

Utah State University

DigitalCommons@USU

---

All Graduate Theses and Dissertations

Graduate Studies

---

5-2023

## Practical Improvements for Pivot and Surface Irrigation

Jonathan A. Holt  
*Utah State University*

Follow this and additional works at: <https://digitalcommons.usu.edu/etd>



Part of the [Earth Sciences Commons](#), [Environmental Sciences Commons](#), and the [Plant Sciences Commons](#)

---

### Recommended Citation

Holt, Jonathan A., "Practical Improvements for Pivot and Surface Irrigation" (2023). *All Graduate Theses and Dissertations*. 8742.

<https://digitalcommons.usu.edu/etd/8742>

This Dissertation is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact [digitalcommons@usu.edu](mailto:digitalcommons@usu.edu).



PRACTICAL IMPROVEMENTS FOR PIVOT AND SURFACE IRRIGATION

by

Jonathan A. Holt

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Plant Science

Approved:

---

Matt Yost, Ph.D.  
Major Professor

---

J. Earl Creech Ph.D.  
Committee Member

---

Burdette Barker, Ph.D.  
Committee Member

---

Grant Cardon, Ph.D.  
Committee Member

---

Alfonso Torres, Ph.D.  
Committee Member

---

D. Richard Cutler, Ph.D.  
Vice Provost of Graduate  
Studies

UTAH STATE UNIVERSITY  
Logan, Utah

2023

Copyright © Jonathan Holt 2023

All Rights Reserved

## ABSTRACT

## Practical Improvements for Pivot and Surface Irrigation

by

Jonathan A. Holt, Doctor of Philosophy

Utah State University, 2023

Major Professor: Dr. Matt Yost  
Department: Plant Soils and Climate

Irrigation is critical to meeting global food and fiber demands. Optimizing agricultural irrigation may help sustain production levels, while reducing its demand for water. This research evaluated precision sprinklers and drip irrigation for pivots, five pivot track mitigation tools, three scientific irrigation scheduling (SIS) methods, sensors for surface irrigation cutoff, and automating surface systems to implement surge irrigation. With pivots and surface irrigation being the most common methods for irrigation in the West, small improvements from these tools could result in significant water savings.

Low energy precision application (LEPA) sprinklers and mobile drip irrigation (MDI) were tested on two pivots. LEPA did not often maintain yield, even with similar application amounts to the mid elevation sprinkler application (MESA) control. MDI reduced yield by 6 – 25% in 2018, while applying half as much water as MESA. In following years, MDI rarely maintained yield, even when applying more than MESA. For

LEPA and MDI to maintain yield with less water, the correct situations and proper adaptations must be carefully chosen.

With the intent to improve pivot wheel tracks, installing LEPA around the pivot tower was the best of five tested methods, reducing track depths by 47 – 63% in one year. Adapting the correct method to field conditions and position on the pivot can result in shallower wheel tracks without sacrificing yield.

The use of soil moisture sensors, a commercial irrigation scheduler, and a free irrigation scheduler to determine irrigation amounts, were compared with the rates chosen by farmers. At some farms, the SIS methods maintained yield with 10-15% less irrigation. These benefits were usually when precipitation was high, which the SIS methods accounted for well.

Surface irrigators found that sensors helped reduce irrigation application by correctly timing the cutoff, saving them time, water, and money. Automation to implement surge irrigation increased irrigation use efficiency by 43% the first year, but had less drastic results in the final year, likely due to the severity of an ongoing drought. These collective results demonstrate that simple water optimization techniques could reduce irrigation diversions by 15 and possibly up to 25% or more in some cases.

(160 pages)

## PUBLIC ABSTRACT

### Practical Improvements for Pivot and Surface Irrigation

Jonathan Holt

Irrigation is critical to meeting global food and fiber demands. Optimizing agricultural irrigation may help sustain production levels, while reducing its demand for water. This research evaluated precision sprinklers and drip irrigation for pivots, five pivot track mitigation tools, three scientific irrigation scheduling (SIS) methods, sensors for surface irrigation cutoff, and automating surface systems to implement surge irrigation. With pivots and surface irrigation being the most common methods for irrigation in the West, small improvements from these tools could result in significant water savings.

Low energy precision application (LEPA) sprinklers and mobile drip irrigation (MDI) were tested on two pivots. LEPA did not often maintain yield, even with similar application amounts to the mid elevation sprinkler application (MESA) control. MDI reduced yield by 6 – 25% in 2018, while applying half as much water as MESA. In following years, MDI rarely maintained yield, even when applying more than MESA. For LEPA and MDI to maintain yield with less water, the correct situations and proper adaptations must be carefully chosen.

With the intent to improve pivot wheel tracks, installing LEPA around the pivot tower was the best of five tested methods, reducing track depths by 47 – 63% in one year. Adapting the correct method to field conditions and position on the pivot can result in shallower wheel tracks without sacrificing yield.

The use of soil moisture sensors, a commercial irrigation scheduler, and a free irrigation scheduler to determine irrigation amounts, were compared with the rates chosen by farmers. At some farms, the SIS methods maintained yield with 10-15% less irrigation. These benefits were usually when precipitation was high, which the SIS methods accounted for well.

Surface irrigators found that sensors helped reduce irrigation application by correctly timing the cutoff, saving them time, water, and money. Automation to implement surge irrigation increased irrigation use efficiency by 43% the first year, but had less drastic results in the final year, likely due to the severity of an ongoing drought. These collective results demonstrate that simple water optimization techniques could reduce irrigation diversions by 15 and possibly up to 25% or more in some cases.

## ACKNOWLEDGMENTS

I am filled with gratitude to God and the good people who have supported me through everything it has taken to complete this degree. My sweet wife, my supportive parents and family, my friends and colleagues near and far: you are my giants. Thank you for being in my life and this grad school journey.

Many thanks to Dr. Matt Yost and my committee for being wonderful to work with and learn from. I would also like to acknowledge Utah State University Extension, The National Alfalfa & Forage Alliance, and the Natural Resources Conservation Service of the U.S. Department of Agriculture for making this important work possible through their funding. Thank you.

Jonathan A. Holt



## CONTENTS

ABSTRACT.....	iii
PUBLIC ABSTRACT .....	v
ACKNOWLEDGMENTS .....	vii
LIST OF TABLES .....	xi
LIST OF FIGURES .....	xiv
CHAPTER 1 .....	1
INTRODUCTION .....	1
CHAPTER 2 .....	4
OPTIMIZING IRRIGATION WITH SPRINKLER PACKAGES REQUIRES CAREFUL SELECTION AND ADAPTATION .....	4
2.1 INTRODUCTION.....	4
2.2 MATERIALS AND METHODS .....	7
2.2.1 Site Characteristics.....	8
2.2.2 Pivot Sprinkler Packages .....	9
2.2.3 Alfalfa Analysis .....	10
2.2.4 Silage Corn Analysis.....	11
2.3 Statistical Analysis.....	12
2.4 RESULTS AND DISCUSSION.....	13
2.4.1 LEPA and MESA Comparison .....	13
2.4.2 MDI and MESA Comparison .....	17
2.4.3 LEPA, MDI, and MESA Comparison .....	19
2.4.4 Severe MDI Reduction in Alfalfa and Corn .....	21
2.4.5 CONCLUSIONS.....	24
CHAPTER 3 .....	36
IMPROVING PIVOT RUTS WITH SIMPLE SPRINKLER MODIFICATIONS.....	36
3.1 INTRODUCTION .....	36
3.2 MATERIALS AND METHODS.....	37
3.2.1 Site Characteristics.....	37
3.2.2 Sprinkler Equipment Approaches .....	38
3.2.3 Polyacrylamide Soil Conditioner.....	42

3.2.4 Experimental Design.....	42
3.3 CROP AND WHEEL TRACK MEASUREMENTS .....	43
3.3.1 Alfalfa Analysis .....	43
3.3.2 Silage Corn Analysis.....	44
3.3.3 Wheat Analysis .....	45
3.3.4 Wheel Track Depths .....	45
3.4 STATISTICAL ANALYSIS .....	46
3.5 RESULTS AND DISCUSSION.....	46
3.5.1 Advantage Booms in Multiple Crops .....	46
3.5.2 Various Track Management Options for Alfalfa.....	47
3.5.4 Various Track Management Options for Silage Corn .....	51
3.5.5 CONCLUSIONS.....	55
CHAPTER 4 .....	73
SOIL MOISTURE SENSORS AND IRRIGATION SCHEDULING PROGRAMS ARE A HELPFUL RESOURCE FOR IRRIGATORS .....	73
4.1 INTRODUCTION .....	73
4.2 MATERIALS AND METHODS.....	76
4.2.1 Site Characteristics.....	76
4.2.2 Irrigation Scheduling Approaches .....	77
4.3 CROP YIELD AND QUALITY.....	80
4.3.1 Alfalfa Analysis .....	81
4.4 STATISTICAL ANALYSIS .....	82
4.5 RESULTS AND DISCUSSION.....	82
4.5.1 Soil Moisture Sensors .....	82
4.5.2 Commercial Irrigation Scheduler.....	84
4.5.3 Irrigation Scheduler Mobile.....	86
4.5.4 Contrasting the Scheduling Approaches .....	88
4.5.5 Conclusions.....	89
CHAPTER 5 .....	98
SIMPLE TO COMPLEX: TOOLS TO IMPROVE SURFACE IRRIGATION .....	98
5.1 INTRODUCTION .....	98
5.2 MATERIALS AND METHODS.....	101
5.2.1 Site Characteristics.....	101

5.2.2 Irrigation Reduction Scenario .....	101
5.2.2 A Comparison of Before and After Automation for Surge Capabilities ...	102
5.2.3 Irrigation Advance Sensor .....	103
5.3 CROP YIELD AND QUALITY.....	105
5.3.1 Alfalfa Analysis .....	105
5.4 STATISTICAL ANALYSIS .....	106
5.5 RESULTS AND DISCUSSION.....	107
5.5.1 Irrigation Reduction Scenario .....	107
5.5.2 A Comparison of Before and After Automation for Surge Capabilities ...	110
5.5.3 Irrigation Advance Sensor .....	112
CHAPTER 6 .....	121
CONCLUSIONS.....	121
REFERENCES .....	127
CHAPTER II.....	127
CHAPTER III .....	130
CHAPTER IV .....	132
CHAPTER V .....	135
CURRICULUM VITAE.....	139

## LIST OF TABLES

	Page
TABLE 2.1 Site properties for irrigation trials in Cedar City and Elberta, Utah, from 2018 to 2020, including nearest town, year, coordinates, dominant soil texture, slope, drainage classification, irrigation packages tested, and crop .....	26
TABLE 2.2 Sprinkler package designed rates, the true measured output of each treatment, and seasonal accumulative irrigation applied at the Cedar City and Elberta sites from 2018-2020 .....	27
TABLE 2.3 Significance of F tests for the fixed effects of year and treatment and their interaction on yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility (48-h); In Vitro Dry Matter Digestibility, IVDMD; TDN, total digestible nutrients; RFQ, relative forage quality; and starch) at the Cedar City and Elberta sites for alfalfa and silage corn, respectively. Differences were considered statistically significant when $P < 0.05$ .....	28
TABLE 2.4 Alfalfa yield and quality parameters [CP, Crude Protein; NDF, Neutral Detergent Fiber; NDFD, Neutral Detergent Fiber Digestibility (48hr); In Vitro Dry Matter Digestibility, IVDMD; TDN, Total Digestible Nutrients; RFQ, Relative Forage Quality] for each system at the Cedar City site in the full and reduced irrigation rates. Mean separations were conducted by system and parameter and significant differences at $P < 0.05$ are denoted with lowercase letters following means .....	29
TABLE 2.5 Silage corn yield and quality parameters [CP, Crude Protein; NDF, Neutral Detergent Fiber; NDFD, Neutral Detergent Fiber Digestibility (48-h); starch; TDN, Total Digestible Nutrients] for each system at the Elberta site in the full and reduced irrigation rates. Mean separations were conducted by system and parameter and significant differences at $P < 0.05$ are denoted with the lowercase letters following means .....	30
TABLE 2.6 The percentage of occurrences when low-elevation precision application (LEPA) and mobile drip irrigation (MDI) at reduced irrigation rates had significantly different ( $P < 0.05$ ) soil water tension than mid-elevation spray application (MESA) at the full irrigation rate the day before irrigation events. Differences were measured from three replicates of four depths within each system, from the 2018 and 2019 growing seasons in Cedar City and Elberta, Utah .....	31
TABLE 2.7 The percentage of occurrences when low-elevation precision application (LEPA) and mobile drip irrigation (MDI) at reduced irrigation rates had significantly different ( $P < 0.05$ ) soil water tension than mid-elevation spray application (MESA) at the full irrigation rate the day after irrigation events. Differences were measured from three replicates of four depths within each system, from the 2018 and 2019 growing seasons in Cedar City and Elberta, Utah .....	32

TABLE 3.1 Site properties for nine on-farm trials in Utah and Idaho from 2020 to 2022, including nearest town, year, coordinates, soil texture, slope, and drainage .....	57
TABLE 3.2 Site properties for nine on-farm pivot wheel rut trials in Utah and Idaho from 2020 to 2022, including nearest town, crop, methods tested, and pivot motion .....	59
TABLE 3.3 Significance of F tests for the fixed effect of pivot track treatment on crop yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; RFQ, relative forage quality, starch, and test weight), as well as depth of wheel track for sites with only one year (Nibley, Cornish 1, 2, and 3). Differences were considered statistically significant when $P < 0.05$ .....	60
TABLE 3.4 Significance of F tests for the fixed effects of year and treatment, and their interaction on alfalfa yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; and RFQ, relative forage quality), as well as depth of wheel track at the Cornish 4 and Wellsville sites. Differences were considered statistically significant when $P < 0.05$ .....	60
TABLE 3.5 Average alfalfa dry matter yield, alfalfa RFQ (relative forage quality), and wheel track depths at the Cornish 4 (2021-2022), Nibley (2020), and Wellsville (2021-2022) sites, as affected by wheel track treatments. Mean separations were conducted at $P < 0.05$ by variable and by site and are denoted by letters following means .....	61
TABLE 3.6 Significance of F tests for the fixed effects of year, farm, and pivot track treatment, and their interaction on silage corn yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; and starch), as well as depth of wheel track at the Burley, ID sites. Differences were considered statistically significant when $P < 0.05$ .....	62
TABLE 3.7 Impact of pivot track methods on silage corn dry matter yield, NDFD (neutral detergent fiber digestibility 48-h), and wheel track depths at two sites near Burley, ID in 2021 and 2022. Letters of significance denote a difference when $P < 0.05$ .....	63
TABLE 4.1 Site properties for irrigation scheduling trials in Utah from 2018 to 2020, including nearest town, year, coordinates, dominant soil texture, and slope.....	91
TABLE 4.2 Significant differences of F tests for the fixed effect of scheduling method on alfalfa yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; and RFQ, relative forage quality) from 47 measured harvests during 2019-2021 in central Utah. Differences were considered statistically significant when $P < 0.05$ and only significant differences are shown for brevity .....	92

TABLE 5.1 Site properties for three on-farm trials in Utah from 2020 to 2022, including nearest town, year, coordinates, soil texture, and the type of experiment conducted .....	114
TABLE 5.2 Year, cut, irrigation applied for the individual harvest, alfalfa dry matter (DM) yield, and crude protein (CP) for the single and double irrigation treatments at the Delta, UT site. Mean separations were conducted at $P < 0.05$ and differences are denoted by the accompanying letters .....	114
TABLE 5.3 Significance of F tests, at the Delta, UT site, for the fixed effects of cut, treatment, and year, and their interaction on alfalfa dry matter yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; RFQ, relative forage quality; and starch). Differences that were considered statistically significant when $P < 0.05$ are bolded .....	115
TABLE 5.4 Significance of F tests, at the Corinne, UT site, for the fixed effects of position (head, middle, or tail of field) and year, and their interaction on alfalfa yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility (48-h); In Vitro Dry Matter Digestibility, IVTDMD; TDN, total digestible nutrients; RFQ, relative forage quality). Differences that were considered statistically significant when $P < 0.05$ are bolded.....	115
TABLE 5.5 Seasonal irrigation amounts, dry matter alfalfa yield, and irrigation use efficiency (IUE) for the Corinne site from 2020-2022. Letters following means represent significant differences when $P < 0.05$ .....	115

## LIST OF FIGURES

	Page
Figure 2.1 Cumulative growing degree days (GDD) and precipitation for Cedar City, and Elberta. GDD were calculated from the minimum and maximum air temperatures and adjusted to 5°C and 30°C, and 10°C and 30°C, respectively. The 30-yr normal (1981-2010) is shown for reference.....	33
Figure 2.2 Placement of MESA (mid elevation sprinkler application) at a full rate, MDI (mobile drip irrigation) at a full and reduced rate, and LEPA (low energy precision application) at a full and reduced rate on the irrigation pivot at the Cedar City site.....	33
Figure 2.3 Placement of MESA (mid elevation sprinkler application) at a full rate, MDI (mobile drip irrigation) at a full and reduced rate, and LEPA (low energy precision application) at a full and reduced rate on the irrigation pivot at the Elberta site.....	34
Figure 2.4 Plot Map from the Cedar City site displaying harvest areas irrigated by MESA (mid elevation sprinkler application), MDI (mobile drip irrigation), and LEPA (low energy precision application), including areas of reduced flow. Plots marked “BC” were not included in this study.....	34
Figure 2.5 Plot Map from the Elberta site displaying harvest areas irrigated by MESA (mid elevation sprinkler application), MDI (mobile drip irrigation), and LEPA (low energy precision application), including areas of reduced flow. Plots marked “BC” were not included in this study.....	35
FIGURE 3.1 Cumulative monthly precipitation and seasonal growing degree days (GDD) totals for Burley, Cornish, and combined Nibley and Wellsville sites (Logan). GDD calculations were adjusted for corn for Burley, and alfalfa for Cornish and Logan. The 30-yr normals (1991-2020) are shown for reference.....	64
FIGURE 3.2 A depiction of the double part circle method as illustrated from above the pivot tower. Blue shapes represent the irrigation water emitted at the outlets nearest to the pivot tower.....	65
FIGURE 3.3 Two part circle sprinklers mounted to a PVC pipe manifold, attached to a pivot tower, as part of the double part circle method.....	65
FIGURE 3.4 A depiction of the low energy precision application (LEPA) method as illustrated from above the pivot tower. Blue shapes represent the irrigation water emitted at the outlets nearest to the pivot tower. In this case, one sprinkler per side was replaced with three sprinklers.....	66

FIGURE 3.5 Low energy precision application (LEPA) style sprinklers plumbed from the outlet closest to each side of the pivot tower, where mid elevation sprinkler application (MESA) sprinklers were previously mounted.....	66
FIGURE 3.6 A depiction of the “Komet Advantage” method as illustrated from above the pivot tower. Blue shapes represent the irrigation water emitted at the outlets nearest to the pivot tower.....	67
FIGURE 3.7 The “Komet Advantage” method installed on a pivot.....	67
FIGURE 3.8 A depiction of the single suspended boom method as illustrated from above the pivot tower. The blue circle represents the wetting area of the sprinkler attached to the boom, and the pivot would be travelling downward in this example so irrigation is applied behind the pivot .....	68
FIGURE 3.9 A single-boom attached to a pivot, intended to direct water behind the direction of travel.....	68
FIGURE 3.10 A polyacrylamide (PAM) log inside a plastic mesh sack is hung above the wheel track, so as irrigation water contacts the PAM, the log dissolves and enters the wheel track .....	69
FIGURE 3.11 Track depths were measured from the bottom of the wheel track up to a 1 m long plank, which was suspended above the soil surface on two 0.15 m legs to avoid soil ridges alongside the wheel track .....	70
FIGURE 3.12 Alfalfa DM (dry matter) yield and pivot wheel track depth responses to the MESA (mid elevation sprinkler application) control, single boom, LEPA (low energy precision application), PAM (polyacrylamide), and PC (double part circle) methods at the Nibley, Cornish 4, and Wellsville sites .....	71
FIGURE 3.13 Silage corn DM (dry matter) yield and pivot wheel track depth responses to the MESA (mid elevation sprinkler application) control, single boom, LEPA (low energy precision application), PAM (polyacrylamide), and PC (double part circle) methods at the two sites near Burley, ID.....	72
FIGURE 4.1 Cumulative precipitation and growing degree days (GDD) for 10 on-farm trials in Utah, gathered from the closest public weather stations to each site (some had the same station). GDD were calculated from the minimum and maximum air temperatures and adjusted to 5°C and 30°C. The 30 yr normal (1991-2020) is shown for reference .....	94



FIGURE 4.2 Total seasonal irrigation application (mm) for the farmer control and three other irrigation scheduling treatments, averaged across farms for the 2019-2021 growing seasons .....	95
FIGURE 4.3 Dry matter (DM) alfalfa yield results for the 5 of 47 measured harvests where yield was significantly ( $P < 0.05$ ) impacted by scheduling method. Mean separations were conducted at $P < 0.05$ by harvest and differences are denoted by letters above each bar.....	96
FIGURE 4.4 Relative forage quality (RFQ) measurements for 6 of 47 measured harvests where RFQ was significantly ( $P < 0.05$ ) impacted by scheduling method. Mean separations were conducted at $P < 0.05$ by harvest and differences are denoted by letters above each bar.....	97
FIGURE 5.1 Cumulative precipitation and growing degree days (GDD) for the Corinne and Delta, Utah sites. GDD were calculated from the minimum and maximum air temperatures and adjusted to 5°C and 30°C. The 30 yr normal (1991-2020) is shown for reference .....	116
FIGURE 5.2 Irrigation advance sensor developed by Commercial Business Radio.....	117
FIGURE 5.3 “Wet Stake” irrigation advance sensor developed by Prescott Farm Innovations.....	117
FIGURE 5.4 Volumetric water content (VWC) in the single and double irrigated sets, from three sensor depths (150, 460, and 1070 mm) during the 2020-2021 alfalfa growing seasons in Delta, UT.....	118
FIGURE 5.5 Alfalfa dry matter (DM) yield for the head, middle, and tail of the Corinne site before automation and implementation of surge irrigation (2020) and after (2021-2022). Mean separations were conducted at $P < 0.05$ , with yield differences, within each year, denoted by the letters above each bar. Error bars are the standard errors.....	119
FIGURE 5.6 Volumetric water content (VWC) at the head, middle, and tail of the Corinne site at four sensor depths (150, 460, 1070, and 1680 mm) during the 2020-2022 alfalfa growing seasons .....	120

## CHAPTER 1

### INTRODUCTION

Irrigation is an important tool for meeting worldwide demands for food and fiber. Because of irrigation, farmers can multiply the productivity of their land, including producing crops in areas otherwise considered not arable. This often requires significant diversions of water. As droughts arise and populations grow, so does the demand for water. Optimizing agricultural irrigation may help sustain production levels, while reducing its demand for water.

To help advance water optimization and address water scarcity issues this dissertation has four chapters (chapters 2-5) that report four studies aimed at water management improvements in overhead sprinkler and surface irrigation systems. The second chapter of this dissertation covers research on optimizing overhead sprinkler systems. In Cedar City and Elberta, Utah, research was conducted from 2018 to 2020 to evaluate low energy precision application (LEPA) sprinklers and mobile drip irrigation (MDI). On pivots that were using the common mid elevation sprinkler application (MESA), LEPA and MDI were installed and designed to apply the same rate as MESA on a section of the pivot, and a reduced rate on another section. A great deal of research has been conducted with LEPA and MDI, often measuring ~15-20% higher efficiency than MESA. The intent of the reduced sections were to determine if the increased efficiencies of LEPA and MDI would enable them to maintain yield while applying less water.

Pivots can produce deep ruts that can disrupt irrigation uniformity, cause missed crop, and damage equipment. Chapter three of this dissertation presents research on

improving pivot ruts with simple sprinkler modifications. This research evaluated a manufacturer design using eight suspended booms around the pivot tower, a single-boom method used by local irrigation dealerships, LEPA, the use of four part circle sprinklers, and a soil conditioner called Polyacrylamide, for their ability to maintain yield beside the pivot track and create shallower tracks. This research was conducted on cooperating farmer's pivots in Utah and Idaho, from 2020-2022.

Many tools exist for improving irrigation scheduling but few studies have tested various approaches in a replicated way. Chapter four addresses this limitation and focuses on testing three approaches to scientific irrigation scheduling. In 2019, research began on 12 farms across central Utah to compare alfalfa (*Medicago sativa* L.) production from the irrigation application amounts prescribed by the cooperating farmers, and three scientific methods. These three methods were included a set of soil moisture sensors and a water balance spreadsheet, a commercial irrigation scheduler called FieldNET Advisor (Lindsay Corporation, Omaha, Nebraska, USA), and a free scheduler program called Irrigation Scheduler Mobile (Washington State University, Prosser, Washington, USA).

Surface irrigation is a common irrigation method in many parts of Utah and the Western United States. Efficiency of surface irrigation can be improved but few studies have evaluated how new technologies for surface irrigation impact water use and forage production. The fifth chapter of the dissertation covers the testing of new and simple tools to improve surface irrigation. In 2020, research began evaluating three tools for improving surface irrigation. The first tool was evaluated in Delta, Utah, where farmers commonly irrigate twice before the first alfalfa harvest of the year, and once before both second and third harvests. To determine what effects may be incurred if only a single

irrigation were applied prior to the first harvest of the year, part of a field received the traditional two irrigations, while another part was irrigated only once.

Another tool assessed was portable sensors that could be placed in the field to alert an irrigator when it was time to cutoff the water inflow. This research consisted of providing three cooperating farmers with the sensors at the beginning of the growing season and interviewing them after the season to learn about their experience and any water, labor, or monetary savings from the sensor.

The final tool evaluated for surface irrigation was the impact of automating a system and implementing surge irrigation. At Corinne, Utah, yield, crop quality, and soil moisture was measured near the top, middle, and bottom of the field. The field was irrigated manually in 2020, but was automated and using surge for the 2021 and 2022 growing seasons. In summary, this dissertation evaluated precision sprinklers and drip irrigation for pivots, five pivot track mitigation tools, three scientific irrigation scheduling (SIS) methods, sensors for surface irrigation cutoff, and automating surface systems to implement surge irrigation. With pivots and surface irrigation being the most common methods for irrigation in the West, small improvements from these tools could result in significant water savings.

## CHAPTER 2

### OPTIMIZING IRRIGATION WITH SPRINKLER PACKAGES REQUIRES CAREFUL SELECTION AND ADAPTATION

#### 2.1 INTRODUCTION

From 2012 to 2025, the estimated population growth of the earth is a billion people (US Census Bureau, 2021). Considering the mass of food consumed by the average person each day, this is a substantial increase in the demand on agriculture, and food is only one facet. Globally, the area of farmland has been consistently around 37% of total landmass. Within the United States, it has decreased about 4.5% between 1961 and 2018 (FAO, 2011). Many tools are helping agriculture to continue to sustain the demands of this growing population, without increasing the area used. One tool that has drastically improved crop yields is irrigation (Kukul & Irmak, 2019). In the United States, 54% of the total crop sales come from irrigated land, despite that area being comprised of less than 20% of the harvested cropland (USDA, 2021). One severe restriction to this crucial tool is drought, which, especially in recent years, has been affecting much of the western United States and other parts of the world (NOAA, 2022). With the potential for drought, as well as other competition for agricultural water, increasing the efficiency of water application may help irrigation to continue to be an important tool in meeting these growing demands.

In the western United States, the use of center pivots for irrigation is increasing. All along the top of the pivot are outlets where the water can be emitted, directly through pipe-mounted sprinklers, or routed down a hose and through a type of sprinkler or emitter chosen by the purchaser. A common sprinkler package chosen for pivots is called mid-

elevation sprinkler application (MESA). These sprinklers can be 2 – 6 m apart and are usually 1 – 2 m above the soil surface. They use a large wetting diameter (6 – 23 m) to achieve a uniform application, and have been designed to operate under low pressure, to produce large water droplets that reduced wind drift evaporative losses (WDEL) and pumping requirements. Field testing in central Texas (New & Fipps, 2000) reported a water application efficiency (WAE) of 90% for MESA sprinklers 1.5 – 2.1 m above the soil surface, meaning 90% of the water that leaves the nozzles enters the rootzone, while the rest is lost, primarily to WDEL. They noted that a light wind of 25 km h<sup>-1</sup> could reduce the WAE by 17%, and when winds reached 32 km h<sup>-1</sup>, efficiency reductions were over 30%. Other research from Texas reported a WAE of 78% for MESA (Amosson et al., 2011). Similar results were found more recently in eastern Washington, when Sarwar et al. (2019) measured WAE ranging from 75 – 85%, with changing WDEL throughout the season, ranging from 16 – 26%. Though there are small discrepancies among the studies, it is clear that MESA can have high WDEL, despite the sprinkler improvements that have taken place over the 19-year range of those studies.

In 1978, low energy precision application (LEPA) sprinkler packages were developed in Texas by Lyle & Bordovsky (1981). This was in response to limited water supplies and high energy prices that were impacting irrigated agriculture across the Texas plains. This style of sprinkler package has sprinklers spaced 0.75 – 1 m apart, and 0.3 – 0.6 m above the soil surface. Irrigation applications can be customized with several sprinkler attachments to soak, spray, fan, bubble, or rotate. The WAE of LEPA has been measured by researchers in Texas to be 95% (Amosson et al., 2011), and researchers in Georgia found it to be up to 98.4% (Oker et al., 2021). Bordovsky (2019) reviewed

several field studies during 1978-2018 from around the United States and found that when LEPA was compared to other styles of pivot sprinklers, it had its greatest impact on yields in situations of reduced flow. In the same study it was also noted that at a full irrigation rate, LEPA often decreased crop yields. Reduced yields at a full irrigation rate could be due to the concentration of water in small areas, which can easily exceed the infiltration rate of some soils, producing runoff or surface movement of water, soil, and nutrients (Peters et al., 2019). Because of this potential, LEPA is not recommended for fields with slopes exceeding 1% (Senninger Irrigation, 2018). Selecting the correct tillage can help mitigate runoff problems (Bordovsky, 2018), such as furrow-diking in row crops, and may help make LEPA a valuable tool for maintaining yield when water is limited.

Mobile drip irrigation (MDI) is another water application option for pivots. This technology has been around for nearly 50 years but has undergone many changes in the past decade. This system uses drip lines that are attached to rigid drops that are fixed to a cable system installed on the pivot. These cables hold the rigid drops in places, so that as the pivot moves around the field, the drip lines spacing retains its uniformity. The drip lines are often spaced 0.76 – 1 m apart, though spacing can be modified to conform to various cropping methods. These lines have pressure-regulating emitters that are evenly spaced. To compensate for the additional coverage area of the pivot circle, the drip lines progressively get longer as their distance from center increases. New advances allow the irrigator to “shift” the drip lines in an entire pivot span (distance between the wheeled towers) horizontally or vertically, to add precision to the application. For many cropping systems, MESA sprinklers are also required in addition to MDI for germination and

chemigation. Filtration of MDI is critical and requires the removal of finer contaminants than LEPA or MESA. High WAE has been measured in these systems, such as in Georgia, USA, when MDI had a WAE of 98.4% (Oker et al., 2020). In Kansas, MDI was compared with low elevation spray application (LESA) in a corn field trial where minisimeters measured 35% less WDEL losses with MDI (Kisekka et al., 2016). O'Shaughnessy & Colaizzi (2017) also conducted a corn field trial in Northern Texas, evaluating MDI, LESA, and LEPA. They measured similar yields across each method at full irrigation rates, as well as similar water use efficiency (WUE).

Many trials for LEPA and MDI exist. However, these studies are limited in their comparison, often comparing with another low elevation system and not MESA. Few, if any, studies exist that compare MESA, LEPA, and MDI together. Further, nearly all past studies of these systems have evaluated the performance of various systems at the same irrigation rates. If LEPA and MDI have greater WAE, less irrigation should be required. There has also been little research conducted with these systems in alfalfa (*Medicago Sativa* L.) and silage corn (*Zea Mays* L.), the two most important forage crops for many farmers in the western United States. Therefore, this study evaluated how these two pivot irrigation options at full and reduced application rates, and MESA at a full application rate, influenced silage corn and alfalfa yield and quality, and soil water tension. If LEPA or MDI can maintain crop yield and quality, as well as reduce soil water tension, they may be important tools for helping farmers keep production levels up, when drought or water scarcity threatens their ability to irrigate.

## **2.2 MATERIALS AND METHODS**



### 2.2.1 Site Characteristics

On-farm irrigation trials were established in Cedar City and Elberta, Utah in the spring of 2018 (Table 2.1). The Cedar City site was established alfalfa (planted in 2015) and remained alfalfa during the study. The pivot at this site was a seven-tower pivot, covering 51 ha. In Elberta, corn was grown for silage for 2018 and 2019. This field was irrigated by an eight-tower pivot, covering 50 ha, and, like the Cedar City pivot, was operated by the cooperating farmer. Soil classification and textural group were obtained from the University of California-Davis SoilWeb (O'Geen, 2020; Table 1), and the predominant soil type was loam soil in Cedar City and silt loam soil in Elberta. Weather data at both sites were obtained from the Utah Climate Center ([climate.usu.edu](http://climate.usu.edu), Logan, Utah, USA) and were used to calculate cumulative precipitation and growing degree days for the growing season of each crop. Corn and alfalfa growing degree days were calculated using base air temperatures of 10°C (Elmore et al., 2015) and 5°C (Noland & Wells, 2018), respectively, with an adjusted 30°C limit for both. Measured cumulative precipitation and degree days were compared with their respective 30-yr normals (1981-2010) provided by the National Oceanic and Atmospheric Administration ([noaa.gov](http://noaa.gov), Silver Spring, MD, USA) (Fig. 2.1).

At both sites, all management decisions were made by the cooperating farmers, including their irrigation management. Alfalfa and silage corn were managed for optimal production with fertilizers and herbicides where needed. In Elberta, the field was tilled to 200 mm deep using vertical tillage, prior to being planted to silage corn for both site years. No tillage occurred at Cedar City because it was an established alfalfa stand. The experimental design at both sites was a limited randomized block design, with four

replicates in each treatment. Plots were 5.3 to 6 m wide  $\times$  12 m long and located on a part of the field that was near an access road but outside end rows, to minimize damage to the cooperating farmers' crop. Plots were used to ensure yield measurements were taken at replicated locations year after year.

### **2.2.2 Pivot Sprinkler Packages**

The existing pivots at both research sites had MESA sprinkler packages. The second span from the end was replaced with MDI, and LEPA replaced the last span. In previous studies, these advanced-efficiency irrigation packages have all been measured to be 8 – 20% more efficient at getting the irrigation water into the rootzone (Amosson et al., 2011; Sarwar et al., 2019; Oker et al., 2021). Because of these measured efficiency improvements, it seemed feasible for LEPA or MDI to maintain yield with less water, due to less loss. To test this idea, one area on each span of LEPA and MDI had their target flow rates reduced by 20% by installing smaller nozzles, or shorter lengths of drip tubing in the MDI.

In 2019 during the second year of the study, minor changes were implemented to improve the study. In the MDI span at both sites, drip tubing was added to fix a flaw from the drip tube manufacturer, where emitters had over 30% less output than intended. This was determined mid-season in 2018, when flow measurements were taken from each system. It is important to note, for this study and similar research, that the designed output rates and the actual measured output of the sprinklers was often different, making a true comparison extremely difficult at a field scale due to potential confounding from these differences.

Soil water tension was monitored using Model 200SS Watermark (Irrometer

Company, Riverside, CA, USA) solid state electrical resistance sensors. These sensors contain a granular matrix covered by a hydrophilic retention cover inside a stainless-steel mesh body with plastic endcaps. Watermark 900m data loggers (Irrometer Company, Riverside, CA, USA) were used for logging water tension data every 4-h throughout the growing season. Sensors were placed in the soil at 300, 600, and 900 mm depths, in three replicates each of MESA and the reduced irrigation rates of LEPA and MDI systems. In Elberta, sensors were installed parallel, and in close proximity to the corn rows. At the Cedar City site, the sensors were installed parallel with the direction of field operations. Soil water tension values 24-h before each irrigation event were analyzed to evaluate the amount of drawdown between irrigation events, as well as 24-h after to assess the ability of the systems to fill the soil profile with moisture directly after irrigating.

### **2.2.3 Alfalfa Analysis**

In 2018 and 2019, Cedar City alfalfa plots were harvested with a walk-behind sickle-bar mower within 1-2 days before the cooperating farmer harvested the entire field. The center 7.3 m<sup>2</sup> of each plot was harvested at a cutting height similar to the cooperating farmer's usual harvest height of about 75 mm above the soil surface. In 2020, a different harvest technique was used to decrease the time required for each harvest. For the new technique, the cooperating farmer windrowed the field using the Global Positioning System (GPS) and autosteer in the swather. We selected a full windrow and collected and weighed the center 3 m of the windrow within each plot. This method increased the harvest area from 7.3 to 13.8 m<sup>2</sup>. Following either cutting technique, a subsample (about 100 g) was weighed in the field, dried in a forced-air oven at 60°C until constant mass, and used to determine moisture and calculate dry matter yield. Dried

subsamples were ground to pass through a 1mm sieve using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA). Ground samples were analyzed by near-infrared reflectance spectroscopy (NIRS) using a FOSS DS2500 F (Foss North America Inc., Eden Prairie, MN). The 2020 legume hay NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY) were used to estimate dry matter, ash, fat, crude protein (CP), neutral detergent fiber (NDF), neutral detergent fiber digestibility 48-h (NDFD), in vitro dry matter digestibility (IVDMD), total digestible nutrients (TDN) and relative forage quality (RFQ). The following two quality parameters were calculated:

$$\text{[Eq. 1] Total Digestible Nutrients (TDN)} = (100 - (\text{NDF} - 2 + \text{CP} + 2.5 + \text{Ash})) \times 0.98 + \text{CP} \times 0.93 + (\text{Fat} - 1) \times 0.97 \times 2.25 + (\text{NDF} - 2) \times \text{NDFD} / 100 - 7$$

$$\text{[Eq. 2] Relative Forage Quality (RFQ)} = (((0.012 \times 1350 / (\text{NDF} / 100) + (\text{NDFD} - 45) \times 0.374) / 1350 \times 100) \times \text{TDN} / 1.23$$

Yield measurements were taken at each alfalfa cutting. Total yield and average forage quality were calculated each year across all cuttings. This included three cuts in 2018, four in 2019, and four in 2020.

#### **2.2.4 Silage Corn Analysis**

Corn was hand harvested shortly before the cooperating farmer's harvest, when corn was at approximately 650 g kg<sup>-1</sup> moisture content. In each plot, plants were cut 150 mm above the soil surface in 3 m of the center two rows. All cut plants were weighed in the field, and a subsample of four plants from each plot were chipped in an Echo Bear Cat SC3206 Chipper Shredder (Crary Industries, West Fargo, ND, USA). Subsamples of chipped corn (~500 g) were weighed then dried in a forced-air oven at 60°C until

constant mass to determine dry matter yield. Dried samples were weighed, ground to pass through a 1 mm screen, and analyzed for forage quality using the same equipment as alfalfa samples. In 2018 and 2019, grain measurements were taken by retaining an additional four plants from each plot. The ears were removed from the plants, and both were weighed and subsampled to be dried after the same manner. Once dried to constant mass, cobs were stripped of grain, and stover and grain samples were weighed to determine grain yield and harvest index. The 2020 fermented silage corn NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY) were used to estimate CP, NDF, NDFD, and starch and to calculate TDN:

$$[\text{Eq. 3}] \text{TDN} = 100 - (\text{NDF} - 2 + \text{CP} + \text{fat} + \text{ash}) \times 0.98 + \text{CP} \times 0.93 + (\text{fat} - 1) \times 0.97 \times 2.25 + (\text{NDF} - 2) \times \text{NDFD} / 100 - 7$$

### 2.3 Statistical Analysis

One challenge of on-farm irrigation trials is achieving acceptable randomization of the sprinkler treatments and maintaining sufficient irrigation uniformity. Because overlapping spray patterns are critical to the design of the sprinkler packages, and the diameters of wetting area vary so widely amongst the types of packages tested in this study (0 – 23 m), irrigation packages and irrigation rates could not be randomly placed. Therefore, crop yield and quality data were collected from four adjacent plots within each sprinkler package and irrigation rate. When measuring the discharge of the sprinklers, it was determined that there were discrepancies between designed and actual outputs (Table 2.2). A statistical analysis of yield and crop quality were performed by site at  $P < 0.05$  using the MIXED procedure of SAS (SAS Institute Incorporated, Cary, NC, USA). In the

analyses, year and irrigation treatments were considered fixed effects and year was also a repeated measure because the same plots were used each year. Given the restraints in the experimental design (similar to line source irrigation water productivity studies Hanks et al., 1976; Wolfinger et al., 1992), results of the ANOVA need to be interpreted with caution. The first-order autoregressive covariance structure was used because it had the best fit among the several structures evaluated. Replicate and interactions including replicate were considered random at both locations. Dependent variables differed by site but included yield, soil water tension, and various crop quality parameters. The UNIVARIATE procedure of SAS was used to inspect residuals to ensure that the assumptions of normality and equal variance were satisfied. All mean separations were conducted using Fisher's protected LSD at  $\alpha = 0.05$  with the PDIFF option in the MIXED procedure.

## **2.4 RESULTS AND DISCUSSION**

As mentioned previously, the designed reductions in flow rates did not always achieve the ~20% reduction in irrigation rate that was desired. This restricted the comparisons that could be made within and among site-years. Consequently, only results where irrigation rate reductions were achieved will be presented. These results are presented using all available data to compare LEPA and MDI separately and collectively (where possible) with the grower standard of MESA.

### **2.4.1 LEPA and MESA Comparison**

The LEPA and MESA irrigation systems were compared in alfalfa production at the Cedar City site. For this comparison, full and reduced irrigation rates of LEPA were evaluated in conjunction with a full rate of MESA. The experiment was designed to have specific output rates in the different irrigation treatments to avoid confounding from differing application amounts, but in-season measurements each year revealed that there were discrepancies, as reported in Table 2.2. The largest inaccuracy was in 2018, when the MESA output was 148% of design. This was largely due to using the existing, aged sprinkler package, which did not have pressure regulators. Thus, in 2018, the MESA systems had much greater application rates than the LEPA system. This issue was corrected in subsequent years with new sprinklers and regulators, and irrigation rates were much more similar among systems.

When analyzing the 2018 – 2020 growing seasons at Cedar City, the interaction of year  $\times$  treatment was significant (Table 2.3), showing that both LEPA rates (109-113% and 83-87% for the 100 and 80% designed rates, respectively) yielded less than MESA at full irrigation. Alfalfa yield with LEPA was 10.0 and 9.4 Mg ha<sup>-1</sup> across years, for the full and reduced flow rates, respectively, compared to MESA at 11.5 Mg ha<sup>-1</sup>. The interaction did not display any significant differences in the crop quality parameters (Table 2.3). In 2018, the MESA system applied 25% more water than the full rate LEPA, however in 2019 and 2020 it was applying ~11% less water, while continuing to yield significantly greater than both rates of LEPA. Because of this, and the absence of crop quality differences of any value, all three years were retained for the analysis.

The lackluster crop performance under the LEPA system may be partially explained by an in-field observation of ponded water after each irrigation event, which

was not present in the MESA treatments. Soil compaction was not measured, but alfalfa fields are known for becoming highly compacted (Clevenger, 2016) from high traffic resulting from multiple cutting, raking, baling, and stacking events. Compact soil combined with the absence of tillage during alfalfa production, may have created an ideal situation for water to pond on the field under the concentrated application of LEPA, which may be prone to exceeding the infiltration rate of the soil if adjustments to the application amount are not made. This may cause issues during the growing season, when the physiological processes of alfalfa are highly active, the plants are susceptible to damage from lack of oxygen to the roots, particularly when temperatures are high and respiration rates should be high (Putnam et al., 2017). Surface irrigators in Utah submerge crops and still attain high yields, however irrigation frequency may be a distinguishing factor. Utah flood irrigators typically irrigate 4-6 times per season, whereas this field was irrigated 15 times in 2018. The frequency of ponding under the LEPA system may be a reason for the reduced yield.

Soil water tension was measured every 4-h at 300, 600, 900, and 1200 mm depths. The measurements were taken in the full rate MESA treatment, and the reduced LEPA treatment, only. The intent with this was to observe if the assumed greater efficiency of LEPA would enable it to achieve similar soil water tension levels as MESA, even with a reduced irrigation rate. Table 2.6 contains many instances in 2018 where LEPA had lower soil water tension, or more available water, than MESA. At the 300 mm depth, LEPA had lower soil water tension prior to 3 of 15 irrigation events (20%), 1 of 15 events (7%) at the 600 mm depth, and 5 of 15 events (33%) at the 1200 mm depth, while greater soil water tension was measured once, prior to an irrigation event that season, at the 300



mm depth. These results were particularly interesting because the LEPA system had 330 mm less seasonal irrigation than the MESA. In 2019, there were still few instances where soil water tension was significantly different before irrigating, even with 80 mm less irrigation from the LEPA system. In measurements taken 24-h after the irrigation events, LEPA had lower soil water tension at the 900 and 1200 mm depths, after 1 (7%) and 5 (33%) of the 15 seasonal irrigation events, respectively, while showing higher soil water tension at 4 of 15 events (27%) at the 300 mm depth, and at 2 of 15 events (15%) at the 600 mm depth (Table 2.7). In 2019, there were few differences between the MESA and reduced LEPA soil water tension, as the most differences at any depth were in the 600 mm depth, where 1 of 12 irrigation events decreased water tension, and 2 of 12 events measured increased water tension. While soil water tension before and after irrigation events was sometimes different between LEPA and MESA, there were no distinct or consistent patterns to this data. For the majority of irrigation season, soil water tension was similar between MESA and LEPA, when the LEPA system was applying a lower irrigation rate. These findings support the hypothesis of a reduced rate of LEPA matching soil moisture levels of MESA at a larger application rate. A similar study, comparing MESA to LEPA with a 15% flow reduction, had similar results, when finding no significant differences in soil moisture, however the study differed in that LEPA maintained yield at that irrigation reduction (Molaei et al., 2021). These results may suggest that a reduced rate of LEPA has the capability to fill the soil profile similarly to MESA but may need speed or application pattern adjustments to attain optimal crop responses.

### 2.4.2 MDI and MESA Comparison

This section has data collected in alfalfa at Cedar City in 2019 – 2020, and silage corn in Elberta in 2019, comparing full and reduced irrigation rates of MDI compared to MESA at the full rate. Data from 2018 are not included because of the extreme reductions in the MDI irrigation rates due to the design error from the drip line manufacturer. At Cedar City, the interaction of year  $\times$  treatment on yield was significant (Table 2.3). In 2019, the MESA control treatment yielded 14.3 Mg ha<sup>-1</sup> with 630 mm of seasonal irrigation applied, while the full rate of MDI yielded significantly lower at 12.9 Mg ha<sup>-1</sup> with 700 mm, and the reduced rate of MDI yielded 11.2 Mg ha<sup>-1</sup> with 480 mm of irrigation. Results followed a similar pattern in 2020, with yields measuring 11.0, 9.8, and 7.1 Mg ha<sup>-1</sup> for the MESA, full rate MDI, and reduced rate MDI treatments, respectively, with 610, 670, and 460 mm of seasonal irrigation. The full rate of MDI applied nearly 10% more irrigation each season than the MESA, yet yielded 9% and 11% lower in 2019 and 2020, respectively. The reduced rate of MDI was applying around 25% less than the MESA and 31% less than the full rate MDI but continued to reduce yield further yet. This, combined with visual observations of corrugations across the alfalfa in the MDI span, may suggest that there was poor irrigation distribution throughout the rootzone, which has also been recently noted in a study on soil water redistribution, where MDI demonstrated poor horizontal uniformity (Oker et al., 2020). Future work that may be useful is collecting soil moisture data beneath and between the drip lines at shallow depths. This would be to understand how much of the upper 300 mm of rootzone, where the highest amount of water is taken up by alfalfa, is properly wetted through lateral movement of water between the drip lines, and to what extent it is left dry.

No forage quality parameters were influenced by year  $\times$  treatment interaction, because 2020 samples were not analyzed for quality. Analyzing quality data from 2019 with treatment as the main effect displayed some differences (Table 2.3), however nothing that would have changed the market value of the alfalfa.

Silage corn data were collected in 2018 and 2019 at the Elberta site, however only 2019 results will be discussed in this section, as the manufacturer defect in the drip lines caused massive output reductions at this site as well. With treatment as the main effect, silage corn yield was significantly different at  $P=0.0082$  (Table 2.3). The full rates of MESA and MDI yielded similarly at 19.8 and 19.1 Mg ha<sup>-1</sup> (Table 2.5), respectively, while applying 770 and 870 mm of seasonal irrigation (Table 2.2). The reduced rate of MDI yielded lower at 17.0 Mg ha<sup>-1</sup>, with 740 mm of irrigation applied, a 14% yield loss compared to MESA, while applying about 4% less water. The main effect of treatment at this site was significant for some parameters when including LEPA in the analysis (Table 2.3), but there were no significant differences in any of the quality parameters between MDI and MESA (Table 2.5).

The reduced rate of MDI rarely improved (lowered) soil water tension at either site in comparison to full rate MESA, except in 2019 at Cedar City, where at the 600 and 900 mm depths it reduced tension prior to 8% of the irrigation events (1 of 12 events; Table 2.6). Higher soil water tension before an irrigation event was measured at 2 of 12 events (17%) at the 300 mm depth, and at 1 of 12 events (8%) at the 60 and 1200 mm depths with MDI. Measurements after irrigation events never displayed improvements (lowered) to soil water tension with MDI, and frequency of higher water tension was limited to 2 of 12 events (17%) at the 600 mm depth, and 1 of 12 events (8%) at the 1200

mm depth (Table 2.7). The Elberta silage corn field had the most frequent increases in soil water tension with MDI compared to MESA, all at the 600 and 900 mm depths. Leading up to an irrigation event (Table 2.6), higher soil water tension with the reduced MDI, when compared to MESA, was measured at 7 of 23 events (30%) at the 600 mm depth, and at 2 of 23 events (9%) at the 900 mm depth. Measurements following the irrigation events displayed higher soil water tension at 6 of 23 events (26%) at the 600 mm depth, and at 4 of 23 events (17%) at the 900 mm depth (Table 2.7). There were no instances measured at Elberta where soil water tension levels were better (lower) in the MDI, however many instances had similar levels. All of the differences at Elberta occurred in the first half of the growing season (data not shown) when the drip tubing was ~380 mm away from the sensors, which were placed in line with the corn rows. When the corn exceeded 1.5 m tall, it was observed that most of the drip lines would ride up onto the corn plants, causing the water to fall directly at the base of the plants. This may suggest that the water was not moving laterally as quickly at the deeper depths in the MDI areas as MESA, during the beginning of the season when the drip tubing was further away from the sensors and may have had an effect on yield in the MDI.

### **2.4.3 LEPA, MDI, and MESA Comparison**

This section is comprised of a comparison of MDI, LEPA, and MESA from research on alfalfa production at Cedar City, UT in 2019 and 2020. As previously stated, the interaction of year  $\times$  treatment on yield was significant at  $P=0.0194$  (Table 2.3). In 2019, the MESA treatment yielded significantly greater ( $P < 0.05$ ) than the other treatments at  $14.3 \text{ Mg ha}^{-1}$  with 630 mm of irrigation (Table 2.2). The MDI treatment yielded  $12.9$  and  $11.2 \text{ Mg ha}^{-1}$  for the full and reduced rates, respectively (Table 2.4),

with 700 and 480 mm of irrigation. The LEPA treatment yielded 12.8 and 11.7 Mg ha<sup>-1</sup> for the full and reduced rates, respectively, with 710 and 550 mm of irrigation. Because LEPA and MDI yielded less at both rates, the discussion will focus on the reduced rate, and whether either system would provide a benefit when water applications require reductions. For 2019, the reduced rate of MDI applied 24% less irrigation than MESA, and reduced alfalfa yield by 22%, and the reduced rate of LEPA applied 13% less irrigation than MESA and reduced yield by 18%. In 2020, MESA continued to yield significantly greater than all other treatments at 11.0 Mg ha<sup>-1</sup> (Table 2.4) with 610 mm of irrigation (Table 2.2). The full rate MDI treatment yielded 9.8 Mg ha<sup>-1</sup> with 670 mm of irrigation, while the reduced MDI yielded the lowest at 7.1 Mg ha<sup>-1</sup> with 460 mm of irrigation. LEPA yielded 7.9 Mg ha<sup>-1</sup> with 690 mm of irrigation at the full rate, and increased yield in the reduction treatment, producing 8.6 Mg ha<sup>-1</sup> with 530 mm of irrigation. In comparison to MESA in 2020, the reduced rate of MDI yielded 35% lower with 25% less irrigation, and the LEPA reduced rate reduced yield by 22% while applying 13% less irrigation. There were no significant differences in crop quality parameters among the treatments (Table 2.3, 2.4). These results may suggest that without other changes to the irrigation method, such as adjusting the speed of the pivot, these advanced systems can probably not be relied upon to maintain yield at a reduced rate of application, but that alfalfa forage quality should not decline. This research would benefit from the inclusion of a reduced rate of MESA in the future, to evaluate WUE of all three systems, and possibly determine the optimal system if a specified reduction were required.

Soil water tension readings 24-h prior to irrigation events showed that LEPA and MDI were nearly the same in their comparisons to MESA, having lower water tension in 1 of 12 events for both LEPA (at the 900 and 1200 mm depths) and MDI (at the 600 and 900 mm depths; Table 2.6). The frequency of increased soil water tension prior to irrigation events was 2 of 12 events for LEPA and MDI at the 300 mm depth, and 1 of 12 events at the 600 and 900 mm depths for LEPA and MDI. In soil water tension comparisons following irrigation events (Table 2.7), LEPA lowered tension in 1 of 12 events at the 600 and 1200 mm depths, and raised it in 2 of 12 events at the 600 mm depth, while MDI never displayed a decrease in tension at any depth, and raised it in 2 of 12 events at the 600 mm depth, and in 1 event at the 1200 mm depth. These results suggest that in the top 1200 mm of soil, a reduced rate of LEPA (13% reduced) and MDI (24% reduced) may have small, potentially unnoticeable impacts in soil water tension.

#### **2.4.4 Severe MDI Reduction in Alfalfa and Corn**

When this study was established in 2018 the experimental design was to have a full irrigation rate that matched what the pivot output was designed for, as well as a reduced rate that applied 20% less water. As stated previously, the drip tubing for the MDI treatments was emitting 30 – 35% less than specified, due to a flaw from the manufacturer. In 2018, there was also a large discrepancy in the MESA flow rate at the Cedar City site, where the application rate was 48% greater than designed. The MESA system at the Elberta site was also emitting 10% more than designed. This section details the results from the reduced rate MDI treatment, which due to these unique circumstances, applied 69% less irrigation in Cedar City and 58% less in Elberta, than the MESA treatments at each site. MESA values are included to illustrate the potential of the

field under common irrigation conditions for central and southern Utah, with the caveat of the inaccuracies specified.

At Cedar City, alfalfa was harvested four times, however data were only collected for the last three cuttings. The severely reduced MDI yielded at seasonal total of 7.5 Mg ha<sup>-1</sup> of alfalfa, with 260 mm of irrigation (Table 2.2). The MESA system yielded 10.0 Mg ha<sup>-1</sup> with 840 mm of irrigation. When considering how efficiently the water was used to produce biomass, the MDI produced 29 kg for each mm applied per ha, while the MESA produced 12 kg. This extreme difference may be the result of multiple factors, however the MESA was applying much more than the cooperating grower knew, so it is possible that the MESA plots were unknowingly overirrigated. There were small differences in the crop quality parameters, however, there were no statistically significant differences in CP, NDF, and IVDMD between the severely reduced MDI and the MESA treatments (Table 2.4). RFQ calculations were statistically similar as well, at 359 and 361 for the MDI and MESA treatments, respectively. The two quality parameters with significant differences were NDFD (48), where MESA measured 13% and MDI measured 12%, and TDN which was calculated to be 78% for MESA and 80% for the MDI treatment. Despite being statistically different, these would not have had any effect on the market value of the alfalfa as both treatments produced supreme quality alfalfa. Though the discussion is limited to a single season of data, the results demonstrated a yield reduction of 25% while using 69% less irrigation (580 mm), and no negative effects on forage quality. This may suggest that MDI could increase irrigation efficiency and be a tool for situations of severe water restriction.

Soil water tension measurements 24-h before irrigation events showed that at the 300 mm depth was higher for 1 of 15 events (7%), and at the 900 mm depth, MDI had lower tension for 3 of 15 events (20%), and there were no differences at the 600 and 1200 mm depths (Table 2.6). This result is significant, as it shows similar levels of water retained in the soil between irrigations, something notable with such a sizable reduction in the MDI application. When evaluating each systems ability to fill the soil profile by measuring soil water tension 24-h after irrigation, MDI had lower tension than MESA at the 300 mm depth in 1 of 15 events (7%), twice at the 600 mm depth (15%), 5 of 15 events (33%) at the 900 mm depth, and once (7%) at the 1200 mm depth (Table 2.7). The MDI system once had higher soil water tension after an irrigation event, and that was at the 600 mm depth. Considering that MESA applied 223% more water than MDI in this scenario, this may suggest that in some situations, MDI can percolate water deeper and faster than MESA, even when applying less. One may also deduce that a flow reduction as severe as inadvertently tested in 2018 can lead to a depleted soil moisture reservoir more quickly than MESA at a greater rate, but that MDI has some ability to compensate with more concentrated infiltration.

In Elberta in 2018, dry matter silage corn yields were 21.3 and 22.7 Mg ha<sup>-1</sup> for the severely reduced MDI and MESA treatments, respectively (Table 2.5). Seasonal irrigation under the MDI and MESA treatments was 330 and 780 mm, which resulted in productivity totals of 65 and 29 kg of biomass per ha for each mm of irrigation applied. Starch content in the MDI was significantly less than the MESA, measuring 28%, while the MESA treatment produced 32%. There were no differences among the other crop quality parameters. In summary, with 450 mm (58%) less irrigation than MESA, the MDI



system yielded 6% lower and had a negative effect on starch content, but otherwise had little effect on forage quality. Along with Cedar City results, these findings provide evidence that in the right scenario, MDI may be able to minimize yield and quality losses and optimize irrigation in extreme reduction situations. Longer studies are needed to verify if there would be ongoing effects from MDI that may change its efficacy.

Soil water tension measurement before irrigation events showed no occurrences of the severely reduced MDI treatment having lower tension than MESA but tension was higher at the following depths: the 300 mm depth for 11 of 22 events (50%), the 600 mm depth three times (14%), and once at the 1200 mm depth (7%; Table 2.6). Measurements taken after irrigation events again found that the MDI never had lower soil water tension at any depth and had higher tension at 9 of 22 events (41%) at 300 mm, and a single event (5%) at the 600 and 1200 mm depths (Table 2.7). These findings contrast what was measured in Cedar City, but the lack of consistency may prove useful for understanding field situations that may or may not be suitable for MDI. At this site, the drip tubing would form small (<30 mm) channels in the silty loam soil where they travelled. Water movement in these channels could be observed flowing in the direction of the field slope, then mid-season, the drip lines would often ride in the corn canopy. There is a possibility that this surface movement had an effect on the soil water tension measurements in the plot areas, but the 136% of additional irrigation received by the MESA plot areas certainly had a significant impact on the results as well.

#### **2.4.5 CONCLUSIONS**

LEPA and MDI pivot packages often have greater measured irrigation application efficiency than the commonly used MESA, however, as this research shows, increased

efficiency does not guarantee yield, crop quality, or soil moisture improvements. In some situations, adapting the speed of the pivot or the sprinkler type to better match the infiltration rate of the soil may have improved the effectiveness of the LEPA system, as both sites demonstrated that LEPA had difficulty irrigating the area beneath the farthest span of the pivots when using the cooperating farmers' usual rates (32 – 38 mm per irrigation). Initially MDI showed great promise, reducing yield by 6 – 25% in 2018, with much less than half of the total irrigation. The 2019 and 2020 seasons demonstrated poor yields with MDI, even at similar or larger irrigation rates than MESA, and proved to be a system that required substantial amounts of labor to maintain and perform field operations around. Despite inconsistent results from the advanced systems in this study, LEPA and MDI have great potential to maintain yield with less water than MESA given the correct circumstances and proper adaptations to maximize performance, both of which were sometimes restricted in this study. Therefore, the systems (LEPA, MDI, or MESA) cannot be fairly ranked with a generic field performance score, because under the multitude of field scenarios, each will be the optimal system for certain fields. Future research should continue to identify field conditions that might cause LEPA and MDI to be more beneficial and economic than MESA in terms of water savings and crop performance.

**TABLE 2.1** Site properties for irrigation trials in Cedar City and Elberta, Utah, from 2018 to 2020, including nearest town, year, coordinates, dominant soil texture, slope, drainage classification, irrigation packages tested, and crop

<b>Nearest town</b>	<b>Year</b>	<b>Coordinates</b>	<b>Dominant soil texture (classification)</b>	<b>Slope</b>	<b>Drainage classification</b>	<b>Sprinkler Packages</b>	<b>Crop</b>
Cedar City	2018-2020	37.750, -113.073	Loam (Fine loamy, mixed (calcareous), mesic Xeric Torrifluvents)	0 - 2	Well drained	LEPA <sup>a</sup> , MDI, MESA	Alfalfa
Elberta	2018-2019	39.897, -111.954	Silt Loam (Fine-silty, mixed (calcareous), mesic Xeric Torrifluvents)	1 - 2	Well drained	LEPA, MDI, MESA	Silage corn

<sup>a</sup>Low energy precision application (LEPA), mobile drip irrigation (MDI), mid elevation sprinkler application (MESA)

**TABLE 2.2** Sprinkler package designed rates, the true measured output of each treatment, and seasonal accumulative irrigation applied at the Cedar City and Elberta sites from 2018-2020

<b>Nearest town</b>	<b>Year</b>	<b>Sprinkler package</b>	<b>Designed rate</b>	<b>Measured rate</b>	<b>Irrigation applied</b>
			(% of original design)		(mm)
Cedar City	2018	LEPA	80	87	510
		LEPA	100	113	670
		MDI	80	45	260
		MDI	100	57	320
		MESA	100	148	840
	2019	LEPA	80	83	550
		LEPA	100	109	710
		MDI	80	74	480
		MDI	100	109	700
		MESA	100	99	630
	2020	LEPA	80	83	530
		LEPA	100	109	690
		MDI	80	74	460
		MDI	100	109	670
MESA		100	99	610	
Elberta	2018	LEPA	80	95	680
		LEPA	100	118	850
		MDI	80	46	330
		MDI	100	58	420
		MESA	100	109	780
	2019	LEPA	80	95	670
		LEPA	100	118	850
		MDI	80	105	740
		MDI	100	124	870
		MESA	100	109	770

**TABLE 2.3** Significance of *F* tests for the fixed effects of year and treatment and their interaction on yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility (48-h); In Vitro Dry Matter Digestibility, IVDMD; TDN, total digestible nutrients; RFQ, relative forage quality; and starch) at the Cedar City and Elberta sites for alfalfa and silage corn, respectively. Differences were considered statistically significant when  $P < 0.05$

Site	Year	Effect	Yield	CP	NDF	NDFD	IVTDMD	TDN	RFQ	Starch
Cedar City	2018-2020	year	<.0001	<.0001	<.0001	<.0001	0.0164	<.0001	<.0001	n/a <sup>a</sup>
		treatment	<.0001	0.0492	0.0067	<.0001	0.1156	<.0001	0.0608	n/a
		year × treatment	0.0194	0.0501	0.9094	0.5743	0.9646	0.3247	0.8772	n/a
Elberta	2018	treatment	<.0001	0.0429	0.3079	0.7606	0.0063	0.0273	n/a	0.1321
	2019	treatment	0.0082	0.5802	0.0503	0.2327	0.0735	0.0136	n/a	0.049

<sup>a</sup> n/a, not applicable.

**TABLE 2.4** Alfalfa yield and quality parameters [CP, Crude Protein; NDF, Neutral Detergent Fiber; NDFD, Neutral Detergent Fiber Digestibility (48hr); In Vitro Dry Matter Digestibility, IVDMD; TDN, Total Digestible Nutrients; RFQ, Relative Forage Quality] for each system at the Cedar City site in the full and reduced irrigation rates. Mean separations were conducted by system and parameter and significant differences at  $P < 0.05$  are denoted with lowercase letters following means

Year	System	Rate	Yield	CP	NDF	NDFD	IVDMD	TDN	RFQ
			Mg ha <sup>-1</sup>	----- g kg <sup>-1</sup> -----					
2018	LEPA <sup>a</sup>	Full	9.3ef	284.1ab	219.9cd	128.8b	888.0abc	774.0c	325.6cde
		Reduced	8.0gh	285.0ab	207.3de	118.0c	890.3ab	786.6b	345.2abc
	MDI <sup>b</sup>	Full	9.7ef	289.0a	213.9de	124.0b	888.4abc	787.7b	338.6abcd
		Reduced	6.8h	287.4a	201.1e	116.7c	894.2a	801.6a	359.2ab
	MESA <sup>c</sup>	Full	9.1efg	286.7a	211.4de	126.8b	892.8a	775.6bc	361.2a
2019	LEPA	Full	12.8bc	269.3d	238.9a	137.9a	874.8e	751.4d	299e
		Reduced	11.7cd	275.9c	221.7bcd	125.7b	879.4cde	770.7c	316.1cde
	MDI	Full	12.9b	269.7d	236.9ab	137.5a	876.9de	755.1d	307.2e
		Reduced	11.2d	279.8bc	216.9de	126.0b	886.0abcd	776.7bc	328.3bcde
	MESA	Full	14.3a	269.6d	233.4abc	137.6a	881.0bcde	757.0d	313.8de
2020	LEPA	Full	7.9gh	n/a <sup>d</sup>	n/a	n/a	n/a	n/a	n/a
		Reduced	8.6fg	n/a	n/a	n/a	n/a	n/a	n/a
	MDI	Full	9.8e	n/a	n/a	n/a	n/a	n/a	n/a
		Reduced	7.1h	n/a	n/a	n/a	n/a	n/a	n/a
	MESA	Full	11.0d	n/a	n/a	n/a	n/a	n/a	

<sup>a</sup> LEPA, low energy precision application.

<sup>b</sup> MDI, mobile drip irrigation.

<sup>c</sup> MESA, mid-elevation sprinkler application.

<sup>d</sup> n/a, not applicable.

**TABLE 2.5** Silage corn yield and quality parameters [CP, Crude Protein; NDF, Neutral Detergent Fiber; NDFD, Neutral Detergent Fiber Digestibility (48-h); starch; TDN, Total Digestible Nutrients] for each system at the Elberta site in the full and reduced irrigation rates. Mean separations were conducted by system and parameter and significant differences at  $P < 0.05$  are denoted with the lowercase letters following means

Year	System	Rate	Yield	CP	NDF	NDFD	Starch	TDN
			Mg ha <sup>-1</sup>	----- g kg <sup>-1</sup> -----				
2018	LEPA <sup>a</sup>	Full	18.5b	77.7b	440.1a	272.8a	328.8a	716.3ab
		Reduced	20.8b	79.6b	426.5a	267.1a	318.5a	723.7a
	MDI <sup>b</sup>	Full	24.0a	80.2b	421.3a	260.2a	320.1ab	723.3a
		Reduced	19.3b	86.8a	422.5a	271.0a	281.4b	728.1a
	MESA <sup>c</sup>	Full	20.6b	81.4ab	428.0a	260.3a	320.5a	717.2ab
2019	LEPA	Full	18.9ab	99.8a	480.0a	306.3a	213.2c	679.8d
		Reduced	16.5c	101.6a	473.6a	308.3a	228.1bc	684.0cd
	MDI	Full	19.1ab	97.9a	458.2abc	287.1ab	253.8ab	687.3bcd
		Reduced	17.0bc	97.4a	448.8abc	292.0ab	240.9abc	699.0abc
	MESA	Full	19.8a	101.8a	437.2bc	285.0ab	272.5a	703.1ab

<sup>a</sup> LEPA, low energy precision application.

<sup>b</sup> MDI, mobile drip irrigation.

<sup>c</sup> MESA, mid-elevation sprinkler application.

**TABLE 2.6** The percentage of occurrences when low-elevation precision application (LEPA) and mobile drip irrigation (MDI) at reduced irrigation rates had significantly different ( $P < 0.05$ ) soil water tension than mid-elevation spray application (MESA) at the full irrigation rate the day before irrigation events. Differences were measured from three replicates of four depths within each system, from the 2018 and 2019 growing seasons in Cedar City and Elberta, Utah

Site	Year	Depth (mm)	Frequency of lower water tension by system		Frequency of higher water tension by system	
			LEPA	MDI	LEPA	MDI
			% of total irrigation events			
Cedar City	2018	300	20	0	7	7
		600	7	0	0	0
		900	0	20	0	0
		1200	33	0	0	0
Cedar City	2019	300	0	0	17	17
		600	0	8	8	8
		900	8	8	8	0
		1200	8	0	0	8
Elberta	2018	300	0	0	5	50
		600	0	0	9	14
		900	0	0	0	0
		1200	0	0	0	5
Elberta	2019	300	0	0	100	0
		600	0	0	65	30
		900	0	0	0	9
		1200	n/a <sup>a</sup>	n/a	n/a	n/a

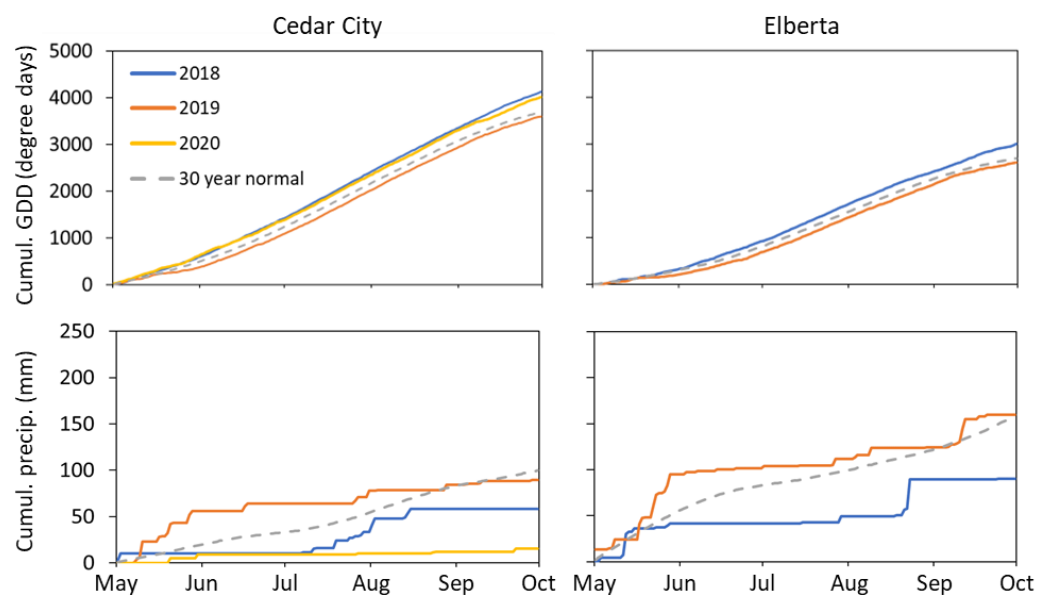
<sup>a</sup> n/a, not applicable



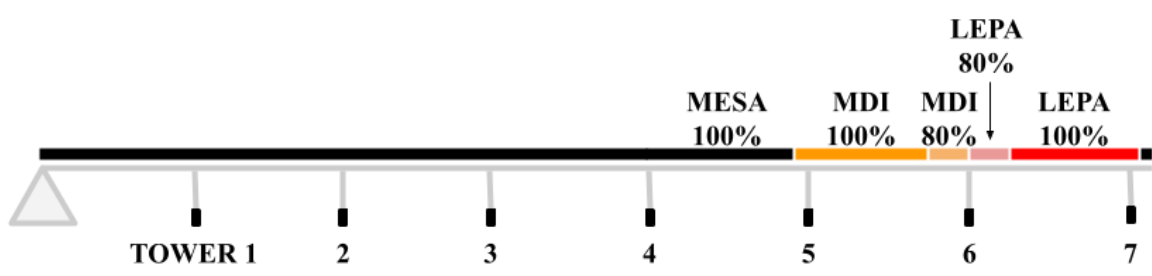
**TABLE 2.7** The percentage of occurrences when low-elevation precision application (LEPA) and mobile drip irrigation (MDI) at reduced irrigation rates had significantly different ( $P < 0.05$ ) soil water tension than mid-elevation spray application (MESA) at the full irrigation rate the day after irrigation events. Differences were measured from three replicates of four depths within each system, from the 2018 and 2019 growing seasons in Cedar City and Elberta, Utah

Site	Year	Depth (mm)	Frequency of lower water tension by system		Frequency of higher water tension by system	
			LEPA	MDI	LEPA	MDI
			% of total irrigation events			
Cedar City	2018	300	0	7	27	0
		600	0	15	15	8
		900	7	33	0	0
		1200	33	7	0	0
Cedar City	2019	300	0	0	0	0
		600	8	0	17	17
		900	0	0	0	0
		1200	8	0	0	8
Elberta	2018	300	0	0	5	41
		600	0	0	5	5
		900	0	0	0	0
		1200	0	0	0	5
Elberta	2019	300	0	0	83	0
		600	0	0	61	26
		900	0	0	0	17
		1200	n/a <sup>a</sup>	n/a	n/a	n/a

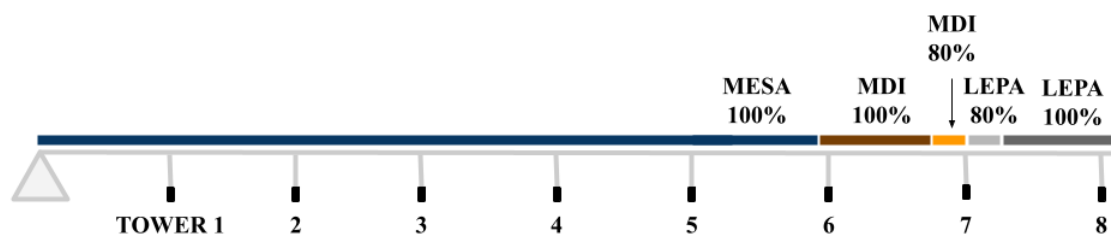
<sup>a</sup> n/a, not applicable



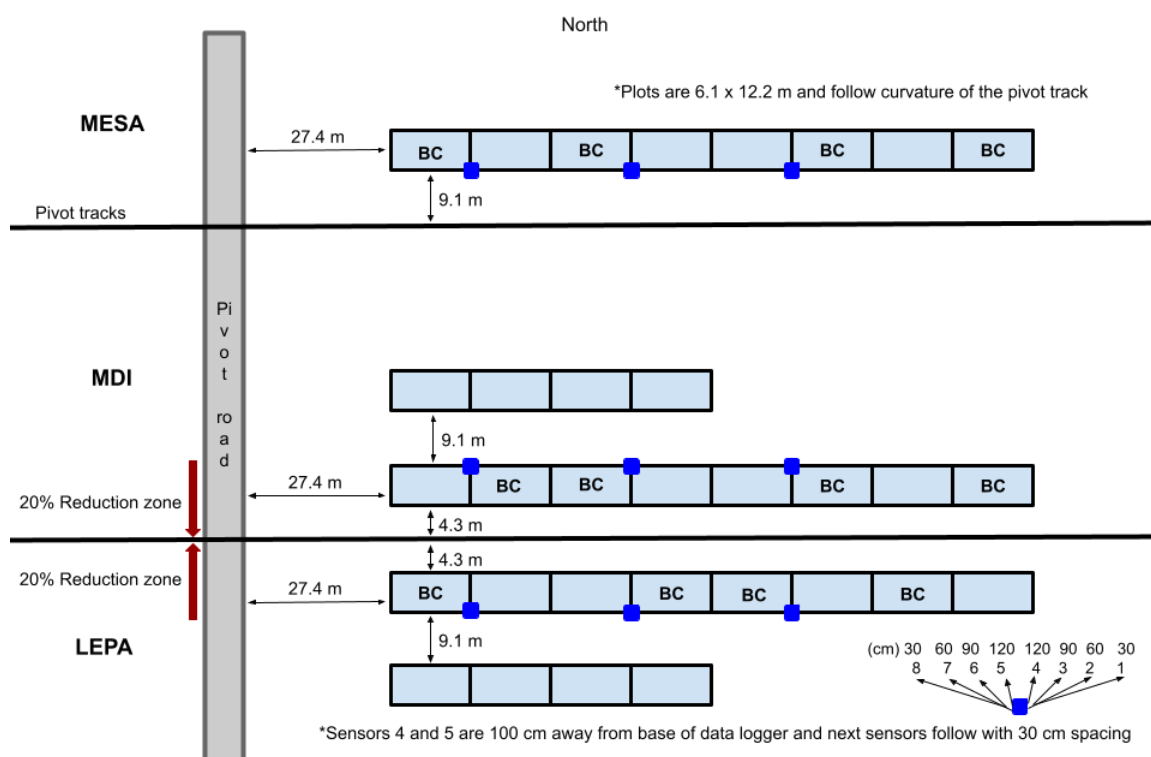
**Figure 2.1** Cumulative growing degree days (GDD) and precipitation for Cedar City, and Elberta. GDD were calculated from the minimum and maximum air temperatures and adjusted to 5°C and 30°C, and 10°C and 30°C, respectively. The 30-yr normal (1981-2010) is shown for reference.



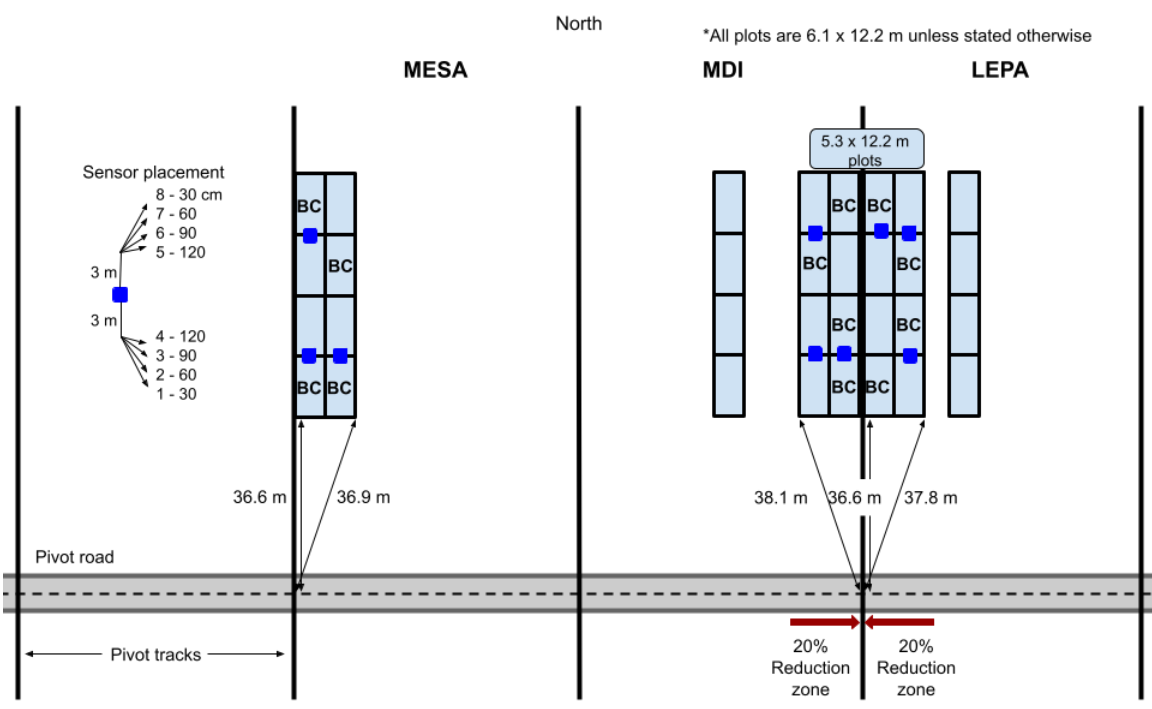
**Figure 2.2** Placement of MESA (mid elevation sprinkler application) at a full rate, MDI (mobile drip irrigation) at a full and reduced rate, and LEPA (low energy precision application) at a full and reduced rate on the irrigation pivot at the Cedar City site.



**Figure 2.3** Placement of MESA (mid elevation sprinkler application) at a full rate, MDI (mobile drip irrigation) at a full and reduced rate, and LEPA (low energy precision application) at a full and reduced rate on the irrigation pivot at the Elberta site.



**Figure 2.4** Plot Map from the Cedar City site displaying harvest areas irrigated by MESA (mid elevation sprinkler application), MDI (mobile drip irrigation), and LEPA (low energy precision application), including areas of reduced flow. Plots marked “BC” were not included in this study.



**Figure 2.5** Plot Map from the Elberta site displaying harvest areas irrigated by MESA (mid elevation sprinkler application), MDI (mobile drip irrigation), and LEPA (low energy precision application), including areas of reduced flow. Plots marked “BC” were not included in this study.

## CHAPTER 3

### IMPROVING PIVOT RUTS WITH SIMPLE SPRINKLER MODIFICATIONS

#### 3.1 INTRODUCTION

For over 70 years, center pivots have been an important part of agricultural irrigation. Water-drives are long gone, the evolution of sprinkler heads has not ceased, and the technological gadgetry available for pivots literally reaches into outer-space. These machines are highly effective at irrigation but can still cause significant problems by creating deep wheel tracks. This is no surprise, considering each tower can weigh 4 Mg when the pipe is full of water, and is constantly operating in wet soil (Agriculture Victoria, 2022). These wheel tracks put additional wear on the pivot, other field machinery, and machinery operators (Meyer & Hoffman, 1983). Irrigation uniformity can also be impacted by wheel tracks, making low-spots worse, because of tire slippage and stuck pivots in those areas (Meyer & Hoffman, 1983). These impacts can result in costly repairs to equipment, such as premature wear of pivot gear boxes (about US\$700 each) and center-drive motors (about US\$550 each), or expensive hydraulic pumps and motors on certain makes of pivots (D. Larsen, personal communication, October, 2022). Labor and crop damage associated with getting the pivot unstuck, as well as yield losses due to downtime, can also come at great expense to the farmer.

Over their 70+ years of existence, many methods for improving wheel tracks have been attempted. Some of the approaches have been directed at making short-term changes to the field with special tillage equipment and soil conditioners, or track fillers for long-term improvements. Filling tracks with gravel can be highly effective, but is expensive, permanently alters the field and often dictates how future field operations

must be conducted (working the field in circles instead of straight). Further, filling tracks with gravel can reduce farmable area by over 1%. There have also been many attempts directed at decreasing the downward pressure through larger tires, more tires, lower pressure tires (Foley, 2008), tracks over the tires, paddles, steel wheels, plastic wheels, and more. Other attempts have been directed at the sprinkler packages, reducing flow rates around the towers, or moving the sprinklers behind the direction of travel with a suspended boom. In interviews with several farmers, it was revealed that for some situations, farmers have found solutions within the aforementioned options, but many farmers still report that they have not found economic ways of improving the pivot ruts on their farm. There has been little to no third-party research conducted on most of the options currently available, despite the interest of farmers in improving their pivot wheel ruts. This may partially be due to the short existence of many products that promise to be a solution. The intent of our research was to evaluate simple, inexpensive changes to pivot sprinkler packages that might improve wheel tracks with better water management around the track, in hopes of finding a solution that can be effective in a variety of soil types and crops.

## **3.2 MATERIALS AND METHODS**

### **3.2.1 Site Characteristics**

In 2020, on-farm trials were established near Cornish, UT, where the land under a pivot was divided into three separate fields, and Nibley, UT at one pivot. Due to unforeseen changes at these farms, research was discontinued at each site at the close of the initial growing season. In 2021, new fields were added near Cornish and Wellsville,

Utah, as well as two fields near Burley, Idaho. Soil classification, textural group, slope, and drainage classifications for each site were obtained from the University of California-Davis SoilWeb (O'Geen, 2020; Table 3.1). Weather data at all eight sites were obtained from the Utah Climate Center (climate.usu.edu; Logan, Utah; Fig. 3.1) and were used to calculate cumulative precipitation and growing degree days for the growing season of each crop. Corn (*Zea Mays* L.) and alfalfa (*Medicago Sativa* L.) growing degree days (GDD) were calculated using base air temperatures of 10 and 5°C, respectively, with a 30°C upper limit. Measured cumulative precipitation and degree days were compared with their respective 30 yr normal (1991-2020) provided by the National Oceanic and Atmospheric Administration (NOAA, 2022). All farming practices, including irrigation, were managed by the cooperating farmers. This included the direction of travel for the pivots, which often, particularly under the half circle pivots, meant irrigation was delivered both directions of travel.

### **3.2.2 Sprinkler Equipment Approaches**

Four sprinkler package changes were evaluated in this study, and compared to new, mid elevation sprinkler application (MESA) packages. This included the use of part circle sprinklers, low energy precision application (LEPA) sprinklers at 30 cm spacing, eight suspended booms, and a single suspended boom, all of which will be explained in further detail (Table 3.2). For each of these variables, the pivot tower for each method was selected at random. The last tower on each pivot was excluded because the weight load is different than inner towers. For the towers that would be measured as the “control” treatment of the study, new equipment (regulators, sprinkler heads, and nozzles) were installed if the existing sprinkler package was nearing the manufacturer's

suggested lifespan. The designed water output of the pivot outlets that received equipment changes for any of the treatments remained the same as the control. All irrigating was done at the will of the cooperating farmer and was not altered in any manner for this study.

#### 3.2.2.1 Double Part Circle

In the farmer interviews conducted in the planning of this study, many farmers stated that they had made attempts to reduce pivot ruts by using part circle (PC) sprinklers on each side of the tower, but most abandoned these designs quickly due to poor irrigation and crop uniformity. To combat uniformity issues yet capitalize on the ability of PC sprinklers to accurately direct the spray pattern, this study evaluated the use of four PC sprinklers to replace the two MESA style sprinklers closest to each side of the pivot tower (Fig. 3.2). In place of the two MESA sprinklers, rigid drops or hoses with extra weights were fitted with PC sprinklers directed toward one of the pivot tower tires. Then, a simple PVC manifold was mounted to the tower and plumbed into an outlet not being used (Fig. 3.3). This manifold was made to be long enough to have PC sprinklers mounted directly in line with the pivot track, to spray parallel to it. Because many models of PC sprinklers do not spray a full 180°, these were aimed to spray toward the opposite side of the tower than the other two PC sprinklers. As this approach uses four sprinklers in place of the original two, flow adjustments were required. This was accomplished by determining the area covered by each of the PC sprinklers and dividing the original output volume of the two MESA sprinklers amongst them according to the area. These calculations often resulted in the PC sprinklers on the manifold receiving 25-33% of the output, while the PC sprinklers in the placement of the original MESA sprinklers



received the remainder. Options for PC sprinklers have a large range of prices. In the establishment year of the study, this approach cost \$100 – 175 per tower, depending on the sprinkler selected.

#### 3.2.2.2 Low Energy Precision Application

Low energy precision application (LEPA) sprinkler packages combine low sprinkler height and close spacing, commonly replacing one MESA sprinkler with three LEPA heads. In previous LEPA studies in Utah, it was observed that the pivot ruts were often much shallower on the towers surrounded by LEPA sprinklers, as opposed to MESA sprinklers. For the current research trial, the outlet closest to each side of the tower was converted to LEPA, by replacing the MESA sprinkler with three to four Senninger (Clermont, Florida) Low Drift Nozzle sprinklers ( $61 - 4811 \text{ L h}^{-1}$  at pressures between 0.41 to 1.38 bar) positioned 0.45 m above the soil surface and spaced 0.75 – 1 m apart (Fig. 3.4). The original MESA water output of the outlet was then divided equally amongst the three to four LEPA heads. The sprinklers closest to the wheel track were fitted with a Senninger Bubbler Pad Assembly to avoid overspray entering the track area (Fig 3.5). The other sprinklers used a beige Bubble Insert with a shroud to produce some overlap between LEPA heads. If the LEPA head farthest away from the tower could use a grooved, spray pad without spraying water in the track, this option was used to increase overlap with the neighboring MESA style sprinklers that use a large wetting radius to achieve good uniformity. In the establishment year of this study, it cost approximately \$200 per tower for this equipment.

#### 3.2.2.3 Advantage Eight-Boom Design

In the preliminary stages of this research trial, there were many discussions with farmers, as well as professionals from the three largest manufacturers of pivot sprinklers. When discussing potential pivot rut solutions with Komet Innovative Irrigation (Lienz, Tyrol, Austria) they presented a technique coined, “Komet Advantage” (hereafter referred to as Advantage booms). This method utilized two outlets spaced 2.3-3.1 m apart on each side of the pivot tower. At each of these four outlets, two 3-m long suspended booms were attached to the pivot pipe, in opposite directions (Fig. 3.6; Fig. 3.7). The rated output of each outlet was then divided between the two booms at each position. The intent of this design was to improve wheel track impacts by having the water applied to a larger area, where the irrigation would have a better chance of infiltrating the soil instead of ponding and moving into the wheel track. This design cost about US\$1400 per tower in 2021.

#### 3.2.2.4 Single Suspended Boom

One method that irrigation dealers in Idaho and Utah have used, with the intent of reducing wheel tracks, is to install a single, 3-m boom at the location of the sprinkler closest to the tower. This suspended boom is attached to the top pipe of the pivot, and the hose-drop and sprinkler are attached to the suspended end, moving the sprinkler near the rear tire of the tower or beyond (Fig. 3.8; Fig. 3.9). On pivots that irrigate in both directions, a second boom is attached, and both booms are fitted with valves, so that the sprinkler on the leading side may be shut off and irrigation may be applied behind the tower no matter the direction of travel. This research replicated this design. When the experiment started in 2020, this method cost about \$125 or \$260 per tower, depending on whether one or two booms were required.

### 3.2.3 Polyacrylamide Soil Conditioner

At the beginning of each season, a new sack with polyacrylamide (PAM) was hung from the selected towers (Fig. 3.10). The two fields in Burley utilized PAM pucks and the other fields used individual PAM logs. In either case, the PAM was contained inside a sack made of plastic netting, for containment and easy wetting by the pivot sprinkler system. These sacks were suspended directly in line with the pivot wheels, so when the PAM was hit by water, it would drip into the track and theoretically, stabilize the soil. The tracks that had PAM had no irrigation sprinkler modification and were irrigated with MESA sprinklers.

### 3.2.4 Experimental Design

The experimental design was different at each of the sites, in order to collect valuable, replicated data, without affecting the field operations of the cooperating farmers. The Burley, Idaho sites had similar designs, where the double PC, LEPA, single boom, PAM, and control treatments were each randomly assigned to a single pivot tower. When harvest time arrived, data were collected in four plot areas, evenly spaced along the curvature of each wheel track. At the Cornish 1, 2, and 3 sites, where one pivot irrigated all three sites, three pivot towers were randomly assigned to both the control and Advantage booms. Data were collected at four plots, spaced alongside the pivot track, for each of the six towers. At the Cornish 4 site, the double PC, LEPA, single boom, PAM, and control treatments were each assigned to a single pivot tower. Data for those five towers were collected at four plot areas adjacent to the pivot track, at positions throughout the field. The Nibley site had the double PC and LEPA methods with a

control treatment, where each were randomly assigned to three pivot towers. Data were collected from four plots along each of the nine wheel tracks. The double PC, LEPA, and single boom methods were tested with a control treatment at the Wellsville site. Each treatment was randomly assigned to a single pivot tower and evaluated at four places along the wheel track.

### **3.3 CROP AND WHEEL TRACK MEASUREMENTS**

#### **3.3.1 Alfalfa Analysis**

Alfalfa yields were measured beside the pivot wheel track after the cooperating farmer had windrowed the field, but before the windrows were raked. At the Nibley (2020) and Cornish (2021-2022) farms, alfalfa was cut in a circle, following the track of the pivot. The Wellsville and Cornish (2020) farmers windrowed straight across the field. At all sites, 3 m of windrow was collected at four places in the field, for each of the towers in the study. In the cases with circular harvests, the closest windrow on the outside edge of the wheel track was used. For the two fields that windrowed straight, the plot area went across the track. The plant material in the harvest area was gathered in a tote and weighed. A sub sample (about 100 g) was weighed in the field and forced-air oven dried at 60°C until constant mass. From these measurements, a dry matter (DM) yield was calculated beside each pivot track. The subsample was weighed then ground to pass through a 1 mm sieve using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, New Jersey). Ground samples were analyzed by near-infrared reflectance spectroscopy (NIRS) using a FOSS DS2500 F (Foss North America Inc., Eden Prairie,

MN) using the 2021 and 2022 legume hay NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, Kentucky) to estimate dry matter, crude protein (CP), neutral detergent fiber (NDF), neutral detergent fiber digestibility 48-h (NDFD), in vitro true dry matter digestibility 48-h (IVTDMD), total digestible nutrients (TDN), and relative forage quality RFQ. The following two quality parameters were calculated:

$$\text{[Eq. 1] Total Digestible Nutrients (TDN)} = (100 - (\text{NDF} - 2 + \text{CP} + 2.5 + \text{Ash})) \times 0.98 + \text{CP} \times 0.93 + (\text{Fat} - 1) \times 0.97 \times 2.25 + (\text{NDF} - 2) \times \text{NDFD} / 100 - 7$$

$$\text{[Eq. 2] Relative Forage Quality (RFQ)} = (((0.012 \times 1350 / (\text{NDF} / 100) + (\text{NDFD} - 45) \times 0.374) / 1350 \times 100) \times \text{TDN} / 1.23$$

### 3.3.2 Silage Corn Analysis

Corn was hand harvested shortly before the cooperating farmer's harvest, when corn was at approximately 650 g kg<sup>-1</sup> moisture content. In each plot, plants were cut 0.15 m above the soil surface in 3 m of the two rows nearest to the wheel track. All cut plants were weighed in the field, and a subsample of four plants from each plot were chipped in an Echo Bear Cat SC3206 Chipper Shredder (Crary Industries, West Fargo, North Dakota). Subsamples of chipped corn (~0.5 kg) were weighed then dried in a forced-air oven at 60°C until constant mass to determine DM yield. Dried samples were weighed, ground to pass through a 1 mm screen, and analyzed for forage quality using the same equipment as alfalfa samples. The 2022 fermented silage corn NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY) were used to estimate CP, NDF, NDFD, and starch and to calculate TDN:

$$[\text{Eq. 3}] \text{TDN} = 100 - (\text{NDF} - 2 + \text{CP} + \text{fat} + \text{ash}) \times 0.98 + \text{CP} \times 0.93 + (\text{fat} - 1) \times 0.97 \times 2.25 + (\text{NDF} - 2) \times \text{NDFD} / 100 - 7$$

### 3.3.3 Wheat Analysis

Wheat (*Triticum L.*) was harvested at the Cornish site using a small grains plot combine (Almaco, Nevada, Iowa). Harvest areas were about 10 m<sup>2</sup> but were precisely measured for producing accurate yield estimates. Being in a standing crop of wheat, the ability to travel around the field for replication was not possible so the farmer harvested a strip in the middle of the field for the entry of the plot combine and replication was achieved by the random selection of three towers for the treatment and three for the control. For each of the six towers being tested, the harvest areas were parallel to the wheel track, and grain samples were collected from the combine at each plot. This was done on both sides of the track to increase the sample size. These samples were weighed and then dried in a forced air oven at 60°C until constant mass to determine dry matter yield.

### 3.3.4 Wheel Track Depths

Wheel track depths were measured at the end of each growing season at four places along each wheel track, in the same plot areas where yield was measured. Regardless of the track depth, there was usually soil pushed up alongside the wheel track, from the downward pressure of the pivot. To compare track depth to the elevation of the field, and not the soil pushed up along the track, we used a 1-m long board with 0.15 m long pieces attached to each end. This apparatus was then placed perpendicular, across the wheel track, and measurements were taken from the bottom of the wheel track to the

board (Fig. 3.11). Then, 0.15 m was subtracted from the measured depths to account for the pieces that held the 1-m board above the ridges of soil along the track.

### **3.4 STATISTICAL ANALYSIS**

Statistical analyses were performed separately by site due to treatment differences among sites. For multi-year sites, data were analyzed with year, site, treatment, and their interactions as fixed effects and replicate and interactions with replicate as random. Year was also treated as a repeated effect in these analyses. Dependent variables were yield, quality parameters pertinent to each crop, and pivot rut depth. To ensure that the assumptions of equal distribution of residuals and equal variance were met, the UNIVARIATE procedure of SAS (SAS Institute Incorporated, Cary, North Carolina) was used to visually evaluate the results. All analysis were performed at  $P < 0.05$  using the MIXED procedure of SAS. Means separations were conducted using the PDIFF option of the MIXED procedure fat  $P < 0.05$ .

### **3.5 RESULTS AND DISCUSSION**

#### **3.5.1 Advantage Booms in Multiple Crops**

In 2020 the Advantage booms were tested on one pivot that irrigated alfalfa, silage corn, and wheat in different parts of the same field. The crops were analyzed individually, with pivot track treatment as the main effect (Table 3.3). The silage corn

was the only crop that was impacted by the Advantage booms and silage corn yield averaged 13.0 Mg ha<sup>-1</sup> for the control towers and 11.0 Mg ha<sup>-1</sup> for the advantage boom towers, a 15% decrease. Crop quality of alfalfa, silage corn, and wheat were rarely impacted by the Advantage booms near the pivot tracks. The only impact of the Advantage booms was that they reduced alfalfa NDFD from 546 to 539 g kg<sup>-1</sup>. Though statistically different, this change was not substantial enough to make a difference in the market value of alfalfa (USDA, 2023), as overall forage quality measured by RFV or RFQ was not impacted. There were also no differences in track depths caused by the Advantage booms, which averaged 26, 75, and 55 mm deep in the alfalfa, silage corn, and wheat, respectively. One issue worth noting is that the booms on the leading side of the pivot can become damaged as they “push” into the mature corn, instead of being pulled through on the non-leading side of the pivot, as is the common practice for booms on pivots. We could find no other studies evaluating the performance of Advantage booms and the results of this study are evidence that this approach may have negative impacts on the crop, but also may not improve pivot wheel tracks. Expanding the study to fields with different soil types or crops may determine a situation where this method is more beneficial.

### **3.5.2 Various Track Management Options for Alfalfa**

In Nibley, UT, the LEPA and PC sprinklers had no impacts ( $P < 0.05$ ) on alfalfa yield, forage quality parameters, or track depth (Table 3.3; Figure 3.12). Alfalfa yield averaged 3.0 Mg ha<sup>-1</sup> for the control treatment, while the advanced treatments yielded similarly at 3.0 Mg ha<sup>-1</sup> for the LEPA and 3.3 Mg ha<sup>-1</sup> for the PC method (Table 3.5). Alfalfa RFQ levels were 275, 287, and 288 for the control, LEPA, and PC treatments,



respectively. Wheel track depths averaged 88 mm for the control, 56 mm for LEPA, and 67 mm for the PC tracks. Early in the growing season, there were substantial track improvements (i.e., reduced depth) observed from the LEPA and PC methods, however, the benefit to the approaches decreased through the season and resulted in a lack of track improvements overall by the end of the season. This was surprising, as observations were that the LEPA and PC tracks did not get as wet as the control tracks, but would be damp from overspray from the neighboring MESA sprinklers and possibly lateral movement of the water in the topsoil. At this site, in a silty clay loam soil, a reduction of water in the wheel track did not reduce the compaction beneath the pivot tires and may have required an absence of water to be successful.

The “Cornish 4” site provided difficult conditions to test the alternative approaches. This pivot was a long, nine tower machine that irrigated a half circle in both directions. When evaluating the interaction of year and treatment, there were no significant differences in yield, track depth, or forage quality parameters (Table 3.4). However, pivot track treatments did impact yield, NDF, RFQ, and track depth across years. Average alfalfa yield, within 3 m of the wheel track, was greatest with the control at 10.0 Mg ha<sup>-1</sup>, which was statistically similar to the LEPA and PAM treatments at 9.5 and 9.9 Mg ha<sup>-1</sup>, respectively (Table 3.5). The single boom and PC methods both yielded lower at 8.3 and 8.7 Mg ha<sup>-1</sup>, losses of about 17% and 13%, respectively. Although track treatments impacted alfalfa NDF and RFQ values, all NDF values ranged from 25 to 28% and RFQ ranged from 259 to 299. These values indicate that all forage in the trial would be rated as “Supreme” market value in the USDA Hay Quality Designation Guidelines (USDA, 2023) and track method would have no impact on the market value of the alfalfa.

The PC method caused the shallowest wheel track at 105 mm, 27% shallower than the control track which averaged 144 mm deep. The single boom and PAM methods had the deepest wheel tracks at 184 and 209 mm, respectively, and were 28 and 45% deeper than the control. The LEPA track averaged 143 mm deep, which was statistically similar to the control.

The Wellsville site was also a half circle pivot, that was five towers long and would return to the same side of the field prior to the beginning of each irrigation. Due to its shorter length than the other pivots in the study, along with only irrigating in one direction, and already being in an established alfalfa stand, this field was already less prone to rutting than the other fields. The interaction of year by treatment had no effect on crop yield, forage quality, or wheel track depth (Table 3.4). When analyzing the data with the treatment as the main effect, there were no differences in yield or crop quality, however the track depth was different at  $P = 0.0382$ . The control track averaged 32 mm deep, while the single boom and LEPA methods measured significantly shallower at 18 and 13 mm, respectively. The PC method was similar to all treatments, measuring 22 mm deep (Table 3.5). The main effect of year affected yield and forage quality but not track depth. Differences in alfalfa production between years was influenced by the drought, which limited 2022 irrigation to a single, late season irrigation of about 76 mm. The lack of available water caused harvest to occur earlier in the crop growth stage than normal, and less mature alfalfa plants typically have different forage quality due to a higher leaf to stem ratio (Miller, 2018).

**Low energy precision application method.** When considering the results across the three locations (Nibley, Cornish, and Wellsville), LEPA maintained crop yield and

quality near the track while reducing the depth of the wheel track at the Wellsville site. At the Cornish 4 and Nibley sites it was able to maintain yield but did not provide any benefit to decreasing the wheel track depth. The good performance of LEPA at the Wellsville site may be because it was on the fourth tower, and that particular pivot always restarts on the dry side of the field. At the Cornish 4 site it was on the eighth tower, which would require a high flow rate in a concentrated area, and the pivot would restart directly where it finished. One speculation is that though LEPA was accurately applying water outside of the wheel track, the lateral movement of water in the topsoil would reach the track and saturate the area, particularly when applying a high rate in already wetted soil. There were similar observations from the Nibley site, where during the early irrigations of the season, LEPA preserved a shallow wheel track, but when peak evapotranspiration rates demanded more frequent irrigations, the soil saturation spread to include the wheel tracks. This may suggest that LEPA could be a good option to be considered for helping with wheel tracks, but sprinklers may need to be moved even further from the tower or the irrigation timing and rate may need to be finely tuned.

**Single boom method.** There were track improvements with the single boom at the Wellsville site but tracks at all towers were acceptable for performing field operations across. In contrast, the Cornish 4 site was a site with potential for terrible tracks, and in that situation, the single boom method had negative effects to yield and created deeper wheel tracks than the control tower. These were surprising results, because the same sprinklers were used on the boom, as were used on the control tower.

**Polyacrylamide method.** The PAM method was only used at the Cornish 4 site, where it maintained yield and quality, but left a track that measured 45% deeper than the control.

It was not surprising that crop yield and quality were unchanged, as there were not modifications to the sprinkler package. However, it was difficult to reason that it not only did not have a similar track depth as the control track, but it made it worse. This may have been impacted by the ability of PAM to increase soil infiltration rates, as has been commonly found by other researchers (Sojka et al., 1998; Zhang & Miller, 1996; Lentz & Sojka, 1994) who evaluated PAM in surface irrigation systems, finding infiltration increases up to 30%. If infiltration inside the wheel track were increased with PAM, the depth of wet soil could be deeper than then control tower, which may have allowed the 4 Mg pivot tower to sink deeper and increase rutting.

**Part circle method.** The PC method maintained yield and forage quality at the Nibley and Wellsville sites and had small improvements to the wheel tracks at each site. Its largest impact was at the Cornish 4 site, where it reduced the wheel track by 27%, but it also reduced yield by 13%. At August 2022 alfalfa prices (~USD\$330 Mg<sup>-1</sup>; Hay and Forage Grower, 2022), this lost yield could cost a farmer about \$445 ha<sup>-1</sup> on the area that falls within 3 m of the pivot towers. The area within this zone would differ depending on pivot size and motion but has the potential to be several hectares of a field. Savings from reduced equipment repairs and lower energy costs of moving the pivot are difficult to quantify, particularly when the pivot track has not been eliminated and there could still be detrimental effects from the remaining wheel track. Therefore, pivot track sprinkler modifications that do not impact the yield around the track and reduce the track depth are critical for optimizing profits.

### **3.5.4 Various Track Management Options for Silage Corn**

The two silage corn fields near Burley, ID were analyzed together because the same treatments were used at both sites. The interaction of farm  $\times$  year  $\times$  treatment was significant for yield, NDFD, and track depth (Table 3.7). The LEPA treatment maintained silage corn yield in all site-year except Burley 1 in 2021 where it increased silage corn yield by 7.14 Mg ha<sup>-1</sup> or 31% along the wheel track compared to the control treatment (Table 3.7). The PAM treatment had the next most consistent results and it decreased yield by 3.5 Mg ha<sup>-1</sup> (18%) compared to the control in a single site-year (Burley 1 in 2022). The single boom approach was less consistent, as it decreased yield compared to the control both years at the Burley 1 site by 6.6 to 6.7 Mg ha<sup>-1</sup> (29 to 35%), yet maintained or increased yield at the Burley 2 site. The PC method decreased yield by 5.7 to 9.4 Mg ha<sup>-1</sup> (25-41%) compared to the control at both sites in 2021 but maintained yield at both sites the following year. This improvement is likely due to some changes before the 2022 growing season, where the sprinklers were aimed properly to achieve maximum uniformity (this did not happen in 2021 and caused a severe irrigation reduction beside the wheel track), and nozzles were changed to a single size larger.

NDFD (48-h) is a description of the percentage of a feedstock that a cow could digest in 48-h, with higher values being desired. In 2021, the LEPA and PAM treatments reduced NDFD (48-h) at the Burley 1 site, from 68.0% to 59.8 and 64.1%, respectively (Table 3.7). At the Burley 2 site, NDFD (48-h) values were also different in 2021, with the control treatment being 58.2%, while LEPA, PAM, and the PC method measured 64.0, 62.8, and 64.2%, respectively. In 2022, there were no NDFD (48-h) differences at either site. Wheel track depth differences were most pronounced in 2021. That year, at the Burley 1 site, the control track depth was 183 mm, which was only similar to the PAM

treatment, which measured 200 mm deep (Table 3.7). The single boom, LEPA, and PC treatments measured 105, 97, and 64 mm deep, respectively, 43, 47, and 65% less deep than the control. These changes did not carry into 2022 at that site, where all treatments had similar depths to the control, ranging from 106 to 121 mm deep. At the Burley 2 site, the control track measured 68 mm in 2021. This was similar to the PAM treatment, which measured 87 mm, but worse than the LEPA and PC treatments, which were 25 and 40 mm deep, respectively. These were improvements of 63 and 41% with the LEPA and PC methods, respectively. The PAM treatment had the worst tracks at 129 mm deep, 90% deeper than the control. In 2022, the single boom method was the only method to affect track depth, where it was 111 mm deep, 46% deeper than the control track which measured 76 mm deep.

With treatment as the main effect, there were many differences to crop quality (Table 3.6). The average CP level for the control treatment was the lowest of the study at 8%, and the other treatments, despite statistical differences, were all under 9%. NDF levels were highest in the control treatment at 40%, which was statistically similar to the LEPA and PAM treatments which measured 38% and 39%, respectively. The single boom and PC methods were significantly lower than the control, measuring 37% and 36%, which are valuable improvements towards a higher value, more palatable feed, however it likely came due to the lower yielding, immature plants which would have been a larger loss to the farm. The control had the lowest TDN level at 72.4%, which was similar to the LEPA and PAM treatments which totaled 73.1 and 72.9% respectively, all sufficient levels for 'supreme' alfalfa. The single boom and PC treatments were slightly higher at 73.9 and 74.4%. Starch levels were statistically similar between treatments,

ranging from 30 to 32%, except for the part circle method which measured 34.11%.

**Low Energy Precision Application method.** LEPA consistently maintained or increased silage corn yield and had a lower average track depth than the control. In 2021, LEPA track depths were significantly better, by 47% at Burley 1 and by 63% at Burley 2 (Table 3.7). Track depths for LEPA and the control did not differ in 2022 at either site. These results may suggest that LEPA can be a safe option with respect to crop production and can improve track depths in some but not all years. At about US\$200 per tower for equipment and a simple installation, this may be a low-cost and simple option for growers to experiment with to improve track depths and crop yield.

**Single Boom method.** The single boom method was inconsistent, making the track 43% shallower at Burley 1 in 2021, but having no effect the following year at that site (Table 3.7). At the Burley 2 site, the single boom made tracks that were 88% and 46% deeper than the control, in 2021 and 2022, respectively. At the Burley 1 site, this method reduced yield both years, but at the Burley 2 site it improved yield in 2021 and maintained it in 2022. These results suggest that there is risk for significant, expensive crop losses, if the single boom method is not tailored well to the field conditions, and that in many situations it will not be helpful for improving the wheel track.

**Polyacrylamide method.** The PAM method did not improve wheel tracks at either site or in either year. However, unlike in the alfalfa trials, it did not cause deeper wheel tracks. Despite the impressive performance of PAM in surface irrigation and low cost to introduce it to pivot wheel track reduction strategies, it is a method that may not improve pivot wheel tracks.

**Double Part Circle method.** This method decreased track depth in 2021, however this was when the sprinkler heads were not oriented properly and there were significant yield decreases. In 2022, the PC approach and control treatment had similar track depths, as well as crop quality and yield. This may suggest that the PC method may not affect silage corn yield and quality, but it may not improve the wheel tracks either, especially in situations where potential for lateral movement of the water is high, such as: heavy irrigations, wiper-motion pivots, or bare soil in row crops.

### 3.5.5 CONCLUSIONS

This research evaluated several methods to help reduce wheel tracks on pivots. The eight-boom design (i.e., Advantage booms) had mostly positive crop responses but did not create shallower wheel tracks. The single boom method used by irrigation equipment dealers in Northern Utah and Southern Idaho often maintained crop quality, but there were multiple instances and crops that had reduced yield, and unimproved or worse wheel tracks than the control areas. PAM had few effects on crop yield and quality, or wheel track depth. The PC method provided much shallower track depths at one site, but it came at the expense of a lower crop yield. At other sites there were minimal effects to yield and quality with the PC method, but the early-season, shallow wheel tracks did not usually last through the heaviest time of irrigating. LEPA was the most reliable method for maintaining crop yield and quality, while improving wheel tracks. In situations where there was high potential for the soil to become saturated, the LEPA approach could saturate the pivot track and allow the creation of deep ruts, but further experimentation with the sprinkler spacing, application method, and speed may be able to minimize these occurrences. Due to the concentrated application of LEPA, it is



not recommended on fields with slopes greater than 1%, because of the potential for surface movement in the field and runoff (Senninger Irrigation, 2023). There was no approach in the study that maintained yield and reduced pivot track depth in every scenario, but the LEPA method displayed the greatest potential for uniformly irrigating the area near the wheel track to maintain crop yield and quality, while minimizing water entering the track, to help reduce burdensome pivot ruts.

**TABLE 3.1** Site properties for nine on-farm trials in Utah and Idaho from 2020 to 2022, including nearest town, year, coordinates, soil texture, slope, and drainage

<b>Nearest town</b>	<b>Year</b>	<b>Coordinates</b>	<b>Dominant soil texture (classification)</b>	<b>Slope<sup>a</sup></b>	<b>Drainage classification</b>
Burley, ID 1	2021- 2022	42.506, -113.705	Clay Loam (Fine loamy, mixed, mesic Xerollic Haplargids)	n/a	Well drained
Burley, ID 2	2021- 2022	42.475, -113.724	Loam (Coarse-loamy over sandy or sandy-skeletal, mixed, mesic Durixerollic Camborthids)	n/a	Well drained
Cornish, UT 1	2020	41.994, -111.967	Fine Sandy Loam (Coarse-loamy, mixed, mesic Calcic Haploxerolls)	0-2%	Moderately well drained
Cornish, UT 2	2020	41.990, -111.961	Fine Sandy Loam (Coarse-loamy, mixed, mesic Calcic Haploxerolls)	0-2%	Moderately well drained
Cornish, UT 3	2020	41.998, -111.958	Fine Sandy Loam (Coarse-loamy, mixed, mesic Calcic Haploxerolls)	0-2%	Moderately well drained
Cornish, UT 4	2021- 2022	42.003, -111.973	Silty Clay Loam (Fine, mixed, mesic Calcic Pachic Argixerolls)	0-2%	Well drained

Nibley, UT	2020	41.664, -111.879	Silty Clay Loam (Fine, mixed, mesic Aquic Argiustolls)	0-3%	Somewhat poorly drained
Wellsville, UT	2021- 2022	41.662, -111.917	Loam (Fine-silty, mixed, mesic Aquic Calciustolls)	0-3%	Somewhat poorly drained

---

<sup>a</sup> n/a, not available.

**TABLE 3.2** Site properties for nine on-farm pivot wheel rut trials in Utah and Idaho from 2020 to 2022, including nearest town, crop, methods tested, and pivot motion

<b>Nearest town</b>	<b>Crop</b>	<b>Methods tested<sup>a</sup></b>	<b>Pivot motion</b>
Burley, ID 1	Silage corn	LEPA, Part circle, PAM, Single boom	Half circle
Burley, ID 2	Silage corn	LEPA, Part circle, PAM, Single boom	Half circle
Cornish, UT 1	Alfalfa	Advantage booms	Full circle
Cornish, UT 2	Silage corn	Advantage booms	Full circle
Cornish, UT 3	Wheat	Advantage booms	Full circle
Cornish, UT 4	Alfalfa	LEPA, Part circle, PAM, Single boom	Half circle
Nibley, UT	Alfalfa	LEPA, Part circle	Half circle
Wellsville, UT	Alfalfa	LEPA, Part circle, PAM, Single boom	Half circle

<sup>a</sup> LEPA, low energy precision application; PAM, polyacrylamide.

**TABLE 3.3** Significance of *F* tests for the fixed effect of pivot track treatment on crop yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; RFQ, relative forage quality, starch, and test weight), as well as depth of wheel track for sites with only one year (Nibley, Cornish 1, 2, and 3). Differences were considered statistically significant when  $P < 0.05$

Site	Crop	Yield	CP	NDF	NDFD	IVTDMD	TDN	RFQ	Starch	Test	Depth
----- <i>P</i> > <i>F</i> -----											
Nibley	Alfalfa	0.3598	0.7712	0.8619	0.5474	0.9276	0.8919	0.9255	n/a	n/a	0.2535
Cornish 1	Alfalfa	0.1375	0.5538	0.8166	<b>0.0369</b>	0.2475	0.1648	0.3302	n/a	n/a	0.2102
Cornish 2	Corn	<b>0.0133</b>	0.2794	0.7436	0.8337	0.9866	0.3787	n/a	0.4017	n/a	0.5523
Cornish 3	Wheat	0.2309	0.5417	n/a <sup>a</sup>	n/a	n/a	n/a	n/a	n/a	0.4512	0.3878

<sup>a</sup> n/a, not applicable

**TABLE 3.4** Significance of *F* tests for the fixed effects of year and treatment, and their interaction on alfalfa yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; and RFQ, relative forage quality), as well as depth of wheel track at the Cornish 4 and Wellsville sites. Differences were considered statistically significant when  $P < 0.05$

Nearest Town	Effect	Yield	CP	NDF	NDFD	IVTDMD	TDN	RFQ	Depth
----- <i>P</i> > <i>F</i> -----									
Cornish 4	Year (Y)	0.373	0.094	0.273	0.649	<b>0.007</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.477
	Treatment (trt)	<b>0.006</b>	0.170	<b>0.025</b>	0.340	0.138	0.087	<b>0.012</b>	<b>&lt;0.001</b>
	Y × trt	0.355	0.830	0.477	0.139	0.542	0.903	0.167	0.865
Wellsville	Year (Y)	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.190	<b>&lt;0.001</b>	0.189
	Treatment (trt)	0.357	0.448	0.174	0.782	0.276	0.256	0.135	<b>0.038</b>
	Y × trt	0.577	0.381	0.225	0.862	0.518	0.767	0.309	0.962

**TABLE 3.5** Average alfalfa dry matter yield, alfalfa RFQ (relative forage quality), and wheel track depths at the Cornish 4 (2021-2022), Nibley (2020), and Wellsville (2021-2022) sites, as affected by wheel track treatments. Mean separations were conducted at  $P < 0.05$  by variable and by site and are denoted by letters following means

Site	Method <sup>a</sup>	Yield Mg ha <sup>-1</sup>	RFQ	Track depth mm
Cornish 4	Control	10.04a	282ab	144b
	Single boom	8.33c	299a	184a
	LEPA	9.53ab	260c	143b
	PAM	9.86a	278abc	201a
	Part circle	8.69bc	272bc	105c
Nibley	Control	3.02a	275a	88a
	LEPA	2.98a	287a	56a
	Part circle	3.31a	288a	67a
Wellsville	Control	6.37a	233a	32a
	Single boom	5.87a	222ab	18b
	LEPA	6.46a	212b	13b
	Part circle	6.30a	218ab	22ab

<sup>a</sup>LEPA, low energy precision application; PAM, polyacrylamide.

**TABLE 3.6** Significance of F tests for the fixed effects of year, farm, and treatment, and their interaction on yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; and starch), as well as depth of wheel track. Differences were considered statistically significant when  $P < 0.05$ .

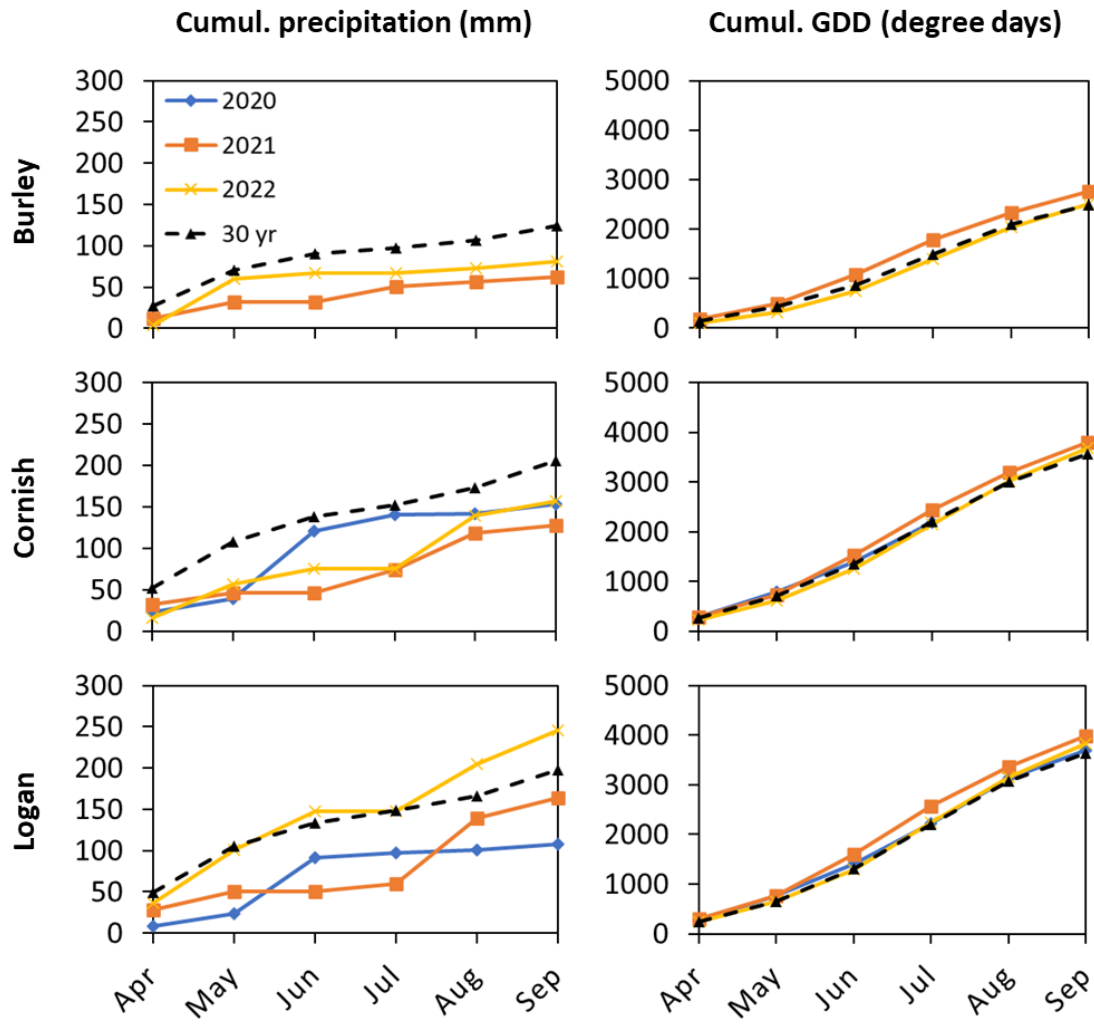
<b>Effect</b>	<b>Yield</b>	<b>CP</b>	<b>NDF</b>	<b>NDFD</b>	<b>TDN</b>	<b>Starch</b>	<b>Depth</b>
	----- $P > F$ -----						
Year (Y)	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.391	0.207
Farm (F)	<b>0.034</b>	<b>0.001</b>	0.169	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.307	<b>&lt;0.001</b>
Treatment (trt)	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.016</b>	<b>0.005</b>	<b>0.001</b>	<b>0.025</b>	<b>&lt;0.001</b>
Y × trt	<b>&lt;0.001</b>	0.192	0.858	<b>0.003</b>	0.771	0.500	<b>&lt;0.001</b>
Y × F	0.471	0.047	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.134
F × trt	<b>&lt;0.001</b>	<b>0.002</b>	0.280	<b>&lt;0.001</b>	<b>0.006</b>	0.120	<b>&lt;0.001</b>
F × Y × trt	<b>0.023</b>	0.259	0.516	<b>0.001</b>	0.348	0.698	<b>&lt;0.001</b>

**TABLE 3.7** Impact of pivot track methods on silage corn dry matter yield, NDFD (neutral detergent fiber digestibility 48-h), and wheel track depths at two sites near Burley, ID in 2021 and 2022. Letters of significance denote a difference when  $P < 0.05$

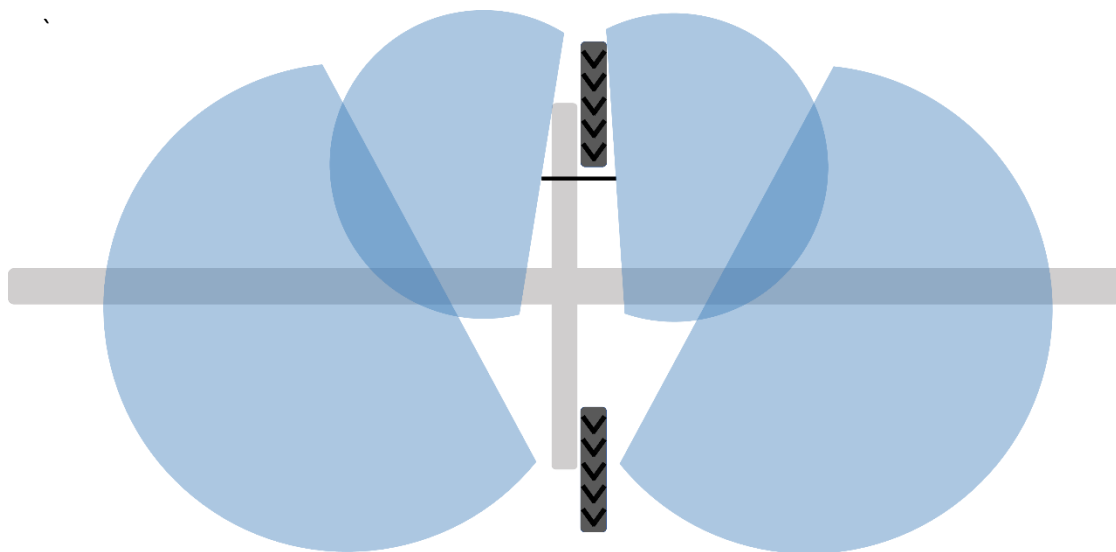
Site	Year	Method <sup>a</sup>	Yield Mg ha <sup>-1</sup>	NDFD g kg <sup>-1</sup>	Depth mm
Burley 1	2021	Control	22.81cd	680e	183a
		Single boom	16.17fgh	705de	105bcde
		LEPA	29.95a	598g	97cdef
		PAM	25.35bc	641f	200a
		Part circle	13.40hi	699e	64ghi
	2022	Control	19.29ef	736abc	121bc
		Single boom	12.56i	763a	116bcd
		LEPA	20.41de	732bcd	106bcd
		PAM	15.84ghi	754abc	108bcd
		Part circle	18.13efg	735bc	111bcd
Burley 2	2021	Control	22.91cd	582g	68fgh
		Single boom	27.44ab	599g	128b
		LEPA	19.79de	640f	25j
		PAM	25.42bc	628f	87defg
		Part circle	17.17efg	642f	40ij
	2022	Control	20.18de	730bcd	76efgh
		Single boom	20.37de	728cd	111bcd
		LEPA	17.01efg	757ab	54fij
		PAM	19.10efg	742abc	64ghi
		Part circle	19.19efg	744abc	52hij

<sup>a</sup> LEPA, low energy precision application; PAM, polyacrylamide.





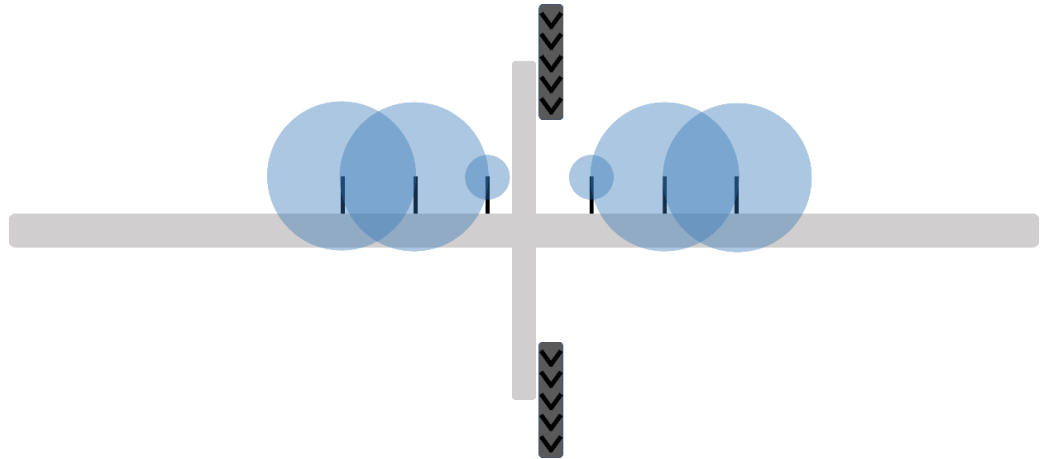
**FIGURE 3.1** Cumulative monthly precipitation and seasonal growing degree days (GDD) totals for Burley, Cornish, and combined Nibley and Wellsville sites (Logan). GDD calculations were adjusted for corn for Burley, and alfalfa for Cornish and Logan. The 30-yr normals (1991-2020) are shown for reference



**FIGURE 3.2** A depiction of the double part circle method as illustrated from above the pivot tower. Blue shapes represent the irrigation water emitted at the outlets nearest to the pivot tower



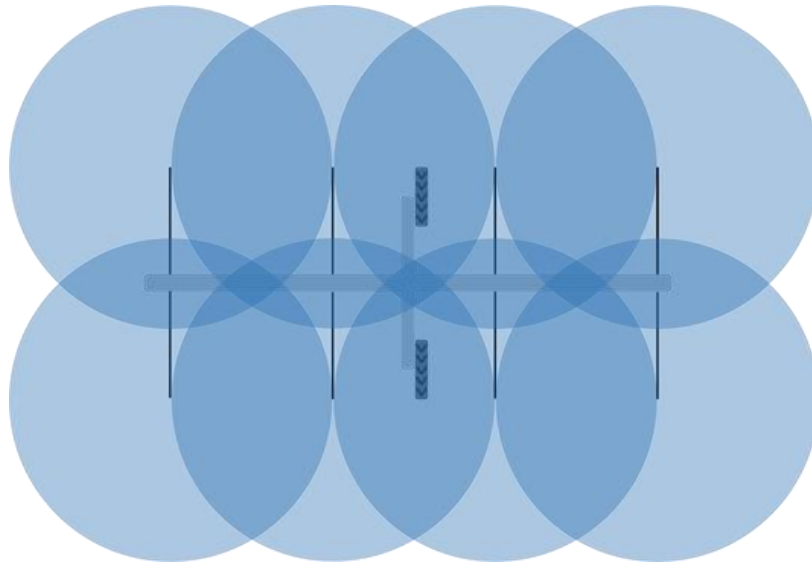
**FIGURE 3.3** Two part circle sprinklers mounted to a PVC pipe manifold, attached to a pivot tower, as part of the double part circle method



**FIGURE 3.4** A depiction of the low energy precision application (LEPA) method as illustrated from above the pivot tower. Blue shapes represent the irrigation water emitted at the outlets nearest to the pivot tower. In this case, one sprinkler per side was replaced with three sprinklers



**FIGURE 3.5** Low energy precision application (LEPA) style sprinklers plumbed from the outlet closest to each side of the pivot tower, where mid elevation sprinkler application (MESA) sprinklers were previously mounted

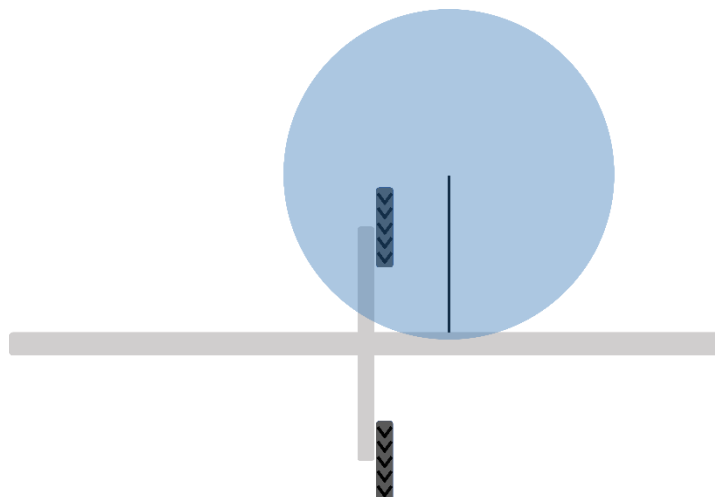


**FIGURE 3.6** A depiction of the “Komet Advantage” method as illustrated from above the pivot tower. Blue shapes represent the irrigation water emitted at the outlets nearest to the pivot tower



**FIGURE 3.7** The “Komet Advantage” method installed on a pivot





**FIGURE 3.8** A depiction of the single suspended boom method as illustrated from above the pivot tower. The blue circle represents the wetting area of the sprinkler attached to the boom, and the pivot would be travelling downward in this example so irrigation is applied behind the pivot



**FIGURE 3.9** A single-boom attached to a pivot, intended to direct water behind the direction of travel

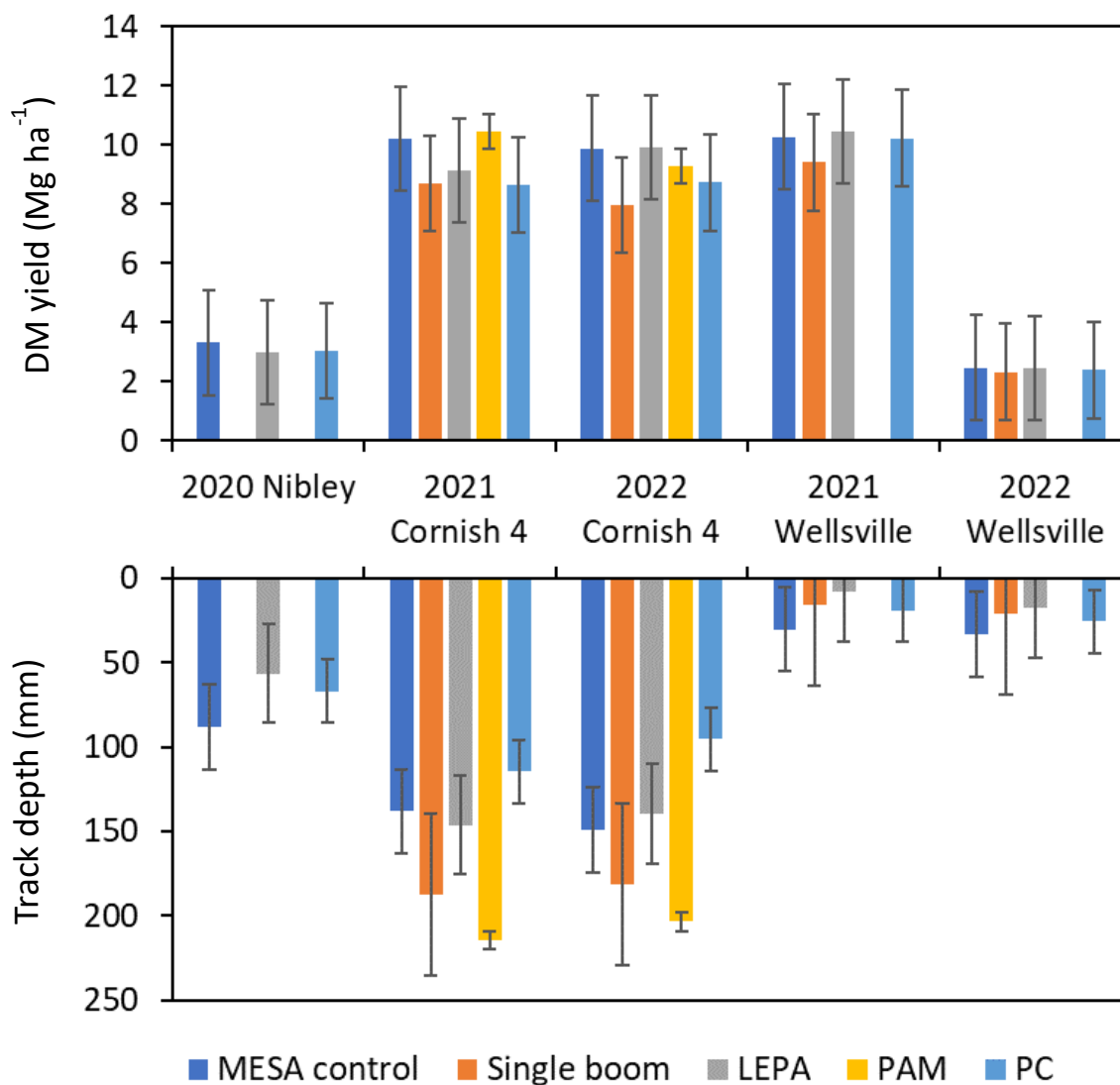


**FIGURE 3.10** A polyacrylamide (PAM) log inside a plastic mesh sack is hung above the wheel track, so as irrigation water contacts the PAM, the log dissolves and enters the wheel track



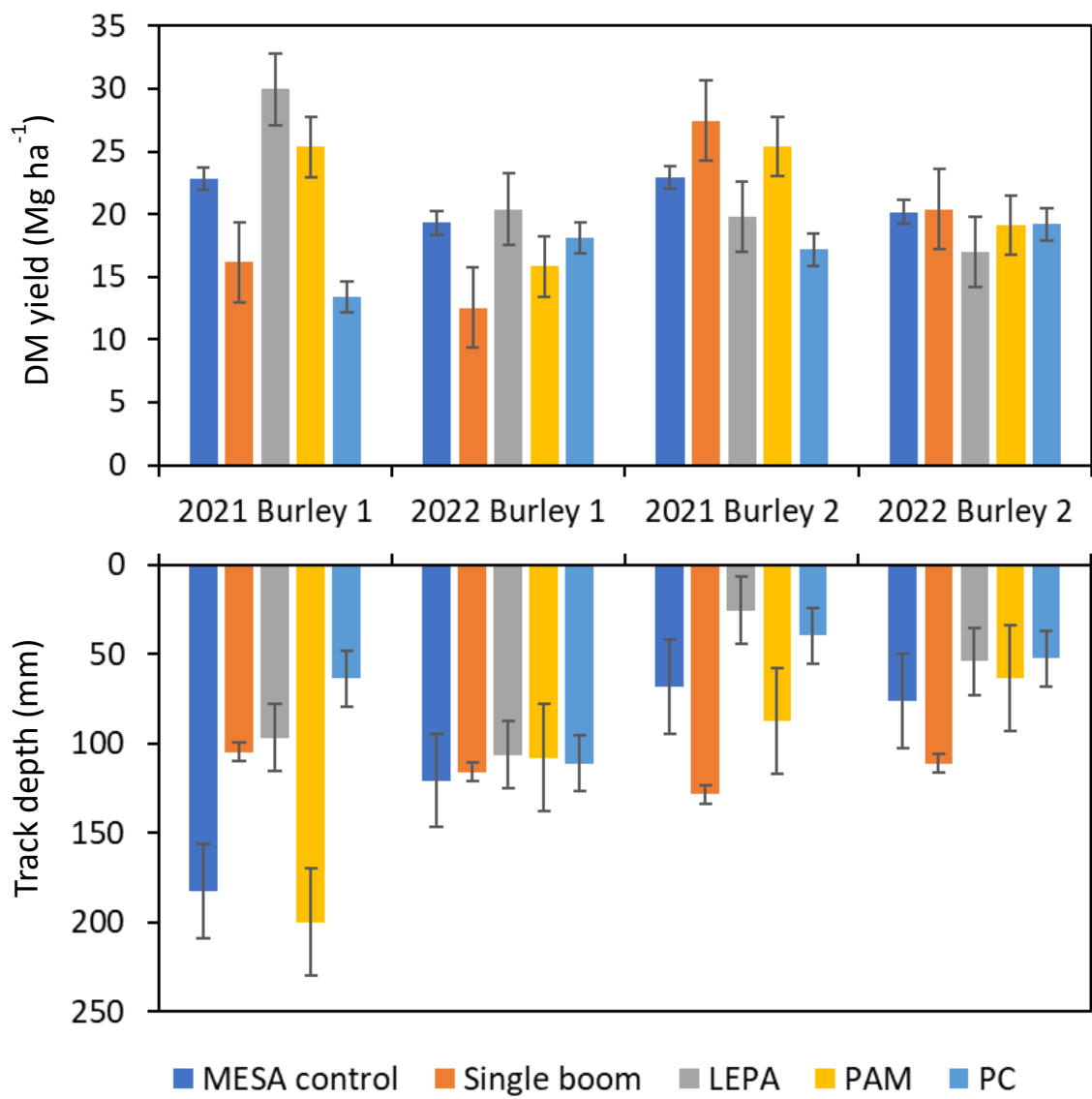


**FIGURE 3.11** Track depths were measured from the bottom of the wheel track up to a 1 m long plank, which was suspended above the soil surface on two 0.15 m legs to avoid soil ridges alongside the wheel track.



**FIGURE 3.12** Alfalfa DM (dry matter) yield and pivot wheel track depth responses to the MESA (mid elevation sprinkler application) control, single boom, LEPA (low energy precision application), PAM (polyacrylamide), and PC (double part circle) methods at the Nibley, Cornish 4, and Wellsville sites





**FIGURE 3.13** Silage corn DM (dry matter) yield and pivot wheel track depth responses to the MESA (mid elevation sprinkler application) control, single boom, LEPA (low energy precision application), PAM (polyacrylamide), and PC (double part circle) methods at the two sites near Burley, ID

## CHAPTER 4

### SOIL MOISTURE SENSORS AND IRRIGATION SCHEDULING PROGRAMS ARE A HELPFUL RESOURCE FOR IRRIGATORS

#### 4.1 INTRODUCTION

Water scarcity due to drought frequently affects much of the United States (NOAA, 2022). This is concerning, since 54% of all crop sales in the country come from irrigated land that comprises less than 20% of the harvested cropland (USDA, 2022), signifying how important irrigation is to meeting the needs of Americans. Another facet is that about 2335 people are added to the U.S. population each day (US Census Bureau, 2022), furthering the demand for commodities grown on what has been a diminishing number of acres nationally (FAO, 2011). Irrigation has proved to be a tool that can increase crop yields (Kukal & Irmak, 2019), and will likely be increasingly important in meeting the current and future population demands. Methods for optimizing water in drought situations are needed to ensure that the high demands of those limited irrigated areas can still be met. One possible solution is using scientific irrigation scheduling (SIS), including soil moisture sensors, water balance programs, or commercial irrigation schedulers to more precisely schedule irrigation amounts and timing.

At a conference of the American Society of Agricultural Engineers, Howell (1996) presented the limitations of irrigation scheduling, suggesting that it could not save significant amounts of water by reducing transpiration because it would reduce yield. The high consumer demand and low margins received by farmers requires irrigation management solutions that maintain yield, eliminate wasteful application, and not affect transpiration. A good starting point for this may be accurately evaluating what level of

water is available to the plant roots. This often happens on the farm with shovels or soil probes, but sensors can also provide reliable, useful information for knowing and responding to irrigation needs (Campbell & Campbell, 1982). In a large study in Nebraska, USA, 32 corn (*Zea mays* L.) fields with no irrigation scheduling method implemented were compared to 19 corn fields using tensiometers at 300, 600, and 900 mm depths at three to four places in the field (Kranz et al., 1992). They found that 11% less water was applied in the fields utilizing the tensiometers, and yield was maintained or increased. This would suggest that the tensiometers helped reduce wasteful application, without reducing crop transpiration, however, the study did not include replicated treatments within the same field. Challenges to soil moisture sensors that may limit their effectiveness or feasibility on some farms include inaccuracies from incorrect calibration (Sui, 2017) or difficult installations that require minimal soil disturbance (Aguilar et al., 2015). Another challenge is soil variation that may require many sensors throughout a field to attain an accurate field representation, while placing the sensors in positions representative of the rootzone poses another challenge (Jones, 2004). Equipment and labor costs of installing sensors at several places in a field can quickly become expensive, particularly if the farmer is not guaranteed a monetary return on the investment. There is also a degree of inconvenience from having to modify field operations to avoid damaging sensors and loggers.

Several universities and private entities have developed irrigation scheduling programs or applications that use weather data from local stations, crop growth models, and user input to determine a root zone water balance for scheduling irrigation. These programs are usually simple to use, do not require equipment to be installed in the field,

and can be inexpensive or free. Brajovic et al. (2015) provided an overview of some of these programs and noted that they are important tools to help feed the growing population. Vellidis et al. (2016) created an irrigation scheduling tool for cotton and found that using it increased the available water and water use efficiency. However, that same study also stated two challenges to using an irrigation scheduling program, noting that precipitation at the field can be much different than the precipitation measured at the local weather station, and tillage impacts not factored-in by the programs introduce inaccuracies in the irrigation recommendations (Vellidis et al., 2016). Washington State University developed a free irrigation program called Irrigation Scheduler Mobile (ISM) that is available across the western US and Canada (Peters, 2014). Additional coverage is possible by adding private weather stations to their network. ISM uses local weather data, a crop coefficient, and soil available water capacity estimates based off soil texture to determine available water content of the root zone. It then displays this data in a fuel-gauge style graphic, with “Full” being field capacity (FC) and “Dead” being the permanent wilting point, as well as a read-out with the current estimated soil water deficit and time until crop water stress. Once a field is setup, the only information required by the farmer is to enter irrigation amounts and harvest dates. There are also options for users to fine-tune crop coefficients, soil available water holding capacity, crop growth, and actual precipitation at the field to increase the accuracy of the recommendations. The ability to make adjustments in ISM may help it overcome some of the cited inaccuracies of irrigation scheduling tools and may help it to be a useful tool for tracking soil available water and knowing the precise needs of the crop.

One commercially available tool for irrigation scheduling is FieldNET Advisor

(FNA) from Lindsay Corporation (Omaha, Nebraska, USA). Using soil maps and water storage data provided by the Natural Resources Conservation Service, proprietary crop canopy and root growth models, and local weather data, FNA estimates available soil water in each soil type in a field. From that data, it creates a variable rate irrigation plan that can alter the speed of the pivot to apply differing amounts of irrigation. In a study conducted by Lindsay Corp., FNA increased corn yields by 3%, while applying 17% less water (Lindsay Corporation, 2018). There is little, if any, published, third party research of FNA.

The objective of this study was to determine the effects of four irrigation scheduling approaches (farmer standard, a water content soil moisture sensor set, the Irrigation Scheduler Mobile program, and FieldNET Advisor) on alfalfa (*Medicago sativa* L.) yield, forage quality, and water use.

## **4.2 MATERIALS AND METHODS**

### **4.2.1 Site Characteristics**

This experiment was established in the spring of 2019 on 12 farm fields in Utah, prior to the start of the growing season. Due to various logistical and equipment constraints, the study was continued at 10 of the 12 fields in 2020, and six for the final season of 2021. All fields were established alfalfa stands with center pivot irrigation. Soil classification, textural group, and slope classifications were obtained from the University of California-Davis SoilWeb (O'Geen, 2020; Table 4.1). Weather data were obtained from the Utah Climate Center ([climate.usu.edu](http://climate.usu.edu); Logan, UT, USA; Table 4.2) and were

used to calculate cumulative precipitation and GDD. Weather stations were located on the field edge or within 5 km of each field. Fields with close proximity to existing weather stations were prioritized in field selections. Growing degree days were calculated using a base air temperature of 5°C and an adjusted maximum of 30°C. Measured cumulative precipitation and GDD were compared with their respective 30 yr normals (1991-2020) provided by the National Oceanic and Atmospheric Administration (noaa.gov; Silver Spring, MD, USA). At each farm, field operations were conducted by the cooperating farmer, and the irrigation management was a cooperative effort among collaborators.

#### **4.2.2 Irrigation Scheduling Approaches**

In this study, three irrigation scheduling tools were compared with each cooperating farmer's chosen application amount. To accomplish this, the cooperating farmers would communicate their desired amount for each irrigation as a depth. Using speed control in FieldNET (Lindsay Corporation, Omaha, Nebraska, USA), application amounts from the three irrigation scheduling tools and the cooperating farmer's desired amount were each applied to a large section of the field in 2019 (12 – 16 degrees each). For 2020-2021, the design was changed to included four, smaller sectors (3 - 5 degrees each) for each treatment in the field, for a total of 16 sectors assigned randomly. The rest of the field was then irrigated to the cooperating farmer's desired rate. This sequence was followed for every irrigation event at each field unless a periodic uniform fertigation or chemigation application was needed. These were typically low irrigation application rates to rapidly apply chemicals through irrigation. Harvest areas for yield measurements were

taken from the middle of each sector, in a plot area that was the same for each alfalfa harvest.

#### 4.2.2.1 Soil Moisture Sensor with a Water Balance Spreadsheet

Prior to the 2019 growing season, Teros 10 volumetric water content (VWC) sensors (Meter Group, Pullman, WA, USA) were installed at 300, 600, 900, 1200, 1500, and 1800 mm depths, by insertion into the wall of a 100 mm bore hole. At three farms (Beaver, Fillmore 1, and Milford), sensors were installed at 150, 300, 450, 600, 750, and 900 mm depths, because the equipment to install deeper was not yet available. Soil moisture data were collected by ZL6 data loggers (Meter Group, Pullman, WA, USA) and were monitored remotely through the ZENTRA Cloud online application. The wet spring of 2019 was ideal for estimating FC at each sensor depth (Figure 4.1). After significant rain events, the water content was monitored closely to observe when the soil would quickly drain excess water, then pause at a constant level. This point was recorded as the estimated FC for each soil moisture sensor.

To generate irrigation recommendations from the VWC readings, a simple spreadsheet was created where the current VWC readings were subtracted from the previously determined FC at each depth. Those calculations were summed together to determine the amount of irrigation required to refill the rootzone. That value was then divided by 80%, to account for pivot efficiency losses common to the mid elevation sprinkler application (MESA) sprinkler packages used on the pivots in the study (New & Fipps, 2000; Amosson et al., 2011; Sarwar et al., 2019). Though this was not commonly an issue, irrigation amounts were never permitted to exceed 90 mm in a single irrigation event. A management allowable depletion (MAD) level was set at 60%, as a guide to

keep VWC above that level to limit crop stress. This was followed as closely as water schedules and water availability would permit. Annual costs for this irrigation scheduling method are estimated at around USD\$2000 per pivot, when spreading the upfront costs of equipment and installation over five years, and accounting for annual subscriptions and operational labor (Utah State University Extension, 2023).

#### 4.2.2.2 Commercial Irrigation Scheduler

The computer program used to apply the irrigation treatments was FieldNET from Lindsay Corporation. An option within FieldNET is to add additional programming called FieldNET Advisor (FNA). According to their product summary, FNA can, “Track the available soil water throughout the field by combining a soil map of the field, proprietary dynamic crop canopy and root growth models, hyper-local weather data and the applied irrigation history,” to generate irrigation recommendations. The program divides a circular field into 360 sectors, that each receive a recommendation from the data sources previously mentioned. According to 2023 pricing, the costs associated with this tool are an annual FieldNET subscription (~USD\$255 per pivot), an annual FNA subscription (~USD\$383 per pivot), and the labor to manage the app. Farms with several pivots can benefit from small price breaks on the subscriptions, or a reduced annual FieldNET subscription of USD\$153 per pivot if a radio base-station (~USD\$2000 for up to 100 pivots) is utilized with on-farm internet (R. Moyle, personal communication, February, 2023). To test FNA as the example of a commercial irrigation scheduler, the sectors that contained the plot area would receive the amount of irrigation as recommended by the program on the day the cooperating grower chose to irrigate. In 2021, recommendations were not entered correctly for these treatment areas, as the



general recommendation for the entire field was mistakenly used instead of the individual sector prescriptions. Therefore, results from this year for this treatment need to be considered in this context.

#### 4.2.2.3 Irrigation Scheduler Mobile

Each field was entered into ISM prior to the start of the 2019 growing season. Throughout the growing seasons, ISM estimates the available water content of the soil and displays what the current soil water deficit is. Like the procedure for using a soil moisture sensor, the deficit was divided by 80% to account for irrigation water lost due to efficiency losses of the pivot sprinkler package. Every irrigation event was recorded in ISM to keep the water balance up to date. Harvest dates of the alfalfa were also input into ISM, to keep the model accurate for changes in ET as the crop is harvested and begins to regrow. Though the program is free, it is estimated that USD\$824 per pivot is required annually to cover the labor costs of operating the program over a 20-week irrigation season (Utah State University Extension, 2023).

Upon completion of the study, researchers learned that net irrigation amounts were supposed to be entered into ISM, not gross irrigation amounts. Due to this oversight, the water balance equation used by the program would have been incorrect by the amount of irrigation loss during application, which for MESA style sprinklers is generally believed to be about 20% (New & Fipps, 2000; Amosson et al., 2011; Sarwar et al., 2019). Despite possible underirrigation due to this error, the authors believe that the results still include important information to potential users of this program.

### **4.3 CROP YIELD AND QUALITY**

### 4.3.1 Alfalfa Analysis

Alfalfa yield was measured after cooperating farmers had windrowed each field, but before the windrows were raked. Farmers harvested according to their preferred schedules using windrowers that were 5 – 6 m wide. At all sites, a length of 3 m was measured from each windrow and all alfalfa in that section was collected and weighed within each of the 16 plot areas in each field. This resulted in four replications per treatment. A subsample (about 100 g) was weighed in the field and then forced air oven dried at 60°C until constant mass to measure moisture and calculate dry matter yield of each plot. Subsamples were weighed then ground to pass through a 1 mm sieve using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA). Ground samples were analyzed by near-infrared reflectance spectroscopy (NIRS) using a FOSS DS2500 F (Foss North America Inc., Eden Prairie, MN) and the 2019-2021 legume hay NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY) to estimate dry matter, ash, fat, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and neutral detergent fiber digestibility 48-h (NDFD). The following two quality parameters were calculated:

$$[\text{Eq. 1}] \quad \text{Total Digestible Nutrients (TDN)} = (100 - (\text{NDF} - 2 + \text{CP} + 2.5 + \text{Ash})) \times 0.98 + \text{CP} \times 0.93 + (\text{Fat} - 1) \times 0.97 \times 2.25 + (\text{NDF} - 2) \times \text{NDFD} / 100 - 7$$

$$[\text{Eq. 2}] \quad \text{Relative Feed Quality (RFQ)} = (((0.012 \times 1350 / (\text{NDF} / 100)) + (\text{NDFD} - 45) \times 0.374) / 1350 \times 100) \times \text{TDN} / 1.23.$$

#### **4.4 STATISTICAL ANALYSIS**

Data from each individual harvest at each farm were analyzed for differences among the dependent variables of crop yield and the quality parameters. Treatment was considered a fixed effect and no interactions of year or site were evaluated due to design changes between years, and communication errors with cooperating farmers and weather events that resulted in missed harvests. Differences were considered significant at  $P < 0.05$  while using the MIXED procedure of SAS (SAS Institute Incorporated, Cary, NC, USA). The UNIVARIATE procedure of SAS was used to inspect residuals to ensure that the assumptions of normality and equal variance were satisfied. All mean separations were conducted using Fisher's protected LSD at  $\alpha = 0.05$  using the PDIFF option in the MIXED procedure of SAS.

#### **4.5 RESULTS AND DISCUSSION**

##### **4.5.1 Soil Moisture Sensors**

The use of a single set of soil moisture sensors and a water balance spread sheet resulted in the lowest irrigation application rate of all four scheduling methods. In comparison with ISM and FNA scheduling, this method had on average 12 and 6% less water application in 2019, respectively, and 15 and 26% less in 2020 (Figure 4.2). These results differed from 2021, where the ISM treatment received 3% less water, and FNA received 19% more. In comparison with the control method, the sensors recommended 12% less water in 2019, 7% more in 2020, and 9% less in 2021. Out of 47 measured

harvests, the soil moisture sensor treatment area never had significantly reduced alfalfa yield, and had increased yields twice at the Sigurd site, from 4.0 to 4.6 Mg ha<sup>-1</sup> (15%) in 2019, and from 2.1 to 3.3 Mg ha<sup>-1</sup> (57%) in 2021 (Table 4.2; Figure 4.3). The soil moisture sensor treatment affected CP levels twice, once in 2019 where it measured 28.9%. This was statistically greater than the ISM treatment which measured 27.6%, and the commercial scheduler treatment which measured 25.9%. The other time that CP levels were impacted was in 2020, when it reduced CP levels to 23.8 compared to 25.2% for the control treatment (i.e., irrigation rates used by cooperating farmers). All these protein levels were within the 'supreme' forage quality ranking for alfalfa (USDA, 2023) and may not alter the market value of the forage, but for operations feeding their own livestock, these differences may be important, as protein can be expensive to supplement into rations. NDF levels are important to understanding the digestibility of feedstuffs; high values suggest difficult digestion and low values signal a low fiber content (OSU Extension, 2001). Over the duration of the study, the soil moisture treatment once raised NDF levels significantly higher than the control treatment, from 27.5 to 32.4%, and never caused a significant decrease from the control treatment (Table 4.2). NDFD (48-h) levels were reduced by the soil moisture sensor treatment in three cuttings to 52.0, 47.0, and 52.9%, which were reductions of 12, 11, and 9%, respectively, compared to the control. The sensor treatment also once raised NDFD levels by 8%, when the control treatment measured 45.6 and the soil moisture sensor treatment measured 49.1%. TDN levels were affected by the sensor treatment three times during the study, lowering TDN levels from 76.2 to 74.0% and from 77.4 to 73.8%, and raising them once from 54.5 to 60.7%, respectively, compared to the control. RFQ calculations are a key metric for valuing

forages as they estimate intake and energy and include the TDN in the calculation. This metric was impacted in only two cuttings by the soil moisture sensor treatment, where in both instances, it resulted in significantly lower RFQ than the control (Table 4.2). This occurred at a late season cutting at the Milford site in 2019, where the RFQ was reduced from 243.2 to 200.8 (17%), and in an early season cutting in 2021 at the Sigurd site, where it reduced RFQ from 292.7 to 257.4 (12%) (Figure 4.4).

Across the 47 harvests of the study, there were few differences in yield or quality due to scheduling irrigation based on soil water content measurements from one spot of the field, and when averaged across all the farms, there were some valuable water savings. One may choose to deduce that using a set of sensors is more accurate at determining the crop needs than the other methods, simply because it is using an actual measurement inside the field, whereas the control and the other tools tested rely heavily on soil and crop estimates, as well as precipitation measurements that can differ widely from the weather station to the field location. Some pitfalls of using soil moisture sensors were the extra labor required to install and monitor the sensors, along with maintaining a water balance spreadsheet. Other manufacturers have user friendly interfaces that perform the calculations and generate recommendations for the user, however the sensors used in this study were selected primarily for accuracy and telemetry.

#### **4.5.2 Commercial Irrigation Scheduler**

The FNA program offers a computer-generated, 360 sector, speed-controlled plan that is easily implemented. In the first year of the study, it prescribed an average of 1100 mm of irrigation across all farms, which was about 6% less than the farmer control treatment application of 1196 mm (Figure 4.2). In 2020 and 2021, when the cooperating

farmers were making cutbacks due to drought, the commercial scheduling program prescribed about 43 and 11% more than the control treatment, with an application rate that averaged 1253 and 887 mm in 2020 and 2021, respectively. The 2021 numbers are substantially lower in all treatments, as many of the cooperating farmers only had water available for part of the growing season. Out of the 47 measured harvests, the commercial scheduling program impacted yield in three harvests, all at the Sigurd site, raising yields each time (Table 4.2; Figure 4.3). In 2019, it raised yields compared to the control for the third and fourth cuttings from 2.9 and 4.4 Mg ha<sup>-1</sup> to 3.4 and 4.8 Mg ha<sup>-1</sup>, representing 15 and 10% yield increases, respectively. In 2021 yield was raised with FNA compared to the control from 2.3 to 5.0 Mg ha<sup>-1</sup>, a 115% yield increase. However, this was with 81% more water applied to the FNA plots than the control plots, as the cooperating farmer was trying to conserve water. The effects of the FNA treatment on alfalfa CP content were minimal (Table 4.2), and it only impacted levels once, reducing CP from 25.2 to 22.4% compared to the control. NDF levels were increased in three harvests and reduced once by FNA, each on separate farms. In 2019, NDF levels were increased from 27.5 to 30.5% and in 2020, NDF increased from 31.9 to 37.5% and from 26.2 to 32.8% with FNA compared to the control. Further, at one farm in 2020, NDF levels were reduced from 40.7 to 34.2%. NDFD (48-h) measurements and TDN calculations shared similar results (Table 4.2), where there were differences in five and three harvests, respectively, but all values remained within an acceptable range to qualify for a 'supreme' alfalfa rating. RFQ values were reduced with FNA compared to the control at the Milford site in 2019 and 2020, and at the Sigurd site in 2020 and 2021 (Table 4.2; Figure 4.4). The 2021 reduction at the Sigurd site was likely in response to the control treatment area receiving 81% less

water that year, resulting in much less mature alfalfa. The four cases where RFQ was significantly reduced was from 243.3 to 216.9 (11%), 206.5 to 163.3 (21%), 265.7 to 199.2 (25%), and 292.7 to 243.8 (17%). There were two harvests during the study that the FNA treatment raised RFQ levels, both in 2020, where it increased levels from 153.0 to 192.8 (26%) at the Centerfield site, and from 150.2 to 193.5 (29%) at the Circleville site (Figure 4.4). These would be valuable differences that would affect the market value of alfalfa if it was sold off-site. However, occurrences of reduced RFQ were infrequent over the 47 measured harvests of the study.

#### **4.5.3 Irrigation Scheduler Mobile**

When reviewing results from the ISM program, it is important to remember that for all three years of the study, gross irrigation application rates were entered in the program, when net application rates should have been used. This oversight caused some inaccuracies in the ISM soil water balance. Despite this error, ISM performed well and including it in the results was deemed valuable for helping farmers and researchers evaluate the program.

In 2019, the ISM program average irrigation recommendation across farms was 1168 mm, a similar amount to the control plots that averaged 1166 mm (Figure 4.2). In 2020 there was a large difference between the ISM and control averages, as they recommended 1094 and 875 mm, respectively. These results differed greatly from 2021, where the average ISM recommendation was 705 mm, and the average control recommendation was 796 mm. The large difference in 2021 was likely due to one of the six remaining farmers applying 2453 mm for their control treatment. Throughout the study, ISM was never consistently recommending above or below the cooperating

farmer's recommendation. This may mean that ISM recommendations may or may not change the amount of application used by many farmers, however it could be a useful tool for supplying information for scheduling irrigation, particularly to irrigators less experienced than the cooperating farmers of this study.

Over 47 alfalfa cuts, yield was impacted in three cases by the ISM program recommendations (Table 4.2). In 2019, it increased yield at the Sigurd site from 2.9 to 3.3 Mg ha<sup>-1</sup>, a 13% increase (Figure 4.3). In 2021, the treatment increased yield at the same farm, from 2.3 to 4.1 Mg ha<sup>-1</sup>, but that was with 78% more water applied to the ISM plots, as the cooperating farmer was attempting to stretch their limited water supply during an extreme drought. After observing the increased yield in the soil sensor, ISM, and FNA scheduling areas, this farmer determined it would have been better to concentrate the limited water to the first cut, as the other methods had recommended (not intuitively, but only as programmed to minimize crop stress), rather than to try to stretch their water into a second cutting, as the saved water was not enough to promote enough regrowth for a second harvest. This resulted in large yield losses, due to the stunted first cutting followed by the failed attempt at a second cutting. The only other time that a yield difference occurred as a result of the ISM treatment was in 2021 when it reduced yield from 3.9 to 2.9 Mg ha<sup>-1</sup> at the Fillmore 1 site (Figure 4.3.), but that was with 44% less water applied. At that field, the ISM season recommendation was for 1381 mm, while the control recommendation was the previously mentioned 2453 mm, an amount that is not typically used Utah farmers.

The crop quality analysis showed occasional differences due to the ISM treatment (Table 4.2), but these were limited and would have had little effect on the market value of



the crop. CP and NDF levels were never changed by the ISM treatment. NDFD (48-h) calculations had the greatest significant differences and was impacted by ISM in seven harvests throughout the study, but these changes were never drastic enough to change the monetary value of the alfalfa. TDN calculations were only impacted by ISM in three harvests, but again the differences were minimal and would have had little effect on the value of the crop to be fed on-farm or sold off-site. RFQ values were increased by the ISM treatment in a single harvest, from 153.0 to 188.7, at the Circleville site in 2020 (Table 4.2; Fig 4.4). This would have increased the feed and market value of the alfalfa, and because this occurred on the first cutting of the season, where yields are typically highest, it would have been particularly beneficial to the cooperating farmer. The other instance where the ISM treatment affected RFQ was when it decreased RFQ from 292.7 to 250.9 at the Sigurd site in 2021 (Figure 4.4). Though a 14% decrease is a significant amount, the alfalfa would still be rated as 'supreme' (USDA, 2023) and the change would not impact the market value.

#### **4.5.4 Contrasting the Scheduling Approaches**

For a farmer that has decided to adopt a scheduling approach from the three evaluated, there are several variables that are important in choosing, such as cost, time, and the level of affinity one has for inputting data and completing calculations, none of which were evaluated in this study. Based only on measured performance in this study, using a set of soil moisture sensors with a water balance spreadsheet will likely produce the most conservative irrigation prescriptions, that will still meet the water demands for alfalfa yield and crop quality standards. The ISM program helped save a little water in the wetter years and is also a safe and inexpensive option for maintaining crop yield and

quality. Commercial schedulers, such as FNA, may prescribe a little more irrigation than using soil moisture sensors, but are likely to maintain crop yield and quality, and require the least amount of effort to use. From 47 measured harvests in this study, all scheduling methods performed well, with few changes to crop yield and quality (Table 4.2), which suggests that any of the options can be useful tools to help optimize water use.

#### **4.5.5 Conclusions**

Each of the irrigation scheduling methods tested can provide useful information to assist farmers in irrigation decisions. However, they often did not reduce water application in comparison with what the cooperating farmers in this study were choosing to apply (Figure 4.2). This may have been due to the drought conditions present throughout the latter two years of this study. Under these conditions, all three scheduling methods, besides the control, lacked the incorporation of data that may have been even more crucial to the cooperating farmers, such as how limited their water turn was or how quickly their irrigation district would be shutting off water, which for some farmers and fields in the study was after only one or two cuts. These neglected facts often resulted in higher recommendations from the three scheduling methods tested. These recommendations would likely have increased yields and would have been desired by the farmers, but drought limitations often resulted in a more conservative recommendation from the cooperating farmers.

At some of the farms in the study, the three scheduling methods (soil sensor, ISM, and FNA) helped maintain yield with less irrigation, however there were few cases where there were consistent benefits, and many farms had no improvements at all. For the growing seasons evaluated, Utah was in a drought, and to some degree this impacted the

farmer recommendations used as the control of the study. These results guide the notion that most farmers are extra careful with their water resources, and advanced scheduling methods may not bring drastic results in alfalfa production or water use, but they did provide helpful information to guide irrigation decision making. When farmers have flexibility in scheduling when and how much they irrigate, these tools can provide reliable recommendations that can be trusted to sufficiently irrigate crops and minimize overirrigating. As one of the first studies to directly compare how four irrigation scheduling methods for center pivots affect crop production and water use, the results indicated that all three approaches (soil moisture, ISM, and FNA) had comparable performance, and in some situations can reduce irrigation rates by 10-15% without impacting production. These benefits were especially apparent in 2019 where relatively high precipitation was accounted for better by the tools than the grower control schedule.

**TABLE 4.1** Site properties for irrigation scheduling trials in Utah from 2018 to 2020, including nearest town, year, coordinates, dominant soil texture, and slope

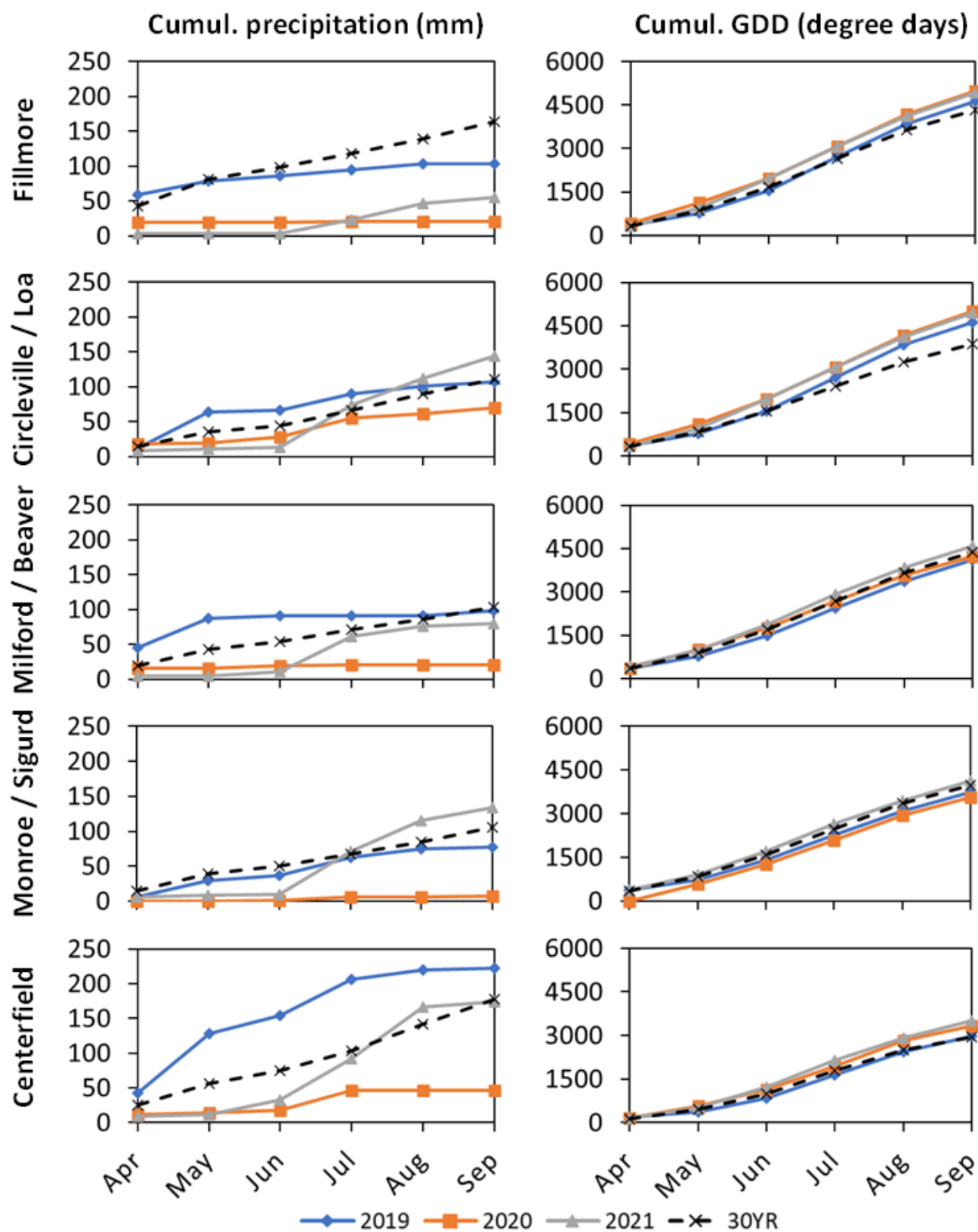
<b>Nearest town</b>	<b>Year</b>	<b>Coordinates</b>	<b>Dominant soil texture (classification)</b>	<b>Slope</b>
				%
Beaver	2019-2021	38.305, -112.658	Loam (Calcic Argixerolls, Fine-loamy over sandy or sandy-skeletal, mixed, mesic Calcic Argixerolls)	1 - 3
Centerfield	2019-2021	39.100, -111.800	Silt loam (Typic Natrargids, fine-silty, mixed, Mesic)	1 - 2
Circleville	2019-2021	38.164, -112.265	Loam (Fine-loamy, mixed, superactive, mesic Cumulic Haploxerolls)	0 - 2
Fillmore 1	2019-2021	38.949, -112.433	Silt loam (Xeric Haplocalcids, fine-loamy, carbonatic, Mesic)	0 - 2
Fillmore 2	2019-2020	39.037, -112.419	Silt loam (Fine-silty, mixed, mesic Torrifuventic Haploxerolls)	N/A
Loa 1	2019-2020	38.382, -111.583	Silt loam (Fine-silty, mixed, superactive, frigid Ustic Haplocambids)	0 - 3
Loa 2	2019	38.369, -111.635	Loam (coarse loamy, mixed, superactive, frigid Ustic Haplocalcids)	2 - 8
Milford	2019-2020	38.485, -113.421	Sandy clay loam (Fine-loamy, mixed, superactive, mesic Typic Haplocalcids)	0 - 2
Monroe	2019-2021	38.629, -112.157	Sandy loam (Coarse-loamy, mixed, superactive, mesic Xeric Haplocalcids)	2 - 4
Sigurd	2019-2021	38.839, -111.978	Loam (Coarse-loamy, carbonatic, mesic Xeric Torrifuvents)	0 - 4

**TABLE 4.2** Significant differences of *F* tests for the fixed effect of scheduling method on alfalfa yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; and RFQ, relative forage quality) from 47 measured harvests during 2019-2021 in central Utah. Differences were considered statistically significant when  $P < 0.05$  and only significant differences are shown for brevity

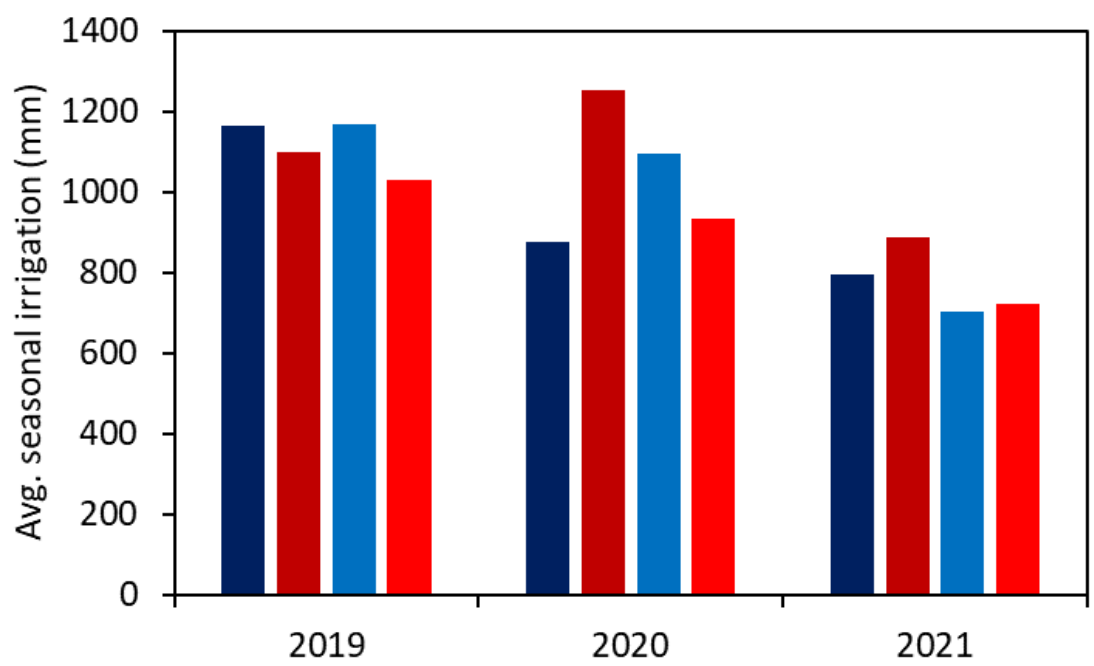
<b>Response variable</b>	<b>Year</b>	<b>Nearest Town</b>	<b>Cut</b>	<b><i>P</i> &gt; <i>F</i></b>
Yield	2019	Sigurd	3	0.014
		Sigurd	4	0.025
	2021	Sigurd	1	0.001
		Fillmore 1	2	0.036
		Monroe	1	0.050
CP	2019	Beaver	3	0.004
	2020	Milford	1	0.019
NDF	2019	Beaver	3	0.000
		Milford	3	0.022
	2020	Sigurd	3	0.041
		Sigurd	4	0.042
		Centerfield	1	0.013
NDFD	2019	Milford	1	0.033
		Fillmore 1	3	0.035
		Fillmore 1	4	0.026
		Monroe	3	0.031
		Fillmore 2	3	0.002
	2020	Fillmore 2	4	0.004
		Sigurd	4	0.033
		Centerfield	1	0.002
		Centerfield	2	0.018
		2021	Sigurd	1
TDN	2019	Fillmore 1	2	0.024
		Fillmore 1	4	0.007
		Beaver	3	0.000
		Loa 2	2	0.038
	2020	Loa 1	3	0.047
		Fillmore 2	3	0.034
		Centerfield	1	0.012
2021	Beaver	1	0.041	
RFQ	2019	Sigurd	1	0.004
		Beaver	3	0.000
	2020	Milford	3	0.033
		Sigurd	3	0.030

	Circleville	1	0.036
	Centerfield	1	0.005
	Milford	1	0.005
2021	Sigurd	1	0.041

---



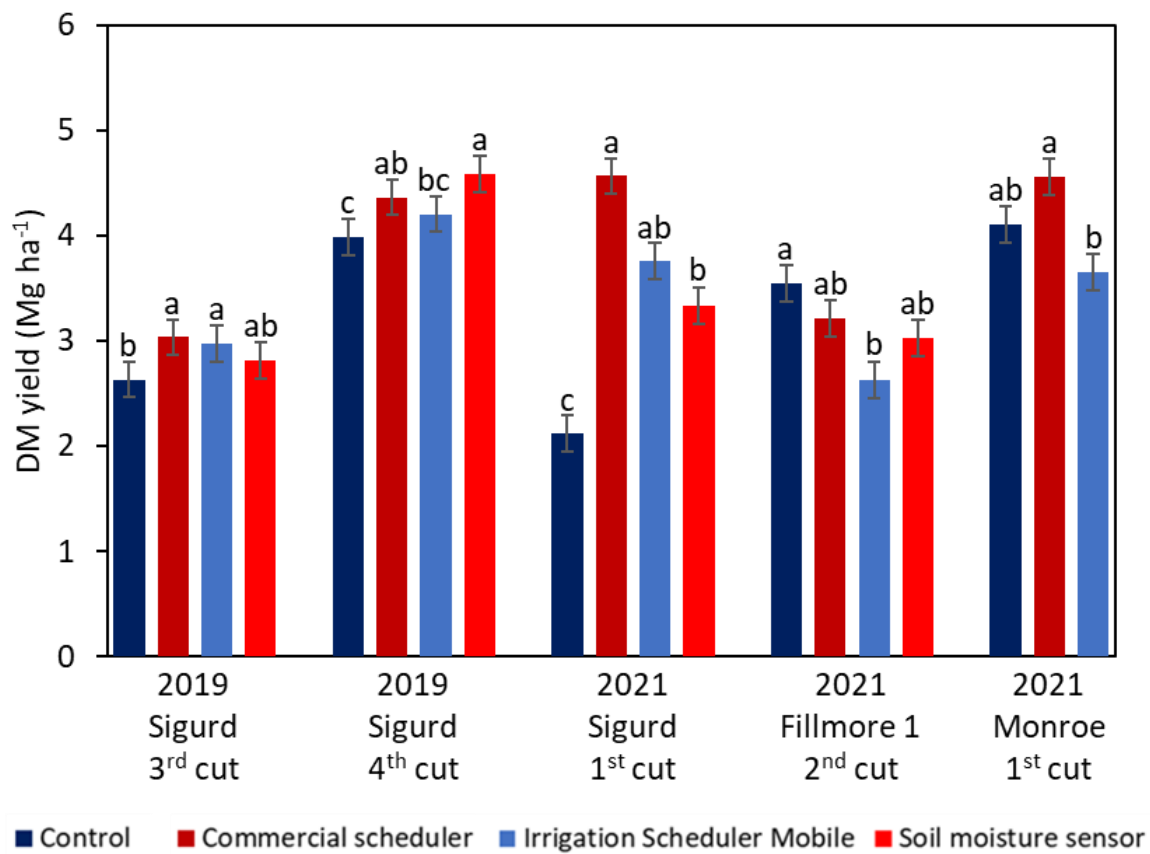
**FIGURE 4.1** Cumulative precipitation and growing degree days (GDD) for 10 on-farm trials in Utah, gathered from the closest public weather stations to each site (some had the same station). GDD were calculated from the minimum and maximum air temperatures and adjusted to 5°C and 30°C. The 30 yr normal (1991-2020) is shown for reference



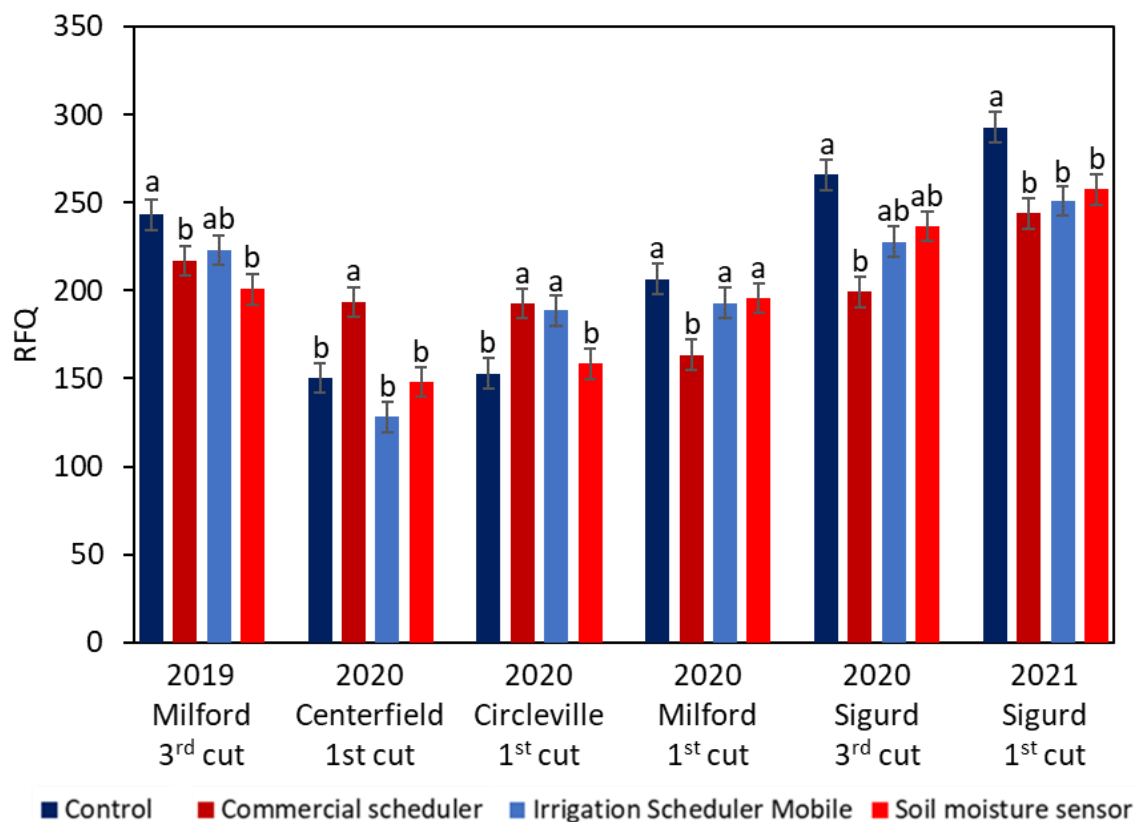
■ Control ■ Commercial scheduler ■ Irrigation Scheduler Mobile ■ Soil moisture sensor

**FIGURE 4.2** Total seasonal irrigation application (mm) for the farmer control and three other irrigation scheduling treatments, averaged across farms for the 2019-2021 growing seasons





**FIGURE 4.3** Dry matter (DM) alfalfa yield results for the 5 of 47 measured harvests where yield was significantly ( $P < 0.05$ ) impacted by scheduling method. Mean separations were conducted at  $P < 0.05$  by harvest and differences are denoted by letters above each bar



**FIGURE 4.4** Relative forage quality (RFQ) measurements for 6 of 47 measured harvests where RFQ was significantly ( $P < 0.05$ ) impacted by scheduling method. Mean separations were conducted at  $P < 0.05$  by harvest and differences are denoted by letters above each bar

## CHAPTER 5

### SIMPLE TO COMPLEX: TOOLS TO IMPROVE SURFACE IRRIGATION

#### 5.1 INTRODUCTION

Surface irrigation is often referred to as “flood irrigation” and is a method of irrigation that involves spreading water across the field by gravity and hydraulic gradient instead of pressurized distribution like sprinkler equipment. This method usually entails the flooding of basins called “basin irrigation”, dividing a field into long strips that are separated by short berms and irrigated individually from one edge of the field called “border irrigation” or directing water down furrows between row crops called “furrow irrigation”. Surface irrigation is a popular means for irrigating several crops, particularly alfalfa (Schwankl & Prichard, 2003). Most of the surface irrigation systems in use in Utah and the Western U.S. irrigate odd-shaped fields that would not be well suited to sprinkler irrigation. One major limitation of surface irrigation is that it usually requires much labor to monitor the irrigation advancement, because it can change throughout a season as stream in-flows vary, crops increase ground cover, and soil surface changes from the irrigation. This leads to another limitation, the labor required to switch sets at appropriate times, which may be moving a tarp dam, closing a gate or valve, or restarting several syphons. Another limitation is achieving a uniform application: if the water is shut off too early it may not sufficiently irrigate the bottom of the field, whereas if it runs too long there will be excessive drainage of water, and possibly nutrients, from the field. These limitations both can result in yield reductions (Hanson et al., 2008; Arnold et al., 2014).

A common method for improving surface irrigation is to use surge irrigation. This method was developed in 1979 at Utah State University (Stringham & Keller). Their research found that instead of continuously conveying the irrigation water until it reaches the bottom of the field, intermittent wetting could promote a more uniform application. The theory is that when the water is shut off, the surface of the wetted area somewhat seals as the water infiltrates into the soil. When the next on-cycle begins, the irrigation water quickly passes over the previously wetted area with one-third to two-thirds less infiltration (Testezlaf, 1987) and slows down once it reaches the new, dry area. This cycle is completed several times until the irrigation water has reached the end of the field. At this point, more on-cycles can be implemented if the desired irrigation depth has not been achieved. Cycling irrigation water on and off can be a time-consuming process for farmers. To make surge feasible, usually two sets are irrigated together with a single valve directing water to one set, then switching to irrigate the neighboring set, and so forth. This typically requires an automated valve. Because the valve switches on-cycles between the two sets, the irrigation mainline or ditch does not need to be shut off.

Several previous studies include evidence that the surge method can produce similar crop yields to the continuous flow method, often with substantially less applied water. Devitt & Andersen's (1995) research in alfalfa measured savings of 33% in overall irrigation application and up to 30% less runoff with surge. Musick et al. (1987) found that corn yield could be maintained with 31% less water, and noted a 6% reduction in tailwater, but they did warn that when the surges were not properly timed, the potential for tailwater was greater than with the continuous flow method. Other studies found irrigation application efficiency improvements ranging between 12 – 50% (Goldhamer et

al., 1987; Israeli, 1988; Miller et al., 1991). Researchers have found that the reduced water application can also result in less nitrogen leaching (Miller & Shock, 1992; Shock & Welch, 2011). However, it was also noted in both of those studies that there is potential for crop stress when using surge if irrigation cutbacks are too drastic and do not meet the evapotranspiration (ET) demand. Humpherys (1989) evaluated which soil conditions might cause the greatest benefits from surge irrigation and found that it worked best in fields with light-textured soil, especially for the first irrigation of the season, after tillage had roughed the soil surface. Because of this, it was suggested that the benefits of surge irrigation may not be as pronounced throughout the season. Surge irrigation may also be difficult or impossible for some situations, such as in areas where water turns are large and infrequent, but careful use of such turns may be able to improve irrigation use efficiency (IUE), the amount of crop produced per unit of irrigation applied. Most studies on surge irrigation were conducted decades ago when automation technologies were much less advanced, and few early or recent studies have had field or large-scale evaluations of surge in on-farm trials. Technology restrictions have limited the use and practicality of surge irrigation in the past. However, recent development, economics, and availability of automation and communication technologies have made surge more feasible on farms.

In order to evaluate the use of surge irrigation in large on-farm trials for current crop production systems in the Western U.S., we initiated research in surface irrigation in 2020 with the intent of conducting simple evaluations of tools that could help Utah farmers optimize their time, water, and irrigation expenses. In addition to adding to the body of surge irrigation and automation research, other tools evaluated included

knowledge of the impacts of eliminating an early-season water turn, and using an in-field sensor to track irrigation advancement. The other focus of the work was to provide opportunities for farmers to learn about the tools and gain enough information to determine what may or may not work for their farm.

## **5.2 MATERIALS AND METHODS**

### **5.2.1 Site Characteristics**

On-farm trials were established in the spring of 2020 in alfalfa fields near Corinne and Delta, Utah. Due to logistical constraints, the Delta site was discontinued after the 2021 growing season. Soil classification, textural group, slope, and drainage classifications were obtained from the University of California-Davis SoilWeb (O'Geen, 2020; Fig. 5.1). Weather data were obtained from the Utah Climate Center (climate.usu.edu; Logan, Utah, USA) and were used to calculate monthly precipitation and cumulative seasonal GDD. Alfalfa GDD were calculated using a base air temperature of 5°C and an adjusted maximum temperature of 30°C. Precipitation and GDD were compared with their respective 30 yr normals (1991-2020) provided by the National Oceanic and Atmospheric Administration (noaa.gov; Silver Spring, Maryland, USA) (Fig. 5.1). At each farm, field operations were conducted by the cooperating farmer, including the irrigation management.

### **5.2.2 Irrigation Reduction Scenario**

Based on feedback from local farmers, the common practice for alfalfa irrigation near Delta, Utah is to irrigate alfalfa four times a season: twice before first cutting, and

once before both second and third cuttings. This is accomplished with the border irrigation method, with large streams of water. A plot trial was established to assess the impacts of eliminating one of the two irrigations for the first cutting of an established alfalfa stand. Two irrigation “sets” divided by the same dike were used for this study. The set on one side of the dike was to only receive a single irrigation before the first cutting, while the other set would receive the traditional two irrigations. In each dike, four neighboring plot areas ( $4.7 \times 9.1$  m each) were established near the midpoint of the field length, in the direction of the irrigation advance. Soil moisture sensing equipment and software from Meter Group (Pullman, Washington, USA) was used to measure volumetric water content (VWC) in each set. To accomplish this, a ZL6 data logger was installed in the dike that divided the sets. Sensor wires for the Teros 10 VWC capacitance sensors were trenched-in from the logger to the edge of the plots in each set. A 100 mm hole was then bored in the soil and sensors were installed in the wall of the hole at 150, 460, and 1070 mm depths. These were programmed to read every four hours throughout the growing season. In 2020, the irrigation area designed to only receive one irrigation prior to first cutting mistakenly received a small amount of irrigation as water was not shut off quick enough. Despite this, there was still a sizeable reduction in irrigation applied (Table 5.1), so 2020 data is still included, and results are similar to 2021 where the treatments were applied correctly.

### **5.2.2 A Comparison of Before and After Automation for Surge Capabilities**

The previously cited research on surge irrigation outlines many benefits to the practice, but few studies have been conducted in established alfalfa. Understanding the performance of surge irrigation in established alfalfa is critical because many factors are

different in comparison to other main crops, such as surface roughness, ground compaction from traffic, and the absence of tillage. The objective of this research was to evaluate automation and surge irrigation in established alfalfa, using the newest technology in automated valves, to help Utah farmers learn if these systems could be feasible for their operations. To accomplish this, yield, crop quality, and soil moisture comparisons were made before and after automation and conversion to surge irrigations.

In 2020, the Corinne site was irrigated with 150 mm alfalfa valves spaced 4.6 m apart, that were hand operated. Prior to the 2021 growing season, these valves were replaced with 300 mm, automated, Fresno-style alfalfa valves (Specialized Analysis Engineering, Inc., Logan, Utah, USA), spaced approximately 28 m apart. The automated valves were used to implement surge irrigation to the entire field in 2021 and 2022. The duration of the surges was set by the cooperating growers and some sets were changed every few hours based on soil infiltration rates and available stream size. Soil moisture was monitored near the top, middle, and tail of the field to evaluate the uniformity of the irrigation along the length of the field. Meter Group (Pullman, Washington, USA) equipment and software was used. A ZL6 data logger was installed in the border dike at each position, and Teros 10 sensors were installed 6 m away from the dike, where a 100 mm hole was bored and sensors installed in the hole wall at 150, 460, 1070, and 1680 mm depths. Plot areas were centered near the soil moisture sensors, at the top, middle, and tail of the field, with four plots per position for replication. Plots were  $4.7 \times 9.1$  m each.

### **5.2.3 Irrigation Advance Sensor**



Another way to optimize water in surface irrigation systems is to shut it off or switch sets at the correct time. In a field experiment at four sites, Arnold et al. (2014) estimated runoff ranging from 13-40% of the initial application, suggesting that in many instances, farmers can better optimize shutting off the inflow. For some farmers that are concerned about this, they may make trips to the field to check the progress of the wetting front. For farmers less concerned about this, extra time may be given so that there is a guarantee that upon their return the wetting front will have reached the end of the field, which also causes some amount of over irrigation. In either scenario and a host of others, time, water, money, or a combination can probably be saved by having a sensor in the field that alerts the irrigator when the wetting front is nearing the time where irrigation will need to be switched to another set or shut off. Two water advancement sensor options were utilized in this study, where the cooperating farmers used a sensor for a year, then reported on their experience and any reduced water application or labor expenses resulting from using it.

One of these sensors was developed by Commercial Business Radio in Delta, Utah (Figure 5.2). This system utilizes a sealed box that can be set on a dike or field edge, with a cable that is stretched out into the field. When water reaches the end of the cable, it activates a transmitter and pages the irrigator to indicate that water has reached the sensor and it is time to cutoff irrigation. The farmer can then retract the sensor by pulling-in the cable (~8 m, but customizable) attached to it (no walking through the wet field), dry it off, and head to the next set. Once the sensor is dry, it is already reset and ready to go. There is no programming or settings, and a shift change is as easy as handing-off a pager to the next irrigator. The battery in the non-solar models requires

periodic charging during the season. Without a radio repeater, these systems will work within about five miles, but for greater coverage a repeater is necessary. For remote areas without a repeater, a satellite option that communicates via text message or email is available.

The other sensor used in this study was from Prescott Farm Innovations in Rigby, Idaho. They developed an irrigation advance sensor called “Wet Stake” (Figure 5.3). The sensor, transmitter, and solar panel are in a self-contained tube that stands vertically in the field with two “legs”. The system is powered on with the push of a button. When water is sensed at the base of the Wet Stake, it will call or text the irrigator to notify them that it is time to change the irrigation set. When starting a new set, a push of the power button resets the Wet Stake. Changing users requires the new irrigator to text the ID number to the phone number printed on the unit. The battery in the Wet Stake will maintain adequate charge if it receives ample sunlight, or it can be charged with a USB cable.

## **5.3 CROP YIELD AND QUALITY**

### **5.3.1 Alfalfa Analysis**

Alfalfa yields in Corinne and Delta were measured after the cooperating farmer had windrowed the field at a cutting height of about 75 mm above the soil surface. To take measurements, 3 m of windrow (4.8 m wide) was collected in each of the plot areas. The plant material in the harvest area was gathered in a tote and weighed. A sub sample (about 100 g) was weighed in the field and forced air oven dried at 60°C until constant mass. From these measurements, a DM yield was calculated for each plot area. The

subsample was weighed then ground to pass through a 1 mm sieve using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, New Jersey, USA). Ground samples were analyzed by near-infrared reflectance spectroscopy (NIRS) using a FOSS DS2500 F (Foss North America Inc., Eden Prairie, Minnesota, USA) using the 2020 legume hay NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, Kentucky, USA) to estimate dry matter, crude protein (CP), neutral detergent fiber (NDF), neutral detergent fiber digestibility 48-h (NDFD), in vitro true dry matter digestibility 48-h (IVTDMD), total digestible nutrients (TDN), and relative forage quality RFQ. The following two quality parameters were calculated:

$$\text{[Eq. 1] Total Digestible Nutrients (TDN) = (100 - (NDF - 2 + CP + 2.5 + Ash)) \times 0.98 + CP \times 0.93 + (Fat - 1) \times 0.97 \times 2.25 + (NDF - 2) \times NDFD / 100 - 7}$$

$$\text{[Eq. 2] Relative Forage Quality (RFQ) = (((0.012 \times 1350 / (NDF / 100) + (NDFD - 45) \times 0.374) / 1350 \times 100) \times TDN / 1.23.}$$

## 5.4 STATISTICAL ANALYSIS

All statistical analyses were performed by site at  $P < 0.05$  using the MIXED procedure of SAS (SAS Institute Incorporated, Cary, North Carolina, USA). At the Corinne site, data were analyzed with year and landscape position as fixed effects. Year was treated as a repeated variable in this analysis and replicate and interactions among replicate and fixed effects were treated as random. Dependent variables were total alfalfa yield and average forage quality across all three to five cuttings each year. At the Delta

site, data were analyzed by year with treatment and cutting as fixed effects. Cutting was treated as a repeated effect and replicate and its interactions with fixed effects was treated as random. Dependent variables were alfalfa yield and forage quality parameters for each cutting. The data at Delta were analyzed by cutting because the treatment was a single vs. double irrigation for the first alfalfa cutting so results by cut was of interest. The UNIVARIATE procedure of SAS was used to inspect residuals to ensure that the assumptions of normality and equal variance were satisfied. All mean separations were conducted using Fisher's protected LSD at  $\alpha = 0.05$  using the PDIFF option of the MIXED procedure of SAS. Randomization of treatments were restricted in these trials due to the nature of on-farm trials with large treatment areas. This is common in on-farm irrigation studies [e.g., Hanks et al. (1976) and Roberts et al. (2022) with line-source studies] and indicates the analysis of variance results should be considered with caution.

## **5.5 RESULTS AND DISCUSSION**

### **5.5.1 Irrigation Reduction Scenario**

In Delta, where a single irrigation compared to two irrigations before the first alfalfa harvest of the season was evaluated, the interaction of year  $\times$  cut  $\times$  treatment was significant for alfalfa yield (Table 5.2). Alfalfa yield was similar between treatments for each of the 2020 harvests, but in 2021 significant differences occurred and the first cut yielded 5.2 Mg ha<sup>-1</sup> (Table 5.1) for the area receiving two early season irrigations, while the area irrigated once yielded 6.3 Mg ha<sup>-1</sup>. This represented a 21% increase in yield, with 49% less water applied up to that point of the season. It was also the only case where

there was an impact on yield due to the reduced irrigation treatment (Table 5.2). The next two harvests of 2021 had no significant yield differences between the treatments.

Maintaining or improving yield with less early season irrigation is important, as well as the lack of any on-going effects in the subsequent cuttings. In this study, there were no negative impacts on yield in the single irrigation treatment area that received 14% less irrigation in 2020 and 28% less in 2021. It is important to note that in 2021 there was a substantial rainstorm in August (Figure 5.1) that delivered 148 mm of rain, which eliminated the need to irrigate the third cutting and somewhat exaggerated the difference of applied irrigation between treatments.

When analyzing the impact of interactions between the treatment and the cut or year on alfalfa forage quality, there were again no significant differences (Table 5.2). However, the three-way interaction of year, cut, and treatment impacted alfalfa CP levels. In the last harvest of 2020, the single irrigation treatment had CP levels of 20.5%, whereas the double irrigated treatment measured 18.4% (Table 5.3). In the first cutting of 2021, the single irrigation treatment measured 19.7% CP, while the double irrigated set measured 17.9%. In both cases, the increased protein levels of the single irrigated treatment area were large enough to attain higher market values in the USDA Hay Quality Designation Guidelines (USDA, 2023). Alfalfa can have higher CP levels when yields are reduced, due to higher leaf to stem ratios from less mature plants (Undersander et al., 2011), however in these instances yields were also higher in the plots with the elevated CP levels. One speculation for the cause of these peculiar results is that there could have been nutrient losses from the additional irrigation on the double irrigated side, but there were no soil or tailwater nutrient measurements to evaluate this possibility.

Because nitrogen levels are so closely associated with CP in crops, this could suggest that some nitrogen was being leached from the soil, or that it was unavailable to the plant for a time, due to longer saturation of the rootzone. Another speculation is that the additional irrigation water created an overabundance of certain nutrients or salts in the soil that affected yield, but no water tests were performed. There were no significant differences between the treatments at the other four harvests in the study.

The volumetric water content of each treatment was similar at the shallow sensor depth of 150 mm (Figure 5.4). In 2021, it is interesting to note how the double irrigation had greater VWC for nearly a month, after the double irrigation was applied, yet it did not impact crop yield and quality (Table 5.3). The single treatment dried out more leading up to the middle of July, but then the irrigation for the second cut brought the treatments back to similar levels. The 1070 mm sensor depth was much different, with the single treatment being 5 – 10% drier for most of both growing seasons. This may signal that skipping the double irrigation at the beginning of the year may not have large differences in the top 460 mm of the rootzone, but the deeper water may not get replenished. This may point towards the need for longer-term research to evaluate if the VWC in the deep rootzone will increasingly become more depleted and begin to cause crop stress. For short term needs, this data contains evidence that skipping the double irrigation will probably not have long-term consequences in the moisture content of the top 470 mm of the rootzone, where most of the water required for transpiration is extracted by the plant.

In this study, there were sometimes differences in yield or CP levels, but there were no definitive patterns, and most of the data had no significant differences. This may suggest that if the two irrigation events leading up to the first harvest of the season were

reduced to one, crop yield and quality would likely be sustained for the season. Due to the study only spanning two growing seasons, further research would need to be conducted to determine if there would be long-term crop effects from adopting this strategy permanently. Additional research may be conducted to analyze the nutrient load of the irrigation water applied to the field, as well as the tailwater, and changes in nutrient availability in the soil, to better understand how the irrigation levels may be affecting nutrient availability and causing some of the CP differences.

### **5.5.2 A Comparison of Before and After Automation for Surge Capabilities**

At the Corinne site there were no significant differences in crop yield when analyzing the interaction of year  $\times$  position (Table 5.4; Figure 5.5). CP was the only crop quality parameter that was significantly ( $P = 0.0172$ ) by the interaction (Table 5.4), but none of these differences would have downgraded alfalfa forage quality from the ‘supreme’ quality or highest market value ranking (USDA, 2023). When analyzing the data with year as the main effect, alfalfa yield was significant ( $P < 0.0001$ ). Some differences are expected; alfalfa yields often tend to increase after planting and then start to decrease in the third year (Undersander et al., 2011). The alfalfa at this site was established in 2019, with 2020 being the first full year of production, yielding an average of  $16.4 \text{ Mg ha}^{-1}$ . In 2021, mean yields increased, as expected, to  $18.3 \text{ Mg ha}^{-1}$ , then decreased to  $13.1 \text{ Mg ha}^{-1}$  in 2022, which coincides with the Alfalfa Management Guide’s pattern for alfalfa stands (Undersander et al., 2011). Something that is notable about these results is the variation in irrigation amounts among years. Automation and surge irrigation began at this site in 2021, a year in which 43% less water was applied, resulting in nearly double the IUE of 2020 (Table 5.5). These drastic results did not carry

into 2022, but the severity of an ongoing drought in the region may or may not have impacted that effect. The main effect of field position did not influence forage quality (Table 5.4). However, it did impact alfalfa yield ( $P = 0.0086$ ), where yield at the tail of the field averaged  $17.1 \text{ Mg ha}^{-1}$ , which was significantly greater than the middle and head of the field that yielded  $15.5$  and  $15.3 \text{ Mg ha}^{-1}$ , respectively.

Volumetric water content readings did not have drastic differences before and after automated surge irrigation (Figure 5.6). If surge irrigation increases irrigation uniformity in different positions of the field, we would anticipate more uniform moisture at the three positions of the field with surge than before surge. This was not apparent in the soil moisture data collected. There were some differences by depth but the general trend of VWC among the three positions (head, middle, tail) were similar before and after surge implementation. As expected, there were differences in soil moisture among years. In 2021, the 1070 and 1680 mm depths were slightly drier than in 2020. It is possible that this was a result of the surge irrigation technique, but perhaps a more likely reason may be that it received 43% less irrigation and transpiration levels were greater, as the increased yield may indicate. In 2022, those two depths were again similar to 2020 levels, but they also had a more rapid depletion (Figure. 5.6). Increased activity at the deeper depths may be the result of the alfalfa root systems becoming more developed and mining water from deeper in the rootzone.

The change from manual to automated surface irrigation at these sites required open ditches to be piped, land to be graded, and the automation system itself with monthly telemetry subscriptions. The Corinne field is difficult to estimate surge irrigation equipment cost for, because, at the time of publication the equipment had not yet been



priced and made available to the public. A nearby site, that was initially involved in the study, had a similar automated system that cost about \$14,000 ha<sup>-1</sup>. The first year after automation in the Corinne field had high yielding, supreme quality alfalfa, with substantially less irrigation applied, nearly doubling the IUE. The 2022 results measured a IUE improvement of 20% over 2020 calculations, or about 0.3 kg of additional biomass per hectare for each mm of irrigation. These data provide evidence that automation and surge can increase IUE and yield uniformity, but the high cost warrants extended research to help provide ample information to guide farmers that may be determining if this is an economic management practice for their farm.

### **5.5.3 Irrigation Advance Sensor**

Each of the three farmers in the study commented on how having a sensor saved them time checking water. This was especially the case on the farm in Delta, because of the high clay content in the soil at some fields, that made timing the end of an irrigation more unpredictable than in other areas of the farm with sandy soil. That same farmer noted the water source often had varying flow, which, combined with a variety of soil textures, produced a significant amount of opportunity to mis-time irrigation cutoff without several trips to the field, so the advance sensors were critical to optimizing water around the farm. These water savings were estimated to be about 4% per day, by properly timing cutoff due to notices sent from the sensors. Across 83 days of irrigating, the accumulation of daily saving reduced the seasonal water expense by about USD\$7,000, while costing the farm USD\$375, annually. The Corinne farmer irrigated a single field, where time savings of checking the wetting advance were estimated to be about 30

minutes for each of the eight seasonal irrigations. The Garland farmer reported a positive experience of using the sensor but was unable to quantify any savings.

Each of the farmers found using a sensor to be a helpful improvement to their irrigating techniques, but there were occasional issues that had to be dealt with. One issue common to both sensor types was rainfall causing false notifications. Sometimes it was difficult to know if sensors were on or off, which occasionally meant no notification was sent when one was needed. With the Wet Stake, the farmers disliked having to walk out into a muddy field to retrieve the sensor, whereas the Commercial Business Radio sensor could be retrieved by retracting the wire from the field edge. Despite these issues, it was unanimously agreed upon that an irrigation advance sensor was a helpful tool for saving labor and water in a surface irrigating system.

**TABLE 5.1** Site properties for three on-farm trials in Utah from 2020 to 2022, including nearest town, year, coordinates, soil texture, and the type of experiment conducted

Nearest town	Years	Coordinates	Dominant soil texture (classification)	Experiment
Corinne, UT	2020-2022	41.553, -112.197	Silt loam (fine-silty, mixed, superactive, mesic Typic Natrixerolls)	Automation, Advance sensor
Delta, UT	2020-2021	39.323, -112.596	Silty clay loam (coarse-silty, mixed (calcareous), mesic Aquic Xerofluvents)	Drought scenario, Advance sensor

**TABLE 5.2** Year, cut, irrigation applied for the individual harvest, alfalfa dry matter (DM) yield, and crude protein (CP) for the single and double irrigation treatments at the Delta, UT site. Mean separations were conducted at  $P < 0.05$  and differences are denoted by the accompanying letters

Year	Cut <sup>a</sup>	Single Irrigation			Double Irrigation		
		Irrigation	Yield	CP	Irrigation	Yield	CP
		mm ha <sup>-1</sup>	Mg ha <sup>-1</sup>	g kg <sup>-1</sup>	mm ha <sup>-1</sup>	Mg ha <sup>-1</sup>	g kg <sup>-1</sup>
2020	1	400	4.81bc	188.2abc	640	5.11b	191.4abc
	2	310	4.53bcd	182.6bcd	250	3.97d	180.9bcd
	3	290	4.50bcd	205.0a	280	3.89d	184.1bc
2021	1	250	6.29a	197.0ab	490	5.22b	178.8cd
	2	280	4.16cd	155.8e	250	4.20cd	166.0de
	3	0	2.97e	185.9bc	0	2.70e	190.4abc

<sup>a</sup> Cut denotes a single harvest in a growing season with three total harvests

**TABLE 5.3** Significance of *F* tests, at the Delta, UT site, for the fixed effects of cut, treatment, and year, and their interaction on alfalfa dry matter yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; TDN, total digestible nutrients; RFQ, relative forage quality; and starch). Differences that were considered statistically significant when  $P < 0.05$  are bolded

Effect	Yield	CP	NDF	NDFD	IVTDMD	TDN	RFQ
Cut <sup>a</sup> (C)	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.002</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.014</b>	<b>&lt;0.001</b>
Treatment (T)	<b>0.013</b>	0.288	0.120	0.853	0.340	0.122	0.119
Y	0.133	<b>0.009</b>	0.367	0.496	0.168	0.011	0.424
C × T	0.853	0.287	0.214	0.442	0.464	0.262	0.376
Y × C	<b>&lt;0.001</b>	0.087	0.332	<b>0.002</b>	0.151	0.629	0.390
Y × T	0.593	0.456	0.541	0.278	0.513	0.950	0.616
Y × C × T	<b>0.013</b>	<b>0.029</b>	0.133	0.882	0.180	0.096	0.178

<sup>a</sup> Cut denotes a single harvest in a growing season with three total harvests

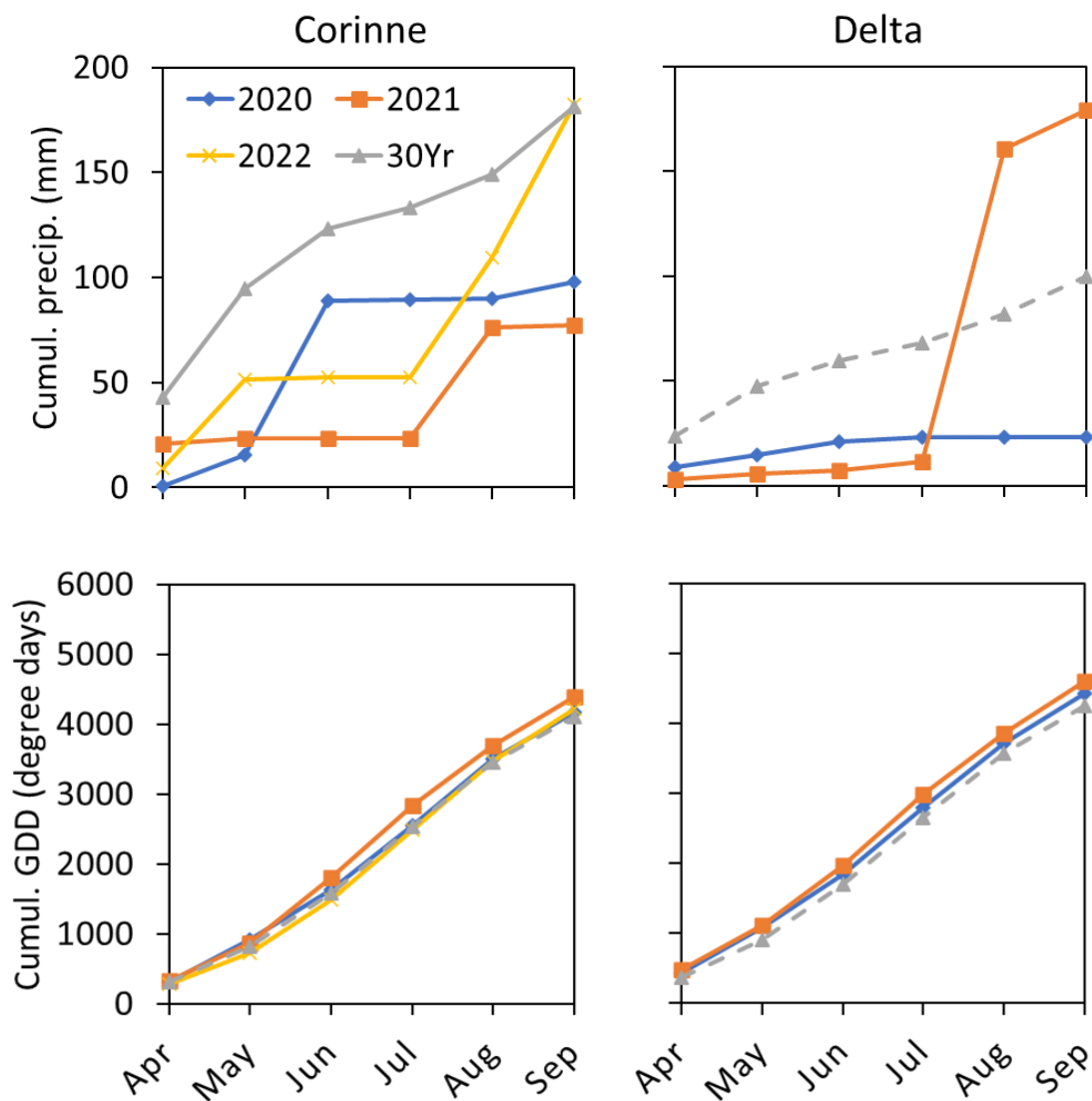
**TABLE 5.4** Significance of *F* tests, at the Corinne, UT site, for the fixed effects of position (head, middle, or tail of field) and year, and their interaction on alfalfa yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility (48-h); In Vitro Dry Matter Digestibility, IVTDMD; TDN, total digestible nutrients; RFQ, relative forage quality). Differences that were considered statistically significant when  $P < 0.05$  are bolded

Effect	Yield	CP	NDF	NDFD	IVTDMD	TDN	RFQ
Position (P)	<b>0.009</b>	0.361	0.981	0.060	0.735	0.853	0.591
Year (Y)	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.877	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>
P × Y	0.176	<b>0.017</b>	0.186	0.715	0.258	0.079	0.454

**TABLE 5.5** Seasonal irrigation amounts, dry matter alfalfa yield, and irrigation use efficiency (IUE) for the Corinne site from 2020-2022. Letters following means represent significant differences when  $P < 0.05$

Year	Irrigation	Yield	IUE <sup>a</sup>
	mm ha <sup>-1</sup>	Mg ha <sup>-1</sup>	Mg mm <sup>-1</sup>
2020	1090	16.43b	0.015
2021	620	18.28a	0.029
2022	740	13.14c	0.018

<sup>a</sup> Mg of alfalfa dry matter per mm of irrigation



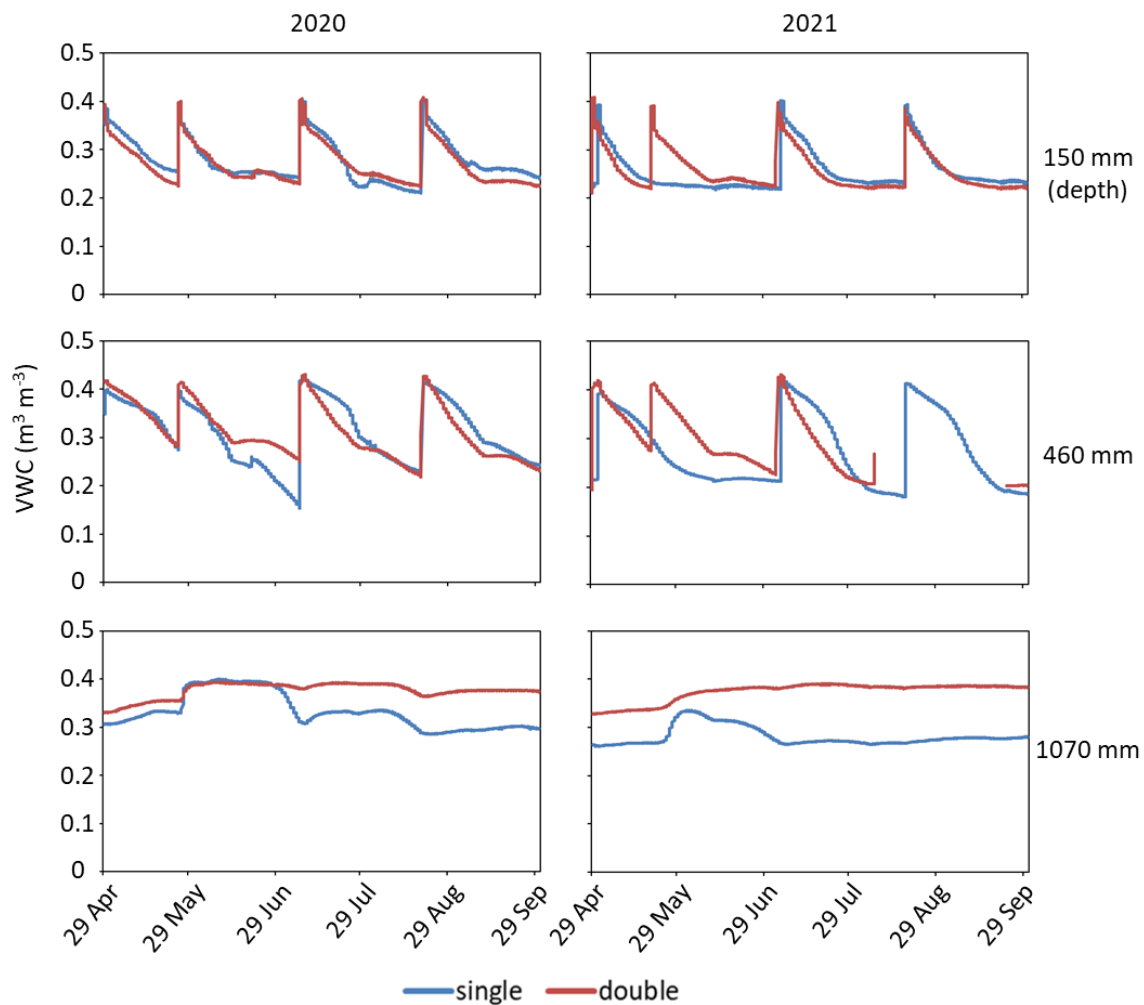
**FIGURE 5.1** Cumulative precipitation and growing degree days (GDD) for the Corinne and Delta, Utah sites. GDD were calculated from the minimum and maximum air temperatures and adjusted to 5°C and 30°C. The 30 yr normal (1991-2020) is shown for reference



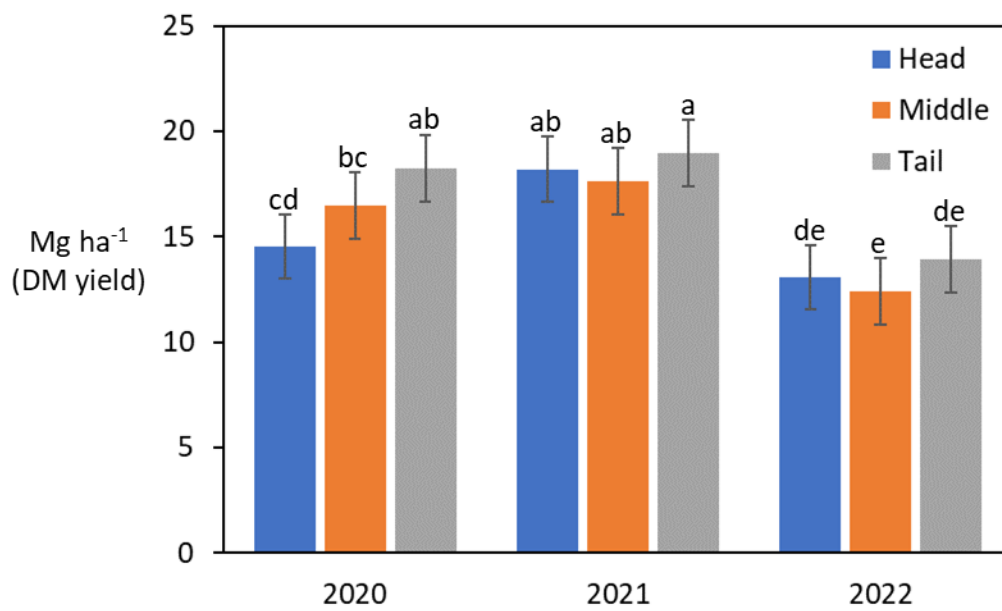
**FIGURE 5.2** Irrigation advance sensor developed by Commercial Business Radio (Photo by Kalen Taylor)



**FIGURE 5.3** "Wet Stake" irrigation advance sensor developed by Prescott Farm Innovations

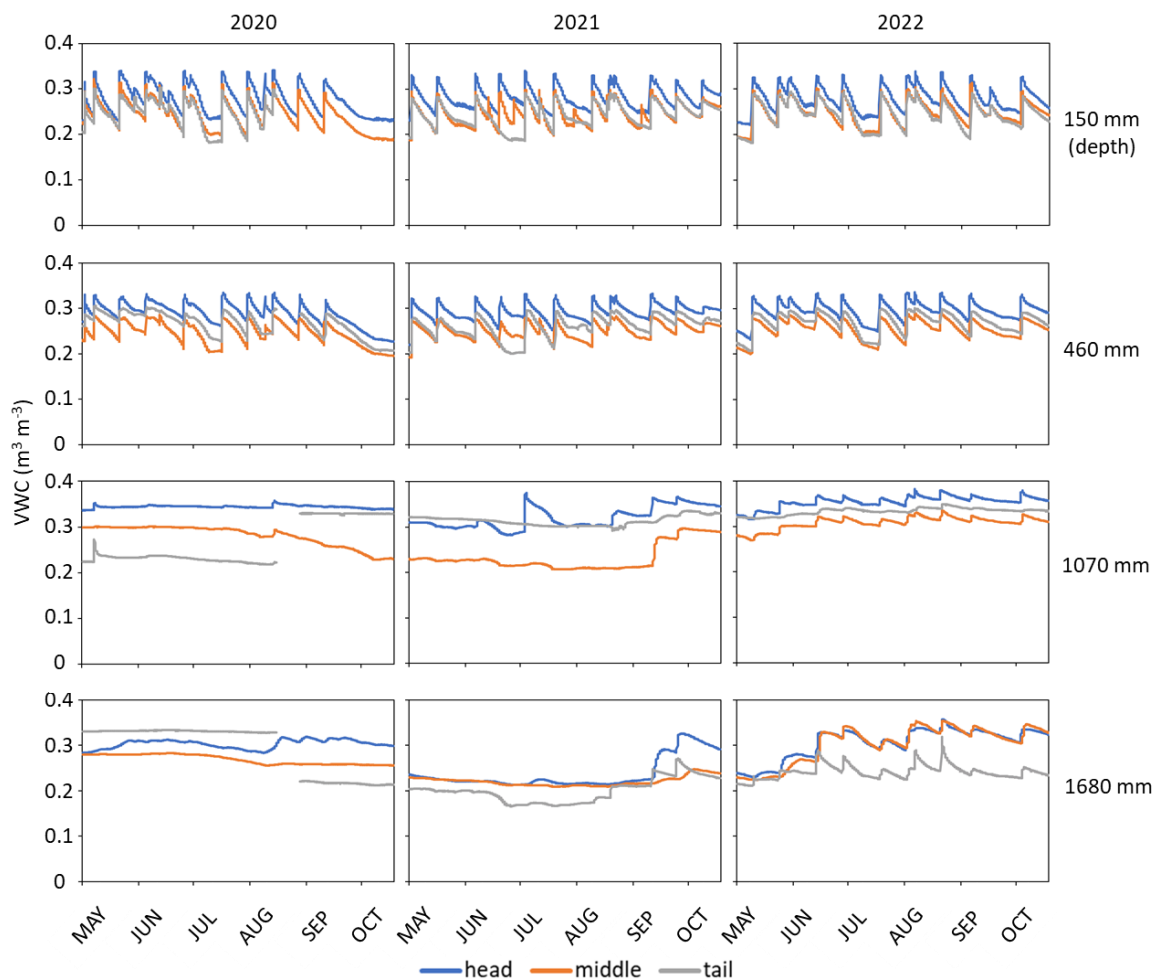


**FIGURE 5.4** Volumetric water content (VWC) in the single and double irrigated sets, from three sensor depths (150, 460, and 1070 mm) during the 2020-2021 alfalfa growing seasons in Delta, UT



**FIGURE 5.5** Alfalfa dry matter (DM) yield for the head, middle, and tail of the Corinne site before automation and implementation of surge irrigation (2020) and after (2021-2022). Mean separations were conducted at  $P < 0.05$ , with yield differences, within each year, denoted by the letters above each bar. Error bars are the standard errors





**FIGURE 5.6** Volumetric water content (VWC) at the head, middle, and tail of the Corinne site at four sensor depths (150, 460, 1070, and 1680 mm) during the 2020-2022 alfalfa growing seasons

## CHAPTER 6

### CONCLUSIONS

With irrigation being of such high importance, finding the best tools for improving it is research of great significance. The research in this dissertation evaluated several irrigation tools to maintain yield and crop quality, while attempting to reduce the amount of irrigation applied, as well as methods to help with an irrigation problem: wheel tracks. A strong conclusion from all of this research is that in agricultural irrigation, there are not tools with any universal guarantees, but selecting the best tool to match the field conditions and creating adaptations to work with the technology is how these tools can provide real benefits.

Results from Chapter 2 showed that LEPA and MDI pivot packages often have greater measured irrigation application efficiency than the commonly used MESA. However, as this research shows, increased efficiency does not guarantee yield, crop quality, or soil moisture improvements. In some situations, adapting the speed of the pivot or the sprinkler type to better match the infiltration rate of the soil may have improved the effectiveness of the LEPA system, as both sites demonstrated that LEPA had difficulty irrigating the area beneath the farthest span of the pivots when using the cooperating farmers' usual rates (32 – 38 mm per irrigation). Initially MDI showed great promise, reducing yield by 6 – 25% in 2018, with much less than half of the total irrigation. The 2019 and 2020 seasons demonstrated poor yields with MDI, even at similar or larger irrigation rates than MESA, and proved to be a system that required substantial amounts of labor to maintain and perform field operations around. Despite inconsistent results from the advanced systems in this study, LEPA and MDI have great

potential to maintain yield with less water than MESA given the correct circumstances and proper adaptations to maximize performance, both of which were sometimes restricted in this study. Therefore, the systems (LEPA, MDI, or MESA) cannot be fairly ranked with a generic field performance score, because under the multitude of field scenarios, each will be the optimal system for certain fields. Future research should continue to identify field conditions that might cause LEPA and MDI to be more beneficial and economic than MESA in terms of water savings and crop performance.

The results from Chapter 3 showed that the eight-boom design (i.e., Advantage booms) had mostly positive crop responses but did not create shallower wheel tracks. The single boom method used by irrigation equipment dealers in Northern Utah and Southern Idaho often maintained crop quality, but there were multiple instances and crops that had reduced yield, and unimproved or worse wheel tracks than the control areas. PAM had few effects on crop yield and quality, or wheel track depth. The PC method provided much shallower track depths at one site, but it came at the expense of a lower crop yield. At other sites there were minimal effects to yield and quality with the PC method, but the early-season, shallow wheel tracks did not usually last through the heaviest time of irrigating. LEPA was the most reliable method for maintaining crop yield and quality, while improving wheel tracks. In situations where there was high potential for the soil to become saturated, the LEPA approach could saturate the pivot track and allow the creation of deep ruts, but further experimentation with the sprinkler spacing, application method, and speed may be able to minimize these occurrences. Due to the concentrated application of LEPA, it is not recommended on fields with slopes greater than 1%, because of the potential for surface movement in the field and runoff (Senninger

Irrigation, 2023). There was no approach in the study that maintained yield and reduced pivot track depth in every scenario, but the LEPA method displayed the greatest potential for uniformly irrigating the area near the wheel track to maintain crop yield and quality, while minimizing water entering the track, to help reduce burdensome pivot ruts.

Each of the irrigation scheduling methods tested in Chapter 4 can provide useful information to assist farmers in irrigation decisions. However, they often did not reduce water application in comparison with what the cooperating farmers in this study were choosing to apply. This may have been due to the drought conditions present throughout the latter two years of this study. Under these conditions, all three scheduling methods, besides the control, lacked the incorporation of data that may have been even more crucial to the cooperating farmers, such as how limited their water turn was or how quickly their irrigation district would be shutting off water, which for some farmers and fields in the study was after only one or two cuts. These neglected facts often resulted in higher recommendations from the three scheduling methods tested. These recommendations would likely have increased yields and would have been desired by the farmers, but drought limitations often resulted in a more conservative recommendation from the cooperating farmers.

At some of the farms in the study, the three scheduling methods (soil sensor, ISM, and FNA) helped maintain yield with less irrigation, however there were few cases where there were consistent benefits, and many farms had no improvements at all. For the growing seasons evaluated, Utah was in a drought, and to some degree this impacted the farmer recommendations used as the control of the study. These results guide the notion that most farmers are extra careful with their water resources, and advanced scheduling

methods may not bring drastic results in alfalfa production or water use, but they did provide helpful information to guide irrigation decision making. When farmers have flexibility in scheduling when and how much they irrigate, these tools can provide reliable recommendations that can be trusted to sufficiently irrigate crops and minimize overirrigating. As one of the first studies to directly compare how four irrigation scheduling methods for center pivots affect crop production and water use, the results indicated that all three approaches (soil moisture, ISM, and FNA) had comparable performance, and in some situations can reduce irrigation rates by 10-15% without impacting production. These benefits were especially apparent in 2019 where relatively high precipitation was accounted for better by the tools than the grower control schedule.

Results for surface irrigation in Chapter 5 showed that eliminating one of the four annual irrigation events in 2020 and 2021 at the Delta site resulted in yield differences only for the first or three harvests of 2021. At that harvest, the area of the field that was only irrigated once, yielded 21% greater with 49% less irrigation applied than the area of the field irrigated twice before first harvest. There were no other yield differences at any of the six measured harvests of the study. Crude protein (CP) levels were significantly different at the last harvest of 2020, where the area of the field that received one less irrigation event measured 20.5%, and the area of the field receiving the full four irrigations was 18.4%. These results carried into the first harvest of 2021, where the area that skipped the second irrigation event had CP levels of 19.7%, while the area receiving all of the irrigation was lower at 17.9%. The duration of the study is too short to provide strong enough evidence that eliminating the second of the four irrigation events is safe to crop yield and quality long term. However, if limited access to irrigation forced this

adaptation for a season or two, this data has evidence that crop yield and quality would probably be maintained. Differences in CP levels may warrant an evaluation of nutrient levels in the irrigation water draining from the field, as reduced levels of CP in the alfalfa may be due to nitrogen removal from the additional, early-season irrigation.

Automation and implementation of surge irrigation began in 2021 at the Corinne site. In the first year of automation and surge, 43% less water was applied, resulting in nearly double the irrigation use efficiency of the previous year where irrigation was done manually, without any surge. These drastic results did not carry into 2022, but the severity of an ongoing drought in the region may or may not have impacted that effect. These data provide evidence that automation and surge can increase IUE and yield uniformity, but the high cost warrants extended research to help provide ample information to guide farmers that may be determining if this is an economic management practice for their farm.

The final tool evaluated was the irrigation advance sensor, which alerts irrigators when to cutoff water inflow. All three farmers shared positive responses to using the sensor, citing reduced labor to check the advancement of the irrigation across the field, and reducing the amount of irrigation draining from the field by timing the cutoff precisely. At one farm, using these sensors had an annual expense of USD\$375 to use three sensors, but reduced the seasonal water expense by about USD\$7,000. A downside to the sensors were occasional false alerts due to rain, but despite this, it was unanimously agreed upon that an irrigation advance sensor was a helpful tool for saving labor and water in a surface irrigating system.

The cumulative results of this dissertation indicate that there are simple and inexpensive ways to increase irrigation efficiency and management in both sprinkler and surface irrigation systems in Utah. Our results showed that sprinkler packages, irrigation scheduling, and surge irrigation have the potential of reducing water use (diversions) in forage crops (alfalfa and silage corn) by 10 and sometimes up to 25%. Future work should examine how these approaches affect water consumption. Further, simple tools such as water advancement sensors and pivot track sprinkler adjustments can often improve water management and help save labor, time, and expenses for irrigators.

## REFERENCES

## CHAPTER II

- Amosson, S., Almas, L., Girase, J. R., Vimlesh, K., & Marek, T. (2011). Economics of irrigation systems. *Texas A&M University Extension*. Retrieved from: <https://cdn.agrilifetoday.tamu.edu/wp-content/uploads/2011/10/Irrigation-Bulletin-FINAL-B6113.pdf>
- Bordovsky, J. P. (2019). Low-energy precision application (LEPA) irrigation: A forty-year review. *Transactions of the ASABE*, 62(5), 1343–1353.  
<https://doi.org/10.13031/trans.13117>
- Clevenger, B. (2016). Wheel traffic effect on alfalfa yield – soil compaction or crown/shoot damage? *Crop Observation and Recommendation Network Newsletter*. <https://agcrops.osu.edu/newsletter/corn-newsletter/wheel-traffic-effect-alfalfa-yield---soil-compaction-or-crownshoot-damage>
- Elmore, R., Daugherty, R. B., & Mueller, N. (2015). Growing degree units and corn emergence. *University of Nebraska-Lincoln Cropwatch*.  
<https://cropwatch.unl.edu/growing-degree-units-and-corn-emergence>
- FAO. (2011). The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk. *The Food and Agriculture Organization of the United Nations, Rome and Earthscan, London*.  
<http://www.fao.org/3/i1688e/i1688e.pdf>
- Hanks, R. J., Keller, J., Rasmussen, V. P., & Wilson, G. D. (1976). Line source sprinkler for continuous variable irrigation-crop production studies. *Soil Science Society of*



*America Journal*, 40(3), 426–429.

<https://doi.org/10.2136/sssaj1976.03615995004000030033x>

Kisekka, I., Oker, T. E., Aguilar, J. P., & Rogers, D. (2016). Mobile drip irrigation evaluation in corn. *29th Annual Central Plains Irrigation Conference*, 2(7).

<https://www.ksre.k-state.edu/irrigate/reports/r17/KisekkaMDI17.pdf>

Kukal, M. S., & Irmak, S. (2019). Irrigation-limited yield gaps: trends and variability in the United States post-1950. *Environmental Research Communications*, 1(6), 061005. <https://doi.org/10.1088/2515-7620/ab2aee>

Lyle, W. M., & Bordovsky, J. P. (1981). Low Energy Precision Application (LEPA) Irrigation System. *Transactions of the ASAE*, 24(5), 1241–1245.

<https://doi.org/10.13031/2013.34427>

Molaei, B., Peters, R. T., Mohamed, A. Z., & Sarwar, A. (2021). Large scale evaluation of LEPA/LESA system compared with MESA on spearmint and peppermint.

*Industrial Crops and Products*, 159(113048).

<https://doi.org/https://doi.org/10.1016/j.indcrop.2020.113048>

New, L., & Fipps, G. (2021). Center pivot irrigation. *AgriLife Extension*, B-6096(7/00), 11–14.

National Oceanic and Atmospheric Administration. (2022). *GDIS - Monitoring Drought /*

*Global Drought Information System (GDIS)*. <https://gdis->

[noaa.hub.arcgis.com/pages/drought-monitoring](https://gdis-noaa.hub.arcgis.com/pages/drought-monitoring)

- Noland, R. L., & Wells, M. S. (2018). Using growing degree days to plan early-season alfalfa harvests. *University of Minnesota Extension*.  
<https://extension.umn.edu/forage-harvest-and-storage/using-growing-degree-days-plan-early-season-alfalfa-harvests#how-it's-calculated-1048710>
- O'Geen, T. (2020). *SoilWeb*. University of California-Davis. Davis, CA. Retrieved October 23, 2020 from <https://casoilresource.lawr.ucdavis.edu/gmap/>
- O'Shaughnessy S. A., Colaizzi P. D. (2017). Performance of precision mobile drip irrigation in the Texas High Plains region. *Agronomy*, 7(4):68.  
<https://doi.org/10.3390/agronomy7040068>
- Oker, T. E., Kisekka, I., Sheshukov, A. Y., Aguilar, J., & Rogers, D. (2020). Evaluation of dynamic uniformity and application efficiency of mobile drip irrigation. *Irrigation Science*, 38(1), 17–35. <https://doi.org/10.1007/s00271-019-00648-0>
- Oker, T. E., Sheshukov, A. Y., Aguilar, J., Rogers, D. H., & Kisekka, I. (2021). Evaluating soil water redistribution under mobile drip irrigation, low-elevation spray application, and low-energy precision application using HYDRUS. *Journal of Irrigation and Drainage Engineering*, 147(6), 04021016.  
[https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001553](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001553)
- Peters, T., Neibling, H., Stroh, R., Molaei, B., & Mehanna, H. (2019). Low energy precision application (LEPA) and low elevation spray application (LESA) trials in the pacific northwest. *Oregon State University Extension Service*.:  
<https://extension.oregonstate.edu/sites/default/files/documents/33601/lepa-lesa-pnw-stroh-revisions.pdf>

- Putnam, D. H., Gull, U., Perez, B., Leinfelder-Miles, M., & Long, R. F. (2017). Flooding and water-logging damage in alfalfa - What to do? *Alfalfa & Forage News*.  
<https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=22996>
- Sarwar, A., Peters, R. T., Mehanna, H., Amini, M. Z., & Mohamed, A. Z. (2019). Evaluating water application efficiency of low and mid elevation spray application under changing weather conditions. *Agricultural Water Management*, 221(July), 84–91. <https://doi.org/10.1016/j.agwat.2019.04.028>
- Senninger Irrigation. (2018). Staying Close: the hot topic of LEPA close spacing. *Potato Grower*. <https://www.potatogrower.com/2018/03/staying-close>
- United States Department of Agriculture. (2021). Irrigation & water use.  
<https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/>
- Wolfinger, R., Miles-McDermott, N., & Kendall, J. (1992). Analyzing split-plot and repeated-measures designs using mixed models. *Kansas State University Annual Conference on Applied Statistics in Agriculture: 4<sup>th</sup> Annual Conference*, Manhattan, Kansas. <https://doi.org/10.4148/2475-7772.1405>

### CHAPTER III

- Agricultural Marketing Service of the United States Department of Agriculture. (2023). Hay quality designation guidelines. *Livestock, Poultry, and Grain Market News*.  
<https://www.ams.usda.gov/sites/default/files/media/HayQualityGuidelines.pdf>

Agriculture Victoria. (2022). Centre pivot wheel rutting. *Agriculture Victoria*.

<https://agriculture.vic.gov.au/farm-management/water/irrigation/centre-pivot-and-lateral-move-systems/centre-pivot-wheel-rutting>

Alfalfa hay prices reported to USDA from selected states. (2022, August 9). *Hay and Forage Grower*. <https://www.hayandforage.com/article-4046-usda-hay-markets--august-9-2022.html>

Foley, J. P. (2008). Centre pivot and lateral move machines. *WATERpak: A Guide for Irrigation Management in Cotton*, 202. (p. 202).

[https://eprints.usq.edu.au/15348/1/Foley\\_WATER2008\\_PV.pdf](https://eprints.usq.edu.au/15348/1/Foley_WATER2008_PV.pdf)

Lentz, R. D., Sojka, R. E. (1994). Field results using polyacrylamide to manage furrow erosion and infiltration. *Soil Science* 158(4), 274-282.

Meyer, R., Hoffman, R. (1983). A statistical analysis of wheel rut depths with center pivot irrigation systems. *Farm Research*, 41(2), 16–17.

<http://hdl.handle.net/10365/10184>

Senninger Irrigation. (2023). LEPA close spacing irrigation. *Senninger Agricultural Irrigation website*. <https://www.senninger.com/lepa-close-spacing-irrigation>

Sojka, R. E., Lentz, R. D., Ross, C. W., Trout, T. J., Bjorneberg, D. L., & Aase, J. K. (1998). Polyacrylamide effects on infiltration in irrigated agriculture. *Journal of Soil and Water Conservation*, 53(4), 325 LP – 331.

<http://www.jswconline.org/content/53/4/325.abstract>

Zhang, X.C., Miller, W.P. (1996). Polyacrylamide effect on infiltration and erosion in furrows. *Soil Science Society of America Journal*, 60, 866-872.

<https://doi.org/10.2136/sssaj1996.03615995006000030027x>

## CHAPTER IV

Aguilar, J., Rogers, D., & Kisekka, I. (2015). Irrigation scheduling based on soil moisture sensors and evapotranspiration. *Kansas Agricultural Experiment Station Research Reports*, 1(5). <https://doi.org/10.4148/2378-5977.1087>

Amosson, S., Almas, L., Girase, J. R., Vimlesh, K., & Marek, T. (2011). Economics of Irrigation Systems. *Texas A&M Agrilife Extension*.

<https://agrilifelearn.tamu.edu/s/product/economics-of-irrigation-systems/01t4x000004OUUBAA4>

Brajović, M., Vujović, S., & Đukanović, S. (2015). An overview of smart irrigation software; An overview of smart irrigation software. *2015 4th Mediterranean Conference on Embedded Computing (MECO)*.

<https://doi.org/10.1109/MECO.2015.7181942>

Campbell, G. S., & Campbell, M. D. (1982). Irrigation scheduling using soil moisture measurements: theory and practice. In D. Hillel (Ed.), *Advances in Irrigation: Volume 1* (1st ed., pp. 25–26). Academic Press, INC.

<https://books.google.com/books?hl=en&lr=&id=->

APgBAAAQBAJ&oi=fnd&pg=PA25&dq=irrigation+scheduling&ots=wzt2opnL  
r&sig=uxZMC2ProZSO8E3tRDC9vUCYqqI#v=onepage&q&f=false

Food and Agriculture Organization of the United Nations. (2011). The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk. *The Food and Agriculture Organization of the United Nations*, Rome, Italy and Earthscan, London. <http://www.fao.org/3/i1688e/i1688e.pdf>

Howell, T. A. (1996). Irrigation scheduling research and its impact on water use. *American Society of Agricultural Engineers, Proceeding* (Nov. 3-6), 21–33.

Jones, H. G. (n.d.). Irrigation scheduling: Advantages and pitfalls of plant-based methods. <https://doi.org/10.1093/jxb/erh213>

Kranz, W. L., Eisenhauer, D. E., & Retka, M. T. (1992). Water and energy conservation using irrigation scheduling with center-pivot irrigation systems. *Agricultural Water Management*, 22(4), 325–334. [https://doi.org/10.1016/0378-3774\(92\)90040-4](https://doi.org/10.1016/0378-3774(92)90040-4)

Kukal, M. S., & Irmak, S. (2019). Irrigation-limited yield gaps: Trends and variability in the United States post-1950. *Environmental Research Communications*, 1(6), 061005. <https://doi.org/10.1088/2515-7620/ab2aee>

Lindsay Corporation. (2018). FieldNET Advisor | Summary of product trial and test results. [https://www.lindsay.com/uploads/files/sections/1029-lindsay\\_fieldnet\\_whitepaper\\_advisor\\_0118\\_web.pdf](https://www.lindsay.com/uploads/files/sections/1029-lindsay_fieldnet_whitepaper_advisor_0118_web.pdf)

- National Oceanic and Atmospheric Administration. (2022). Monitoring drought | Global drought information system (*GDIS*). <https://gdis-noaa.hub.arcgis.com/pages/drought-monitoring>
- New, L., & Fipps, G. (2000). Center pivot irrigation. *Texas AgriLife Extension Service*, 11–13. [https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/86877/pdf\\_1181.pdf?sequence=1&isAllowed=y](https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/86877/pdf_1181.pdf?sequence=1&isAllowed=y)
- Oklahoma State University Extension. (2001). Alfalfa production guide for the southern Great Plains. In *Oklahoma Cooperative Extension Service* (Chapter 5). Oklahoma State University. [http://www.soilcropandmore.info/crops/alfalfa/Oklahoma\\_Alfalfa/contents.htm](http://www.soilcropandmore.info/crops/alfalfa/Oklahoma_Alfalfa/contents.htm)
- O’Shaughnessy, S. A., Evett, S. R., Colaizzi, P. D., & Howell, T. A. (2013). Wireless sensor network effectively controls center pivot irrigation of sorghum. *Applied Engineering in Agriculture*, 29(6), 853–864. <https://doi.org/10.13031/aea.29.9921>
- Peters, T. (2014). Simplified irrigation scheduling on your phone or web browser. 208–378. <http://weather.wsu.edu>
- Sui, R. (2018). Irrigation scheduling using soil moisture sensors. *Journal of Agricultural Science*, 10(1). <https://doi.org/10.5539/jas.v10n1p1>
- Sarwar, A., Peters, R. T., Mehanna, H., Amini, M. Z., & Mohamed, A. Z. (2019). Evaluating water application efficiency of low and mid elevation spray

application under changing weather conditions. *Agricultural Water Management*, 221(July), 84–91. <https://doi.org/10.1016/j.agwat.2019.04.028>

United States Census Bureau (2022). *U.S. and world population clock*.

<https://www.census.gov/popclock/>

United States Department of Agriculture Economic Research Service. (2022). Irrigation & water use. <https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/>

United States Department of Agriculture Agricultural Marketing Service. (2023). Hay quality designation guidelines. *Livestock, Poultry, and Grain Market News*.

<https://www.ams.usda.gov/sites/default/files/media/HayQualityGuidelines.pdf>

Utah State University. (2023). *Irrigation technology cost/benefit analysis calculator*.

Utah State University Crop Resources.

<https://extension.usu.edu/crops/tools/irrigation-technology-cost-benefit-calculator>

Vellidis, G., Liakos, V., Andreis, J. H., Perry, C. D., Porter, W. M., Barnes, E. M., Morgan, K. T., Fraisse, C., & Migliaccio, K. W. (2016). Development and assessment of a smartphone application for irrigation scheduling in cotton.

*Computers and Electronics in Agriculture*, 127, 249–259.

<https://doi.org/10.1016/j.compag.2016.06.021>

## CHAPTER V



- Arnold, B. J., Upadhyaya, S. K., Roach, J., Kanannavar, P. S., & Putnam, D. H. (2014). Water advance model and sensor system can reduce tail runoff in irrigated alfalfa fields. *California Agriculture*, 68(3), 82–88.  
<http://dx.doi.org/10.3733/ca.v068n03p82>
- Devitt, D. A., & Andersen, J. (1995). Moapa Valley surge irrigation study. *Mississippi State University Extension*.  
[http://surfaceirrigation.extension.msstate.edu/sites/default/files/2021-02/UN\\_Moapa Valley Surge Irrigation Study.pdf](http://surfaceirrigation.extension.msstate.edu/sites/default/files/2021-02/UN_Moapa%20Valley%20Surge%20Irrigation%20Study.pdf)
- Goldhamer, D. D., Alemi, M. H., & Phene, R. C. (1987, September). Surge vs. continuous-flow irrigation. *California Agriculture*, 29–32.  
[http://surfaceirrigation.extension.msstate.edu/sites/default/files/2021-02/UCDavis\\_Surge vs Continuous Flow Irrigation.pdf](http://surfaceirrigation.extension.msstate.edu/sites/default/files/2021-02/UCDavis_Surge%20vs%20Continuous%20Flow%20Irrigation.pdf)
- Hanks, R. J., Keller, J., Rasmussen, V. P., & Wilson, G. D. (1976). Line source sprinkler for continuous variable irrigation-crop production studies. *Soil Science Society of America Journal*, 40(3), 426–429.  
<https://doi.org/10.2136/sssaj1976.03615995004000030033x>
- Hanson, B. R., Bali, K. M., Sanden, B. L., Summersand, C. G., & Putnam, D. H. (2008). Irrigating alfalfa in arid regions. In *Irrigated Alfalfa Management in Mediterranean and Desert Zones*. UC ANR.

- Humpherys, A. S. (1989). Surge irrigation: An overview. *International Commission on Irrigation and Drainage*, 38(2), 36–45.  
<https://eprints.nwisrl.ars.usda.gov/id/eprint/533/1/709.pdf>
- Israeli, I. (1988). Comparison of surge and cablegation to continuous furrow irrigation. *American Society of Agricultural Engineers*, 88–2014, 14.
- Miller, J., & Shock, C. (1992). The effect of surge irrigation on onion yield and quality, irrigation efficiency, and soil nitrogen losses. *Oregon State University Extension*.  
<https://agsci.oregonstate.edu/sites/agscid7/files/malheur/attachments/surgeonioneffects.pdf>
- Miller, J. G., Shock, C. C., Stieber, T. S., & Saunders, L. D. (1991). Surge irrigation of bliss spring wheat. *Oregon State University Extension*.  
<https://agsci.oregonstate.edu/sites/agscid7/files/malheur/attachments/surgeblisswheat1991.pdf>
- Musick, J. T., Walker, J. D., Schneider, A. D., & Pringle, F. B. (1987). Seasonal evaluation of surge flow irrigation for corn. *Applied Engineering in Agriculture*, 3(2), 247–251.
- Roberts, C., Yost, M., Robbins, J., Ransom, C. & Creech, E. (2022). Oat companion seeding rate, herbicide, and irrigation effects on spring-seeded alfalfa. *Agronomy Journal*, 115(1). <https://doi.org/10.1002/agj2.21227>

Schwankl, L., & Prichard, T. (2003). Improving irrigation water management of alfalfa. *Western Alfalfa and Forage Symposium*.

<https://alfalfa.ucdavis.edu/+symposium/proceedings/2003/03-67.pdf>

Shock, C. C., & Welch, T. (2011). Surge irrigation. *Sustainable Agriculture Techniques*, 1–2.

Stringham, G. E., & Keller, J. (1979, July 17-20). Surge flow for automatic irrigation. *American Society of Civil Engineers; Irrigation and Drainage Division Special Conference*. Albuquerque, New Mexico, United States.

Testezlaf, R. R., Elliot, L., & Garton, J. E. (1987). Furrow infiltration under surge flow irrigation. *American Society of Agricultural Engineers*, 30(1), 193–197.

Undersander, D., Cosgrove, D., Cullen, E., Grau, C., Rice, M. E., Renz, M., Sheaffer, C., Shewmaker, G., & Sulc, M. (2011). *Alfalfa management guide*. American Society of Agronomy. <https://doi.org/10.2134/2011.alfalfamanagementguide>

United States Department of Agriculture Agricultural Marketing Service. (2023). Hay quality designation guidelines. *Livestock, Poultry, and Grain Market News*. <https://www.ams.usda.gov/sites/default/files/media/HayQualityGuidelines.pdf>

## CURRICULUM VITAE

Jonathan Holt

## EDUCATION

- Utah State University  
 Ph.D. Plant Science.....2023  
 Dissertation: “Practical Improvements for Pivot and Surface Irrigation”  
 GPA: 3.8
- Utah State University  
 M.S. Plant Science .....2020  
 Thesis: “Innovative Water Management Using Advanced Irrigation Systems and  
 Biochar”  
 GPA: 4.0
- Brigham Young University Idaho  
 B.S. Agriculture Education .....2014  
 Agriculture Education Composite degree  
 GPA: 3.7

## CERTIFICATIONS

- Commercial Driver .....2016  
 Alberta Teacher Certification .....2015  
 Idaho Teacher Certification .....2014

## EXPERIENCE

- Utah State University  
 Graduate Research Assistant..... 2018-2023
- Train research assistants and help coordinate their work with the team
  - Conduct experiments on farms across Utah and Idaho
  - Present project results at international meetings and at USU Extension field days
  - Correlate project action steps with growers, advisors, and suppliers, then following through with quality, precise work
- Farming and Ranching..... 2003-2018

- Worked closely with farm managers and provided a review of options when determining crop selections, buying and selling equipment, and marketing a large calf-crop
- Performed field tasks for a variety of crops: alfalfa, barley, canola, dry peas, flax, lentils, durum, mustard, oats, and wheat
- Executed safe and effective animal handling in a 400 pair herd
- Worked with pivots, hand-lines, and wheel-move irrigation systems
- Performed all farm duties on operations ranging between 3,000 and 15,000 acres

Teaching.....2014, 2016

- Planned and operated welding programs that produced students confident in OFW, GMAW, and SMAW processes
- Maximized the number of credits students could earn by carefully selecting modules and making plans that would help students surpass government objectives in a timely manner
- Sought the support of local businesses, which in turn reduced shop expenses by 50% because of their donations

## PRESENTATIONS

2022

1. Holt, J., Yost, M., Creech, E., Barker, B., Cardon, G., and Torres, A. (2022, December 13). Practical Improvements for Pivot and Surface Irrigation. USU Doctoral Dissertation Public Defense. Logan, UT.

2021

2. Holt, Jonathan, (2021, December 8). Irrigation scheduling and application methods for precision irrigation. Guest lecturer at Lethbridge College. Lethbridge, AB, Canada. Invited.
3. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, November 17-18). Reducing pivot ruts with simple sprinkler changes. Proceedings of Western Alfalfa and Forage Symposium. Reno, NV.
4. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, September 6-7). Research of pivot wheel track options. Irrigation Dealer and Crop Advisor Joint Training meeting. Grace, ID. (75)
5. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, August 11). Research of pivot wheel track options. USU Crops Field Day. Wellsville, UT. (30)
6. Yost, M., Holt, J., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, August 4). 2020 Surface irrigation research updates. USU Crops Field Day. Tremonton, UT. (10)
7. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, July 21). Research of pivot wheel track options. USU Crops Field Day. Richfield, UT. (40)

8. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, July 21). Water optimization with advanced irrigation scheduling. USU Crops Field Day. Richfield, UT. (40)
9. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, July 14). Research of pivot wheel track options. USU Crops Field Day. Vernal, UT. (35)
10. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, June 24). Strategies for improving surface irrigation. USU Crops Field Day. Delta, UT. (55)
11. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, June 16). Water optimization with advanced irrigation scheduling. USU Crops Field Day. Beaver, UT. (25)
12. Holt, J., Yost, M., Creech E., Allen, N., and Winward, D. (2021, June 1). Optimizing pivot irrigation with the right sprinkler package. Canadian Water Resources Association Virtual National Conference. Invited.
13. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, May 6). Surface irrigation research and demonstrations. Utah Department of Agriculture and Food Surface Irrigation Field Day. Corinne, UT. (60)
14. Holt, J., Yost, M., Allen, N., Creech, E., Cardon, G., and Torres, A. (2021, March 11). Utah State University flood irrigation work. Virtual cooperative meeting with MSU, U of C, OSU, and USU.

#### 2020

15. Holt, J., Yost, M., Creech, E., Allen, N., and Winward, D. (2020, December 9). Innovative water management using advanced irrigation systems and biochar. USU Masters Thesis Public Defense. Logan, UT.
16. Holt, J., Yost, M., Creech E., Allen, N., and Winward, D., (2020, November 16). MESA, LEPA, and MDI for pivots. Cooperating grower meeting. Cedar City, UT. (8)
17. Holt, J., Yost, M., Creech E., Allen, N., and Winward, D. (2020, November 9). Agricultural water optimization with advanced sprinkler packages for pivots. Virtual ASA, CSSA, SSSA annual meeting.
18. Yost, M., Holt, J., Sullivan, T., Creech, E., Allen, N., Winward, D., and Kitchen, B. (2020, October 10). On-farm testing of advanced sprinklers for pivots. Virtual International Society of Precision Agriculture Conference. Invited.
19. Holt, J., (2020, July 28). Water Conservation in Flood Irrigation. USU Crops Virtual Field Day. (118).
20. Yost, M., Richards, T., and Holt, J. (2020, February 19-20). Soil and water conservation training. Brigham City, UT (65).

#### 2019

21. Holt, J., Yost, M., Creech, E., Reid, C., Winward, D., and Allen, N. (2019, November 19-20). Pivot irrigation innovations can maintain yield with less water. Proceedings of Western Alfalfa and Forage Symposium. Reno, NV.

22. Holt, J., Yost, M., Allen, N., Creech, E., Reid, C., Winward, D., and McAvoy, D. (2019, November 10-13). New irrigation technologies are maintaining yield with less water. ASA, CSSA, SSSA Annual Meeting, San Antonio, TX.
23. Yost, M., Larson, D., Egbert, K., Holt, J., Harper, M., Creech, E., and Allen, N. (2019, August 15-16). Irrigation Training for Extension and Irrigation Dealers. Wellsville, UT (50).
24. Holt, J., (2019, August 15). LEPA, LESA, and MDI trials. USU Irrigation Training. Wellsville, UT (50).
25. Holt, J., (2019, July 25). Irrigation results and field demo. USU Field Day. Elberta, UT (25).
26. Yost, M., Holt, J., and Creech, E. (2019, July 25). Agriculture Water Conservation Field Day. Elberta, UT (25).
27. Yost, M., Holt, J., Reid, C., and Winward, D. (2019, July 12). Agriculture Water Conservation Field Day. Cedar City, UT (40).
28. Holt, J. (2019, July 12). Irrigation results and field demo. USU Field Day. Cedar City, UT (40).
29. Holt, J. and Yost, M. (2019, March 25). Innovative water management using advanced irrigation systems and biochar. 2019. Plants, Soils, and Climate Department Showcase. Logan, UT.
30. Holt, J., Yost, M., Allen, N., Creech, E., Reid, C., Winward, D., and McAvoy, D. (2019, January 6-9). Innovative water management using advanced irrigation systems and biochar. Soil Science Society of America Annual Meeting, San Diego, CA.
31. Yost, M. and Holt, J. (2019, January 6-9). Refining mobile drip irrigation rates for alfalfa. Soil Science Society of America Annual Meeting, San Diego, CA. (45).

2018

32. Holt, J., Yost, M., Allen, N., Creech, E., Reid, C., Winward, D., and McAvoy, D. (2018, November 4-7). Innovative water management for alfalfa using precision mobile drip irrigation and biochar. ASA-CSSA Annual Meetings, Baltimore, MD.
33. Yost, M., Despain, D., and Holt, J. (2018, August 13). Mobile Drip Irrigation Field Day. Holden, UT (10)
34. Holt, J. (2018, August 13). Mobile Drip Irrigation Initial Results. USU Field Day. Holden, UT (10).

## PUBLICATIONS

1. Holt, J., Yost, M., Creech, E., Allen, N., McAvoy, D., Winward, D. Biochar had minor impacts on yield, quality, and water availability of irrigated alfalfa, corn, and wheat. *Agronomy Journal*. American Society of Agronomy, Madison, WI.
2. Holt, J., Yost, M., Allen, N., Taylor, K. (2021) Irrigation advance sensors are having large impacts in surface irrigation. Utah State Univ. Ext. Fact Sheet.

3. Holt, J., Yost, M., Creech, E., McAvoy, D., Allen, N., Austin, J. (2021) Biochar impacts on crop yield and soil water availability. Utah State Univ. Ext. Fact Sheet.
4. Holt, J., Yost, M., Allen, N., Creech, E., Winward, D., and Sullivan, T. (2021). Guide to irrigation application systems for pivots and laterals. Utah State Univ. Ext. Fact Sheet.
5. Holt J. and Yost, M. (2020, April 6). Soil moisture sensing for forage irrigation. Hay and Forage Grower. Penton Media, Inc., New York, NY.
6. Yost, M., Young, T., Allen, N., Larson, D., and Holt, J. (2020). Variable frequency drives for irrigation pumps. Utah State University Extension Bulletin.
7. Yost, M., Holt, J., Reid, C., Winward, D., Creech, E., and Allen, N. (2019). Precision mobile drip irrigation for pivots and laterals. Utah State University Extension Bulletin.

## VIDEOS

1. Holt, J. (2022) What is surge irrigation and why are Utah farmers starting to use it? <https://www.youtube.com/watch?v=orgDmM0HBiA>
2. Holt, J. (2022) Flood irrigation inexpensive time and water saving sensor. <https://www.youtube.com/watch?v=cg8cYs1TviM>
3. Holt, J. (2022) What sprinkler package should I put on my pivot? <https://www.youtube.com/watch?v=mZQqohytW6k>
4. Holt, J. (2022) Scheduling irrigation with soil moisture sensors on the farm. [https://www.youtube.com/watch?v=o\\_s3VjIvL4w&t=300s](https://www.youtube.com/watch?v=o_s3VjIvL4w&t=300s)
5. Holt, J. and Yost, M. (2020). What is surge irrigation? <https://youtu.be/YdnaIeu58qE>.
6. Holt, J. and Yost, M. (2020). Flood irrigation research. <https://youtu.be/45PsxPNC-Yk>.

## VOLUNTEER WORK

- Farm Bureau Volunteer..... 2022-Current
- Judge local FFA competitions
  - Participate in event planning and management
- “Learn to Skate” Coach ..... 2015, 2020-2021
- Taught skating fundamentals to adults and children
  - Created plans for four levels of skating classes
- Race Organizer..... 2012-2016
- Planned and executed lawn mower racing events for the town celebration day
  - Correlated plans with Town Council, participants, and local business owners
- Magrath Emergency Services Firefighter ..... 2007, 2010-2012
- Handled emergency situations as a trust-worthy team member



- Trained in extrication, structure & wildland fire, and ice rescue

Church of Jesus Christ of Latter-Day Saints Missionary..... 2007-2009

- Gave ecclesiastical and humanitarian service to the people of South Africa
- Performed over 50 training meetings for groups of missionaries

## MEMBERSHIPS

Alberta Teachers' Association

American Society of Agronomy

Crop Science Society of America

Canadian Water Resources Association

Soil Science Society of America