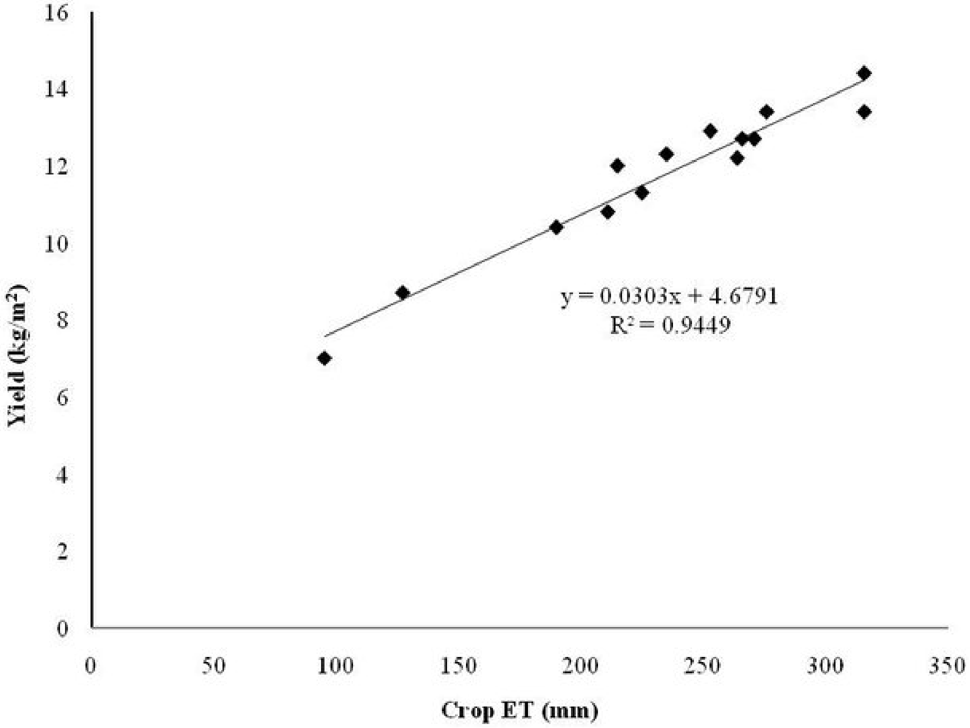


Figure 66 A linear response of cucumber yield with crop ET
(Alomran & Louki, 2011)

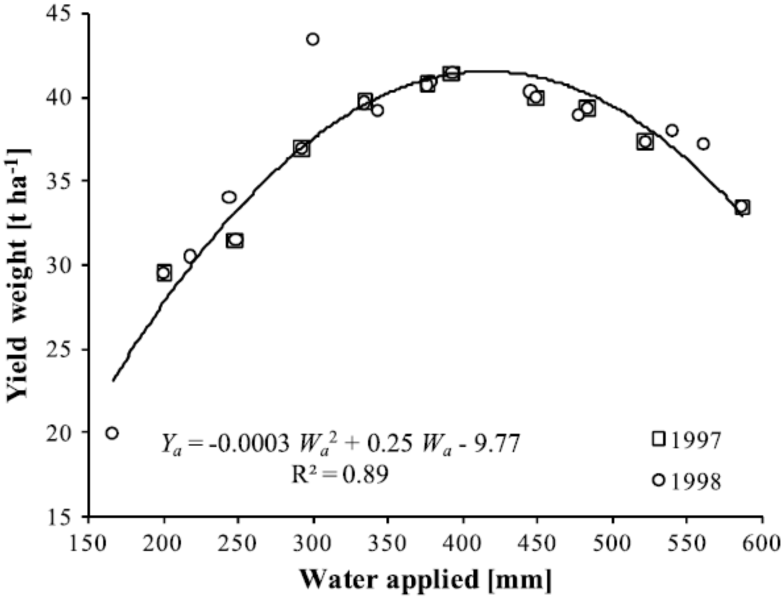


Figure 67. The relationship between onion yield and applied water

(Autovino et al., 2016).

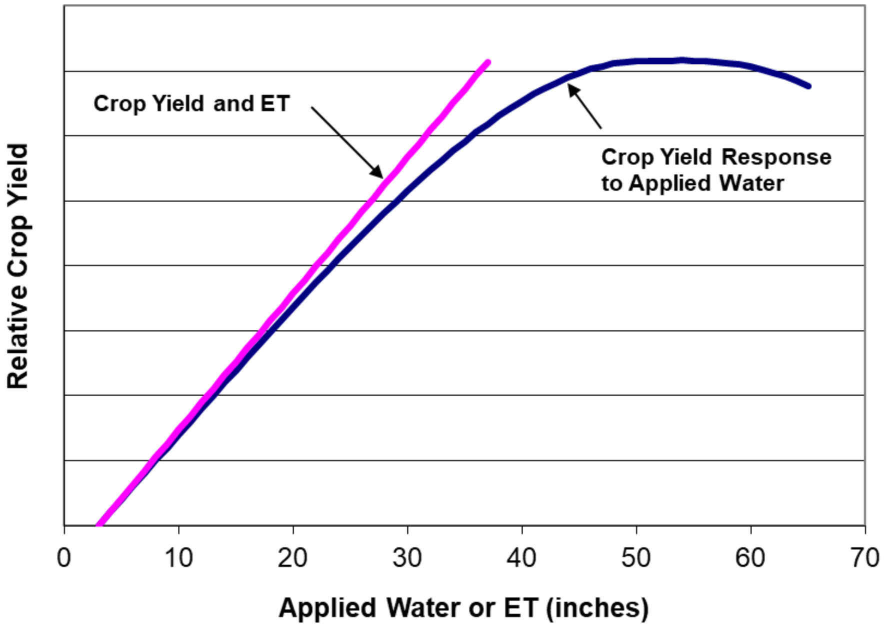


Figure 68. Without water stress, crop yield is limited by the available sunlight and nutrients. As more water is applied to get to maximum yields, more water is lost to deep percolation and soil surface evaporative losses.

It is important to note that although deficit irrigation can reduce water use significantly, it usually means that a much greater percentage of the water is consumptively used. Where, with full irrigation a small percentage of the applied water might be expected to return to the groundwater as deep percolation, deficit irrigation usually eliminates this return flow.

4.7.2 Efficiency Gains

A lot of deficit irrigation studies have shown that a reduction of 20-30% does not result in a corresponding reduction in crop yields. The yields are instead reduced by 5-10%. Additional water reductions after this result in large water stresses (in the linear portion of the crop yield to water applied curve as shown in (Figure 68). Because of this, water reductions beyond 20-30% are usually not recommended. For our calculations we assumed that there would be a 20% reduction in water use with deficit irrigation.

4.7.3 Costs of Implementation and Annual Maintenance

Cost estimates for doing deficit irrigation are presented in Table 27. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 27. Cost estimates for doing deficit irrigation.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	0	$	6
Equipment Lifespan	15	years	7
Upfront Management Labor	10	hours	8
Upfront Unskilled Labor	0	hours	9
Upfront Management Labor	350	$	10
Upfront Unskilled Labor	0	$	11
Total Labor	350	$	12
Annualized Upfront Labor	$29	$/year	13
Annualized Hardware Costs	$0	$/year	14
Total Annualized Upfront Costs	$29	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	2	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	1400	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	1400	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	2	hours/year	22
Labor effort hours/year	-4	hours/year	23
Ongoing Expenses	-762	$/year	24
Total annual management costs	70	$/year	25
Total annual unskilled labor costs	-60	$/year	26
Total Annual recurring costs per year	-751	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$678	$/year	28
Total Cost per Acre per Year	**$5.65**	**$/acre/year**	29

Table 28. Notes, assumptions and explanations for doing deficit irrigation as shown above in Table 27.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumes a fairly large field for equivalent comparison with other technologies.
6	No additional hardware is required. This is equivalent to very good irrigation scheduling.
7	Number of years before the manager needs to be re-trained on deficit irrigation.
8	Education requirement for the manager to learn how to do deficit irrigation. It is assumed that the grower is already using data-based irrigation schedluling.
9	No additional labor required upfront.
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Close monitoring of soil and plant water stress. Sophisticated and precise irrigation management.
17	No additional effort, in fact on average there is usually less labor required because over-irrigation is avoided. This is included the annual recurring costs.
18	No additional expenses.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unkilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Annual deficit irrigation strategy setup and planning.

23	Labor savings is likely, depending on the irrigation system. For example a wheel-line sysem has about 10 irrigations per year, about 8 sets per irrigation, and it takes about 20-30 minutes to change each set. If we saved 2 sets per season (20% reduction in water applied), this would save about (2 irrigations x 8 sets/irrigation x 0.4 hrs/set) = 6.4 hrs per season. However, not all systems (such as center pivots, solid-set, or drip) have labor requirements. So we assumed an average of 4 hrs/season saved.
24	For the entire field we assume a 35 hp pump 0.745 kW/hp x 2000 hrs/season x \$0.073/kW-hr = \$3,807/year pumping costs (Peters et al., 2018). An estimated 20% reduction in pumping energy costs gives a \$761 savings for the whole field.
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

We calculated the cost estimates for doing deficit irrigation three different ways. One (as shown above in (Table 27 and Table 28) was to just calculate the cost without estimating the economic impact of the yield reductions.

However, to try to demonstrate the economic impact of the yield reduction from a 20% deficit irrigation we estimated that this resulted in a 7% yield reduction of an alfalfa field with a \$720/acre/year gross income (4 tons/acre at \$180/ton; NASS, 2019) for that acre. This resulted in an additional cost (loss) to the grower of \$720/acre/year x 0.07 = \$50.40/acre/year. This should be included in the total cost per acre per year to result in **\$56.05/acre/year**, a fairly high cost.

If the grower was allowed to keep the conserved water and spread it to additional acreage (also at a potential gross return of \$720/acre) then the total *cost* of doing deficit irrigation becomes \$56.05/acre/year - \$720/acre/year x 0.2 = **-\$87.95/acre/year**, a net *benefit* to the growers. This is a rough calculation to demonstrate that growers will be motivated to conserve and deficit irrigate if they are allowed to spread that water to additional acreage. If not, they have a strong disincentive.

4.7.4 Benefits/Drawbacks for grower, environment, labor

From a growers' point of view the cost of water is low (usually just the cost of pumping, or a fixed cost for deliver), but the economic benefit that can be derived from the water is high. The grower usually already has paid all of the fixed costs of production for the land, ground preparation, planting, maintenance, equipment capital and maintenance costs. Therefore the minor additional costs paid to fully irrigate, or even slightly over-irrigate as "cheap insurance" is usually seen as a good economic decision. Because of this growers will normally always choose to fully irrigate. They only consider deficit irrigation if they don't have enough water, if they can "spread" the conserved water to additional acreage and use the same amount of water to produce more, or if they are incentivized to use less water.

Allowing growers to spread their conserved water to additional acreage encourage conservation, innovation, and efficient use of water resources by the growers as they try to grow more with the same amount of water. It will likely make growers wealthier and most growers want to be given this opportunity. In areas of Eastern Oregon growers are allowed to “spread” their water to do as much good as they can with it. These growers have proven to be very innovative and productive with their deficit irrigation practices (Yorgey et al., 2018). From the state’s point of view, Utah should expect a larger percentage of Utah’s water resources to result in beneficial use, and Utah as a whole will get more economic benefit from their water. However the state should expect to see less water eventually return to the groundwater and less runoff water available for alternate uses downstream as a larger percentage of the water will be consumptively used (ET) and leave the state as water vapor.

4.8 Tillage to Control Runoff

4.8.1 Description

Runoff is caused when water is applied to the soil surface at a rate that is faster than the soil can take it up. It is often possible to make modifications to irrigation systems to decrease the irrigation application rate (use a larger wetted radius, use boom-backs on center pivots, decrease the nozzle flow rate, etc.). However, this is often not possible or practical. In these cases we try to increase the amount of water that can be stored on the soil surface and try to limit that water's movement across the soil surface so that the water have time to infiltrate where it was applied (Figure 70 and Figure 71). This usually includes using a dammer-diker implement that creates storage pits or reservoirs (Figure 69).

Figure 69. A grower running a dammer-diker through his field.


Figure 70. A dammer-diker implement leaves small pits in a corn field to help increase soil surface water storage and limit runoff.


Figure 71. Furrow dikes are created to limit water movement to create small basins to give the water more time to infiltrate into the soil in the LEPA system with drag-socks.

4.8.2 Efficiency Gains

This type of tillage not only reduces runoff, but it allows irrigation systems, specifically center pivot irrigation systems to apply more water per pass. These less frequent irrigation of greater amounts reduces the water losses from the wet canopy and wet soil surface. There are very few studies on the water savings from this type of tillage. The studies are instead focused primarily on yield effects with measured increases of 31% on corn, 22% on potatoes, and 9.5% on wheat (Longley). However many of these studies stated decreased runoff (Mcguire, 2014) and increased soil water contents compared with a control (Longley). Based on this, we will assume a 5% decrease in total water required for maximum yields.

4.8.3 Costs of Implementation and Annual Maintenance

Cost estimates for using a dammer-diker to increase irrigation water surface storage are provided in Table 29 and Table 30. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 29. Cost estimates for using a dammer-diker to increase irrigation water surface storage.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	2250	$	6
Equipment Lifespan	15	years	7
Upfront Management Labor	2.5	hours	8
Upfront Unskilled Labor	0	hours	9
Upfront Management Labor	87.5	$	10
Upfront Unskilled Labor	0	$	11
Total Labor	87.5	$	12
Annualized Upfront Labor	$7	$/year	13
Annualized Hardware Costs	$188	$/year	14
Total Annualized Upfront Costs	$196	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	0	hours/week	16
Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	0	$/year	19

Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	0	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	5	hours/year	22
Labor effort hours/year	20	hours/year	23
Ongoing Expenses	600	$/year	24
Total annual management costs	175	$/year	25
Total annual unskilled labor costs	300	$/year	26
Total Annual recurring costs per year	1075	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	$1,271	$/year	28
Total Cost per Acre per Year	**$10.59**	**$/acre/year**	29

Table 30. Notes, assumptions and explanations for using a dammer-diker to increase irrigation water surface storage as shown above in Table 29.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumes a fairly large field for equivalent comparison with other technologies.
6	A dammer diker implement is estimated to be around $9000 based on on-line prices. Assume can be used for 4 pivots. $9,000/4 = $2,250.
7	Number of years before hardware has to be replaced and upfront costs are again incurred. Annual maintenance costs are included below.
8	Specifying the implement, purchasing it = 10 hrs / 4 fields = 2.5 hrs.
9	No additional upfront labor costs
10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs

13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	These costs are included in the annual recurring costs.
17	These costs are included in the annual recurring costs.
18	These costs are included in the annual recurring costs.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Help with maintenance, tractor setup, directing labor, etc.
23	Additional time per season to set up the tractor, run it through the field, and put it away.
24	Fuel costs.
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.8.4 Benefits/Drawbacks for grower, environment, labor

Reduced runoff will certainly benefit the environment. The benefits and drawbacks to the grower are included in the cost estimates.

4.9 Conservation Tillage (No-Till and Strip-Till)

4.9.1 Description

The first people to grow crops tilled the ground for two primary reasons: 1) to kill and control weeds, and 2) to ensure good seed germination by ensuring good soil to seed contact and to ensure that the seed is placed at the proper depths. Since tillage moves large amounts of soil and has to over-come both the weight of this soil and the soil's shear strength, tillage takes a lot of energy. Although it varies widely depending on the area, soil, climate, previous crop grown, new crop being planted, and planned harvest or planting dates, it usually takes 2 or 3 tillage passes to prepare a soil for planting. (1) Plowing often takes place in the winter to incorporate soil surface organic matter into the soil so that this straw or residue is broken down by soil microorganisms before spring. (2) Then in the spring the soil is disked again to even out the surface and kill any weeds that may have germinated. (3) This is immediately followed by harrowing and/or culti-packing to break up the clods on the soil surface and smooth out the soil surface. Then the new crop can be planted.

However, tillage destroys soil structure by physically breaking apart the soil's aggregates. These soil aggregates (clumps) are created by the wetted and drying cycles of the soil as well as the freezing and thawing cycles and by roots that hold these aggregates together. Soil with increased structure (aggregates) holds more water, and both allows water into it, and out of it more easily. Tillage uses a lot of tractor fuel (diesel) and destroys most of this soil structure creating surface sealing which prevents water movement into the soil (Waddell & Weil, 1996), kills many beneficial soil-born organisms such as earthworms, decreases the overall water holding capacity of the soil, exposes the soil water to the air for evaporation, increases the breakdown rate of important soil organic matter, and causes volatilization and increased leaching of many important soil nutrients (Angle, 1984).

Chemical weed control has been available for many years. And new tillage implements have been developed that allow direct seeding into the remaining crop stubble without tillage. These tillage implements, usually called no-till drills, move the surface residue out of the way, plants the seed into the soil, and uses a press-wheel to help ensure good soil to seed contact. So instead of three passes with a tractor that is moving a lot of soil (the tractor is "pulling hard") there is one pass with a tractor that is a lighter pull. Not only does this greatly reduce energy (diesel) use, no till helps preserve the soil structure and allows that soil structure to continue to develop. The remaining crop stubble protects the soil surface from the sun and wind and limits soil water evaporation and moderates temperature swings for the soil (Gallaher, 1977). This stubble also holds the soil open which helps keep the water infiltration rate high to reduce water runoff and reduces the wind and water erosion. In addition the crop residue can trap snow, which can result in more spring melt water, prevents soil surface runoff, and helps prevent soil erosion (Wendt & Burwell, 1985)Figure 72

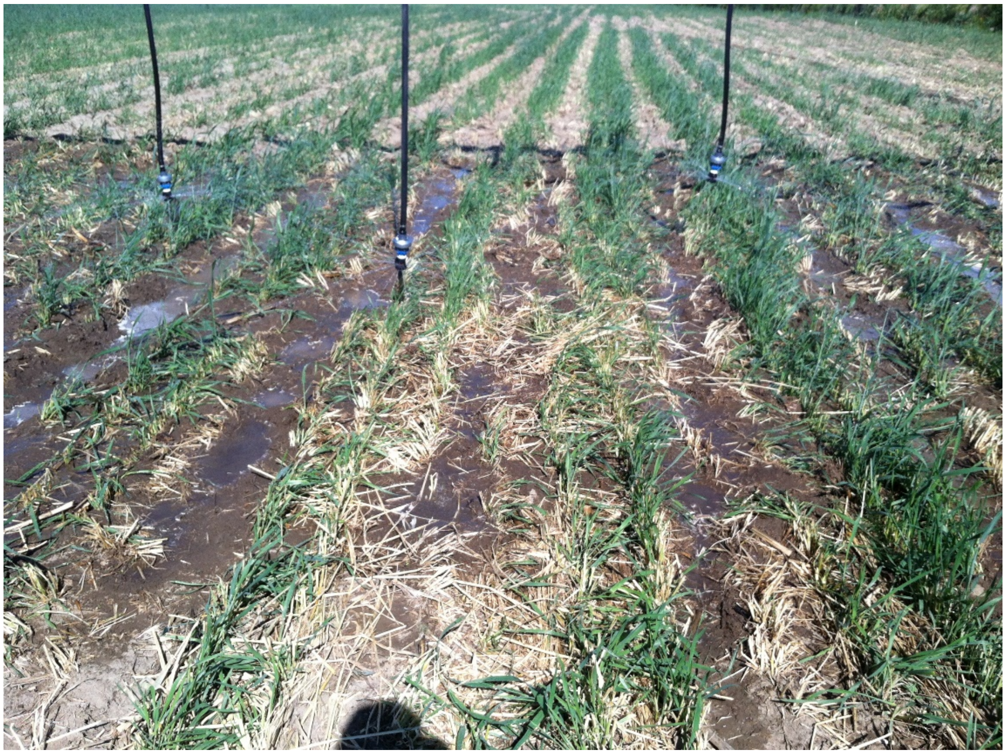


Figure 72. Residue on the soil surface due to no-till helps limit the movement of water and thereby increases the soil surface storage.

The primary drawback of no-till is that the crop residue on the soil surface shades the soil and thus the soil warms up slower than bare soils do. This can slightly delay crop emergence and crop development. Seed germination is also slightly reduced from conventional tillage methods, although continued development on the tillage implements is helping overcome this.

No-till cuts through the soil surface residue, makes a seed furrow, plants the seed, firms the seeds and then closes the furrow all in one pass. Strip-till is a variation of no-till, where they use a light pass to till a narrow strip of soil where the seeds will be planted before planting to help increase seed germination and soil heating in the spring. Strip till almost always requires the precision of GPS-guided tractors to ensure that the seeds are planted in the center of the tilled strips.

4.9.2 Efficiency Gains

No-till doesn't increase irrigation efficiency as much as it helps the applied water get into the soil, and prevents soil water evaporation losses. No till can also help reduce water losses from a wet soil surface, and it can prevent the water losses from the soil during each tillage event. (Jasa, 2013; Warburton & Klimstra, 1984) reported that tillage causes soil water loss of 0.25 to 0.75 inches per tillage pass. Because surface residue reduces runoff and increases infiltration rates much more water can be applied in each irrigation event. Most measurements estimate a 0.08 to 0.10 inch water loss from each irrigation pass. If a center pivot, for example, could apply more water in a pass they can reduce evaporation losses from a wet canopy and soil surface.

No-till has been shown to greatly increase infiltration rates (Bergstrom, 2018). If we assume that we can get 50% more water into the soil in an irrigation pass with No-till (0.75 inch/pass vs 0.50 inch/pass), then at 32 inches of water per season conventional tillage would would require 64 irrigation passes per season (32 in/season / 0.5 in/pass) per season for a total of (0.08 in/pass losses x 64 passes/season) 5.12 inches of water loss to evaporation per season with conventional tillage. If no-till can get 0.75 in/pass into the soil and reduce the center pivot passes to 43 passes per season (32 in/season / 0.75 in/pass) for a total of (0.08 in/pass losses x 43 passes/season) 3.41 inches of water loss to evaporation per season with no-till. This results in a 1.7 in water savings (5.12 in/season – 3.41 in/season). If no-till prevents another 1 inch of water loss from tillage passes (0.5 in/pass x 2 passes conserved), then the total water savings might be close to 2.7 inches. This coincides with a four-year study in Nebraska (Jasa, 2013) that found that no-till saved 2.5 to 5 inches of water per year compared to bare-soil plots. This an estimated 8% water savings (2.7 in/season / 32 in/season) from no-till.

4.9.3 Costs of Implementation and Annual Maintenance

Table 31 and Table 32 shows cost estimates for doing conservation tillage compared with conventional tillage. The blue vales are assumptions, the black values are calculated, and the red values are important calculated outputs.

Table 31. Cost estimates for doing conservation tillage compared with conventional tillage.

General Assumptions	**Value**	**Units**	**Notes**
Management Rate	35	$/hour	1
Unskilled Labor Rate	15	$/hour	2
Operating or Equipment Loan Real Interest Rate	0.03	decimal	3
Irrigation Season	20	weeks	4
Field Size	120	acres	5

Upfront, One-Time, Non-recurring Costs	**Value**	**Units**	**Notes**
Upfront Total Hardware Costs	5000	$	6
Equipment Lifespan	15	years	7
Upfront Management Labor	0	hours	8
Upfront Unskilled Labor	0	hours	9
Upfront Management Labor	0	$	10
Upfront Unskilled Labor	0	$	11
Total Labor	0	$	12
Annualized Upfront Labor	$0	$/year	13
Annualized Hardware Costs	$419	$/year	14
Total Annualized Upfront Costs	$419	$/year	15

Weekly Recurring Costs	**Value**	**Units**	**Notes**
Management effort in hours/week	0	hours/week	16

Labor effort in hours/week	0	hours/week	17
Ongoing Expenses	0	$/week	18
Total weekly Management Costs	0	$/year	19
Total weekly unskilled labor costs	0	$/year	20
Total weekly recurring costs per year	0	$/year	21

Annual Recurring Costs	**Value**	**Units**	**Notes**
Management effort hours/year	5	hours/year	22
Labor effort hours/year	-45	hours/year	23
Ongoing Expenses	-2370	$/year	24
Total annual management costs	175	$/year	25
Total annual unskilled labor costs	-675	$/year	26
Total Annual recurring costs per year	-2870	$/year	27

Total Costs per Year	**Value**	**Units**	**Notes**
Total of all three costs	($2,451)	$/year	28
Total Cost per Acre per Year	**($20.43)**	**$/acre/year**	29

Table 32. Notes, assumptions and explanations for doing conservation tillage compared with conventional tillage as shown above in Table 31.

Note	**Explanation**
1	This is either the rate that you pay a manager, or the opportunity cost of the owner/operator spending their time on this instead of something else.
2	From Utah State Agricultural Statistics (John Hilton & Gentillon, 2018) and 2018 NASS Irrigation Water Management Survey (NASS, 2018)
3	The interest rate on borrowed money to buy hardware, or the opportunity cost of money spent that would otherwise gain interest. Uses an estimated 5% interest rate from average farm and machinery loans and subtracting 2%, which is the average consumer price index (CPI) increase. We subtract CPI since it is assumed that wages and annual costs will increase at this rate and this puts comparisons for future recurring costs into today's dollars (Toth, 2017).
4	Number of weeks that the irrigation hardware will be used and thus have weekly recurring costs.
5	Assumes a fairly large field for equivalent comparison with other technologies.
6	No-till drill at $70k from online auctions. Assume costs can be spread across 4 pivots. Assume it replaces a drill that had to be purchased anyway for $50k. Difference is $20,000/4 fields = $5000/field.
7	Number of years before hardware has to be replaced and upfront costs are again incurred. Annual maintenance costs are included below.
8	Same upfront management costs as conventional tillage.
9	Same upfront labor costs, or less than conventional tillage.

10	Management rate times the management hours
11	Unskilled rate times the unskilled hours
12	Upfront Unskilled + Management Costs
13	Annualized upfront labor costs using the lifespan term and the interest rate above.
14	Annualized equipment costs using the equipment lifespan and the operating or equipment loan interest rate.
15	Annualized Upfront Labor costs + Annualized Hardware Costs
16	Same management costs as conventional tillage
17	Less tractor driver time than conventional tillage. This is included in the annual recurring costs.
18	Similar or less than conventional tillage.
19	The weekly management costs x the number of weeks irrigating x the management cost rate.
20	The weekly unskilled labor costs x the number of weeks irrigating x the unskilled labor cost rate.
21	(Ongoing expenses x the number of weeks/year) + weekly management costs + unskilled labor costs.
22	Assume a little more setup/troubleshooting time than for conventional tillage.
23	This is the saved tractor driver time which is avoided by not plowing, discing, or harrowing. 15 hrs to till 120 acres x 3 passes.
24	Fuel Savings as compared to conventional tillage. Based on USDA-NRCS Energy Estimator (https://ecat.sc.egov.usda.gov/Fuel.aspx).
25	No different than the reference technology (MESA).
26	Unskilled rate times the unskilled hours
27	Ongoing expenses + annual management and unskilled labor costs.
28	Sum of all the above total values for upfront costs, annualized weekly recurring costs, and annual recurring costs.
29	Total of all costs divided by the estimated field acreage size.

4.9.4 Benefits/Drawbacks for grower, environment, labor

Conservation tillage:

- reduces erosion,
- reduces water runoff,
- reduces wind erosion,
- reduces nutrient volatilization,
- reduces the loss of stored soil moisture to evaporation (saves water),
- builds soil organic matter in the soil (carbon retention in the soil), and
- greatly reduces the use of fossil fuels in agriculture.

Some drawbacks of conservation tillage include:

- It requires the purchase and use of different tillage equipment,
- Reduces soil temperatures in the spring which can delay germination and crop development by a few days, and
- Can reduce seed germination compared to conventional tillage.

5.0 Conclusions and Recommendations

This document examines the historic, current and upcoming irrigation technologies and practices applicable to the State of Utah. Irrigators in the State continue to make steady improvements towards adopting technologies that enable them to both improve water use efficiency and improve overall crop productivity while protecting the environment. Recent trends show an increase in sprinkler adoption from 53 to 56% between 2013 and 2018 and a subsequent reduction in surface (furrow) irrigation. While Utah's adoption rate is below several western states, given the significant upfront costs associated with center pivot sprinkler systems (USDA NRCS estimate $75-80k resulting in a total annual operating cost of $144/acre), this 3% increase represents a considerable investment by the irrigation community.

The study examined technologies in relationship to water losses based on permanent "forever" losses versus temporary losses that could go into groundwater recharge or lagged stream return flows. Beyond or as an add-on to traditional center pivot sprinkler systems, there are several promising technologies that would result in better farm water management practices. Ranging from water spreading being the most economical to variable zone irrigation, these practices would enable irrigators to use water more effectively. However, except for water spreading and conservation tillage, most technologies will result in increased costs to the farmers.

The literature generally concludes that except for cases where irrigators are faced with supply shortages, economic and social incentives for water conservation are lacking. Legislative changes that would guarantee that water saved by implementing new irrigation technologies could be used by the adopters to irrigate new acreage would likely speed the rate of conversion. Barring some sort of economic incentive, water conservation efforts will likely occur only when droughts or climate induced shortages force irrigators into spending money to preserve yields.

A summary of the costs per acre per year for each technology and the estimated water that each technology might be able to conserve is provided in the table below (Table 33; Figure 73). Funding for demonstration projects or case studies may improve early adoption particularly in key watersheds where water is limiting. Specific recommendations are provided in the next section of this report (Section 5.1).

Table 33. Summary of the technology costs and potential gains.

Note Ref. #	Technology	Applicable to in UT (acres)	Effic. Gains (%)	Water Saved (in)	Max Water Conservable (acre-ft)	Estimated Cost/Acre/ Year	Cost/ Acre-in/ year
1	Variable Speed Irrigation	43,974	2	0.64	2,000	$ 7.33	$ 11.45
2	Variable Zone Irrigation	43,974	3	0.96	4,000	$ 26.36	$ 27.46
3	LEPA/LESA	270,608	18	5.76	130,000	$ 5.07	$ 0.88
4	Mobile Drip Irrigation	338,260	20	6.40	180,000	$ 18.99	$ 2.97
5	Soil Moisture Monitoring (Own)	885,976	15	4.80	354,000	$ 16.41	$ 3.42
6	Soil Moisture Monitoring (Rent)	885,976	15	4.80	354,000	$ 19.38	$ 4.04
7	ET-Based Irrigation Scheduling	885,976	15	4.80	354,000	$ 6.87	$ 1.43
8	Irrigation Automation	885,976	15	4.80	354,000	$ 34.00	$ 7.08
9	Deficit Irrigation - negating yield costs	1,063,171	20	6.40	567,000	$ 5.65	$ 0.88
10	Deficit Irrigation w/out water spreading	1,063,171	20	6.40	567,000	$ 56.05	$ 8.76
11	Deficit Irrigation with water spreading	1,063,171	20	6.40	567,000	$ (87.95)	$(13.74)
12	Tillage to reduce runoff (Dammer-Diker)	590,651	5	1.60	79,000	$ 10.59	$ 6.62
13	Conservation Tillage	590,651	8	2.56	126,000	$ (20.43)	$ (7.98)

Table 33. Notes related to Table 32 above.

Note #	Notes	Reference System	Reduced Losses Primarily From:	Other (non water conservation) Environmental Benefits	Primary Drawback	Energy savings?	Help during peak demand July/August?	Notes on acreage assumptions (affects total acre-ft of water conservable)
1	Assumes a pivot that can vary it's speed throughout the field.	Uniform Irrigation	Deep percolation	Less nutrient/pesticide leaching.	Very expensive, little savings in arid areas.	Small	No	Assumed that VRI can get 1 inch of water reduction on 13% (similar to Nebraska) of center pivot fields in Utah.
2	Assumes a pivot that can vary the flow rate from banks of sprinklers.	Uniform Irrigation	Deep percolation	Less nutrient/pesticide leaching.	Very expensive, little savings in arid areas.	Small	No	Assumed that VRI can get 1 inch of water reduction on 13% (similar to Nebraska) of center pivot fields in Utah.
3	Runoff can be a problem. Biggest savings during times of greatest shortages.	MESA Center Pivots	Evaporation	Lower pumping energy costs.	Higher cost of sprinklers & hose.	Yes. Pump less water, at lower pressure.	Yes	Assumed that LEPA/LESA can be applied to 80% of center pivots in Utah
4	Use if water savings needed and runoff is a problem. Biggest savings during times of greatest shortages.	MESA Center Pivots	Evaporation	Lower pumping energy costs.	High cost of installation, hoses, and filtration systems.	Yes. Pump less water, lower pressure.	Yes	Assumed that MDI can be applied to all center pivot irrigated fields in Utah.
5	Does not include the benefits of improved yields!	Best-guess irrigation scheduling	Deep percolation	Less deep percolation. Lower pumping energy costs.	High cost of equipment and management.	Usually pump less water.	No	90% of farms don't do it (NASS, 2018). Bigger farms tend to do it more than smaller farms so we used that 75% of the total acreage.
6	Does not include the benefits of improved yields!	Best-guess irrigation scheduling	Deep percolation	Less deep percolation. Lower pumping energy costs.	High cost of equipment and management.	Usually pump less water.	No	90% of farms don't do it (NASS, 2018). Bigger farms tend to do it more than smaller farms so we used that 75% of the total acreage.
7	Does not include the benefits of improved yields!	Best-guess irrigation scheduling	Deep percolation	Less deep percolation. Lower pumping energy costs.	Requires Management Time and Attention.	Usually pump less water.	No	90% of farms don't do it (NASS, 2018). Bigger farms tend to do it more than smaller farms so we used that 75% of the total acreage.
8	Does not include the benefits of improved yields!	Best-guess irrigation scheduling	Deep percolation	Less deep percolation. Lower pumping energy costs.	High cost of engineering.	Usually pump less water.	No	90% of farms don't do it (NASS, 2018). Bigger farms tend to do it more than smaller farms so we used that 75% of the total acreage.
9	Deficit irrigation costs without considering yield losses to the grower	Full irrigation	Deep Percolation, ET	Lower pumping energy costs.	Growers won't do this unless forced.	Yes. Pump less water.	Yes	Assume that 90% of acres in Utah can save water using deficit irrigation (are not already doing it).
10	Deficit irrigation estimating yield losses to the grower.	Full irrigation	Deep Percolation, ET	Lower pumping energy costs.	Growers won't do this unless forced.	Yes. Pump less water.	Yes	Assume that 90% of acres in Utah can save water using deficit irrigation (are not already doing it).
11	Deficit irrigation allowing the grower to spread the saved water to irrigate additional acreage.	Full irrigation	Deep Percolation, ET	Lower pumping energy costs. Expect there to be a net increase in agricultural production.	Growers want to do this. Requires changing laws.	No. Grower will pump all the water.	Yes	Assume that 90% of acres in Utah can save water using deficit irrigation (are not already doing it).
12	Increases soil surface storage.	Conventional tillage.	Runoff. Fewer pivot passes.	Less off-field movement of sediment, fertilizers, and pesticides.	Extra steps in planting and field preparation.	Yes. Pump less water.	No	Assume it's applicable to 1/2 of the total irrigated acreage.
13	Increases soil surface storage. Reduces soil evaporation.	Conventional (full) tillage	Runoff. Soil evaporation. Fewer passes = less evaporation.	Increased carbon sequestration. Less fuel use. Less runoff and erosion. Improved water quality. Increased Water Use efficiency	New tillage equipment required. Cooler soils in the spring = delayed growth. Increased herbicide use.	Yes. Pump less water.	Yes	Assume it's applicable to 1/2 of the total irrigated acreage.

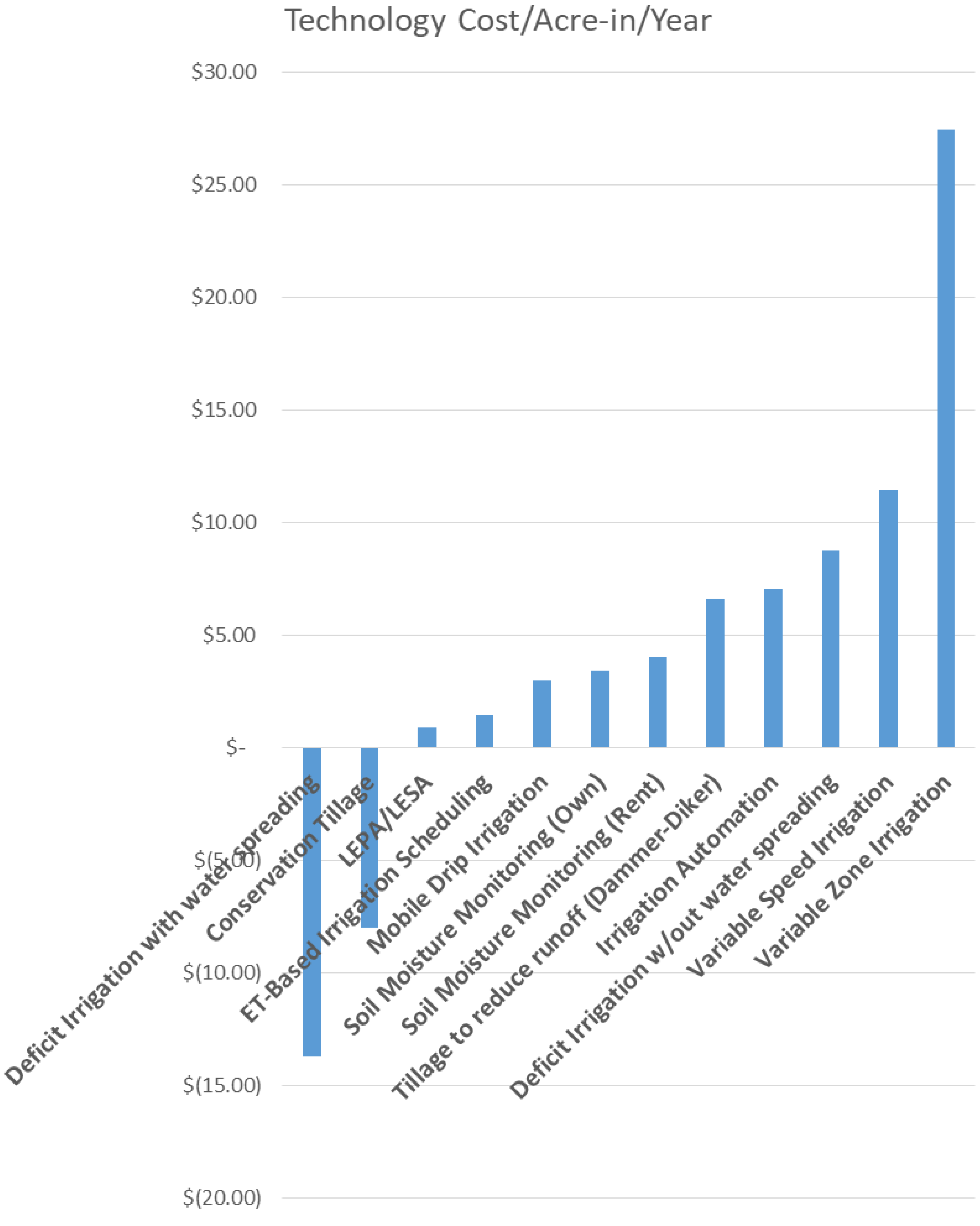


Figure 73. A summary of the estimated costs per acre-in of water conserved per year for each technology (lower is better).

5.1 Recommendations

Ineffective Conservation Programs of the Past

There are limited publications on past public water conservation programs titled "Our Failures" or "How I Wasted Your Money." Instead much is learned from reading through the lines, interpreting results, and from personal interactions and communication. Many of the programs that sounded attractive when they were funded, had lower to no water savings and often came with high costs such as variable rate (precision) irrigation systems. Other programs failed to take into account what actually motivates individuals including: limiting mental and physical stress, status and prestige or the *cool* factor, and money (which generally gets eventually used to buy the first two). For example asking farmers to learn and follow a lot of additional steps that don't have a clearly measurable benefit for them, and may have a time, mental energy, or capital cost without compensating or incentivizing them will not have staying power outside of the social pressure from the person trying to implement the program. It may be possible to creatively use existing social organizations (clubs, church programs, etc.) to allow farmers to show-case their improvements and talk about the benefits/frustrations of these. This may improve their status and incentivize or educate other growers (the *that's-cool* factor).

In particular, irrigation scheduling programs seldom persist even though the ease of use for these has increased over time. Simple lessons that they learn through using these irrigation scheduling programs such as "I've been over-irrigating in the spring" do persist however. To this end, very simple and rough tools (such as a 3x5 card containing a table of the number of irrigations/week by month) are usually more effective in the long run than sophisticated computer models, especially if the computer models require information that they don't know such as the soil's water holding capacity. Programs that convert the system completely or use a different technology (converting sprinkle to drip or MESA to LESA for example) do persist and have long-lasting impacts.

Continue support for irrigation management education and demonstration projects

Knowledge is power and helping growers understand how to get the most out of their limited irrigation water can help them save water, save energy, and make more money for their families and communities. This can include topics such as no-till or strip-till, irrigation scheduling, deficit irrigation, interpreting and responding to soil moisture measurement data, the proper use of the various irrigation technologies, etc. Train-the-trainer events that target conservation district personnel, county-based extension educators, irrigation equipment dealers, and influential growers are especially effective. Focusing on the teaching the economics of these practices can be particularly effective. If they are not economical, be honest about it!

Prioritize the 'biggest bang for the buck'.

Figure 63 can be used as a guide to which irrigation technologies have the potential to actually make growers more money, and which ones have the potential to save the greatest amount of water for the lowest costs. These include some fairly easy wins such as using no-till or strip-till, lowering pivot sprinkler drops as close to the ground as practical, and using ET or soil-moisture-based irrigation scheduling. In Utah, variable rate irrigation systems due to variable soils is unlikely to save significant amounts of water.

Continue to educate and demonstrate No-till and Strip-till

The labor, reduced tractor time, fuel savings, water savings, and soil-building benefits of these technologies are a win-win for everyone.

Move towards on-demand water delivery.

Invest or cost-share on infrastructure that allows irrigation districts and water suppliers to move towards being able to supply on-demand water. Usually this requires in-system water storage (re-regulation reservoirs or ponds), automatic supervisory control and data acquisition systems (SCADA), and larger designed delivery capacities. Moving towards allowing growers to use their allocated water, when, and at the flow rates they prefer is greatly increases their ability to effectively and efficiently manage their irrigation water.

Good irrigation scheduling requires a flexible irrigation delivery system. Deficit irrigation scheduling requires really good irrigation scheduling and management. Turn-based water delivery necessitates less ideal irrigation management. Water users may not have water when they need it, and have to take water when they don't need it, or maybe only need a portion of it. Also requiring long notifications for water delivery also limits an irrigator's ability to irrigate at the proper times and amounts.

Expanded and more flexible irrigation water delivery systems also help make deficit irrigation systems possible. These systems also allow more effective soil water replenishment in between forage cutting, curing, baling, and removal from the field.

Allow Water Spreading

This means allowing them to use conserved water, or at least a portion of it, to irrigate additional acreage. Allowing growers to use all of the water that is allocated to them will encourage maximum beneficial use of the state’s water resources. This is not a water conservation practice as the growers will use *all* of the water allocated to them. But it will incentivize maximum water use efficiency (crop per drop). The growers will usually prove themselves to be resourceful and innovative in finding ways to maximize their production. This will increase their net profits and thus strengthen the economies of their rural communities and of the state as a whole.

Surface irrigation isn’t always bad

Surface irrigation is inefficient because a lower percentage of the water that flows onto the field is stored in the root zone. This is less ideal for irrigation water delivery and timing. However, most of the lost water (deep percolation and runoff) is eventually recoverable and may actually be beneficial in the long term (recharges aquifers, runoff can be irrigated with downstream or it can help create wildlife habitat). Surface irrigation may be the ideal and most efficient irrigation system for flat, saline, and high clay-content soils.

Move center pivot sprinklers as close the ground as possible.

This reduces large amounts of water losses to wind drift and evaporation. Center pivots should be converted to LEPA, LESA, or MDI as money permits or water shortage pressures motivate. This should be considered especially in arid and windy areas. The infiltration problems associated with it can be mitigated by speeding the pivot up slightly. These technologies save the most water and energy in the middle of the summer when there is the greatest water needs, when many crops are most sensitive to water stress, and when there are the greatest shortages of water and energy.

Avoid big guns when possible

Big guns carts, and big guns on the ends of center pivots are inefficient and not very uniform, especially when affected by Utah wind. Almost all of the losses are 'forever' losses. Hand lines and wheel lines are less ideal for similar reasons.

Encourage urban water users to be more efficient

This can be done by cost-sharing on smart irrigation controllers for urban home and garden irrigators (irrigation automation). This can also be done by working to demonstrate the potential beauty and ease-of-care and care-for-the-planet virtue signaling of xeriscaping.

Drip Irrigation

Although drip irrigation is a relatively high cost way to irrigate, the costs can often be justified for high value crops. This is especially the case for vegetables when using drip irrigation leads to improved crop quality and size-uniformity. With drip irrigation many growers are able to get a larger percentage of their field's production to be the ideal size and quality that results in better prices. (USDA, 2020b)

Get Good Irrigation System Designs!

Many irrigation systems were designed by the growers or by someone who was not very knowledgeable or was inexperienced. These systems create uniformity and efficiency problems that can persist for 30-40 years. For example over-designing a system such that it applies more water than the soil can hold in a 12 or 24 hour set means that water will be lost to deep percolation at every irrigation event since growers are seldom interested in moving irrigation sets at odd hours. Over designed systems also require the grower to be better irrigation schedulers to shut them off at appropriate times to avoid over irrigating. Under-designed irrigation systems are not able to meet crop water demands and result in yield losses. Growers should be encouraged to use certified irrigation designers (CID) who are certified through the irrigation association as someone who knows what they are doing and have education, experience, and continuing education requirements. Commissioning a study to find appropriate irrigation design capacities (gpm/acre) for different crops in different areas of the state will greatly aid these irrigation system designers to create appropriate irrigation systems to the crop and area.

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