AN ABSTRACT OF THE DISSERTATION OF


Title: Quantifying the Unproductive Water Lost as Evaporation from Different Irrigation Designs by Analysis of the Soil Stable Water Isotope Compositions.

Abstract approved:
______________________________________________________

Stephen P Good

Abstract

The knowledge about the intensive agricultural irrigation is very limited, but the use of irrigation is rapidly increasing. As an outcome, the sympathetic ecosystem is accepting modern irrigation that will play an essential function in the present and future for agricultural products. My dissertation will display the modification for investigation of the integrating among atmosphere conditions and soil water content, analysis of the stable water isotopes results, fieldwork of experiments, and quantifying unproductive water losses as evaporation ratio from the irrigation designs. This study was covered largely the territories of the Pacific Northwest in the US, in summer over three years, and these farms were alfalfa, corn, potato, and a hazelnut field. My research goal of this academic work that is a study a detailed investigation and analysis of the water lost as evaporation, which is influenced via using various irrigation designs and thus improves agriculture economically. Moreover, this study described the advantages of the isotopic compositions technique that used in this dissertation.
The first section of this dissertation contains an experimental study to assess the influence of irrigation structural configurations on evaporation losses in semiarid agricultural systems by using stable water isotopes. During mid-summer 2017 in eastern Oregon and southeast Washington, we collected soil samples at multiple positions and depths around the central irrigation tower from four different agricultural fields, each with both Mid Elevation Spray Application (MESA) and Low Elevation Spray Application (LESA) configurations. We measured the hydrogen and oxygen stable isotope ratio of soil water at MESA and LESA field locations using H$_2$O liquid–H$_2$O vapor equilibration laser spectroscopy. Though soil moisture contents were similar, the average isotope ratio of soil water under LESA irrigation ($\delta^D = -114.5\%o$, $\delta^{18}O = -14.5\%o$) had lower values than under MESA irrigation ($\delta^D = -108.2\%o$, $\delta^{18}O = -13.1\%o$). Calculated $E/I$ values demonstrated higher sprinkler and soil water evaporation occurring at the MESA irrigated locations ($E/I = 16.1\%$) compared to the LESA irrigated locations ($E/I = 9.0\%$). We find that LESA systems have lower non-productive water losses than MESA systems and are thereby more efficient users of applied water. Our results suggest that stable water isotopes provide a technique for improving the management of water resources through the assessment of irrigation efficiency.

The second section is included the results of the differences in soil evaporation between row and interrow positions in furrowed agricultural fields. At Hermiston city, Oregon, soil evaporation from the row and interrow positions within potato fields of contrasting irrigation timing (daytime vs nighttime) was estimated based on hydrogen and oxygen isotope ratios. Samples collected throughout the 2016 growing season were measured
and used to calculate soil evaporation (E) losses relative to applied irrigation (I). On average, row positions were more enriched in heavy isotopes than interrow positions, indicating that the evaporated fraction of applied irrigation ($E/I$) depends on the position. Within the day irrigated field the estimated (mean ± standard deviation) $E/I$ ratios determined from both stable isotopes for May, July, and September were 18±8%, 10±3% and 19±5% for row samples and 15±6%, 7±2% and 12±4% for interrow samples. Within the night irrigated field during these same months, the $E/I$ ratios were 13±12%, 16±7% and 13±5% for row samples and 12±7%, 9±2% and 6±2% for interrow samples, respectively. These results reveal that there is more evaporation from the row, as compared with interrow, positions. Therefore, management strategies and practices for water conservation should take into account larger non-productive soil evaporation losses from within rows to minimize evaporative soil water losses.

The third section of our dissertation that is estimating evaporation by using stable water isotope from a hazelnut farm with two designs of drip irrigation. Drip irrigation is often considered an efficient means of water delivery, however how the efficiency changes as more emitted are added to a system is unclear as additional water may be lost to evaporation before it can be taken up by roots. In this study, non-productive soil evaporation losses are estimated based on the hydrogen and oxygen isotope ratios of soil moisture for a hazelnut field in the Willamette Valley of the Pacific Northwest. Soil samples from the hazelnut field under single-line and double-line drip irrigation treatments were collected in summer 2018 at multiple depths from different positions in the tree rows. The stable isotope ratio of soil water in these samples was measured using $\text{H}_2\text{O}$ liquid - $\text{H}_2\text{O}$ Vapor equilibration laser spectroscopy. Our results show
average $^{2}\text{H}/^{1}\text{H}$ and $^{18}\text{O}/^{16}\text{O}$ isotope ratios of the single line with drip irrigation were higher than double line with drip irrigation. These results suggest that less soil evaporation occurred from the double-line drip irrigation ($E/I = 17.33 \pm 6\%$) when compared to the single-line treatment ($E/I = 20.93 \pm 6.5\%$), which also had higher soil moisture levels than the single line with drip irrigation that irrigated during the day. This suggests that increasing the number of drip emitters can lead to an increase in the efficiency of drip irrigation when efficiency is defined as the fraction applied that is used productively by plants.
Quantifying the Unproductive Water Lost as Evaporation from Different Irrigation Designs by Analysis of the Soil Stable Water Isotope Compositions.

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Firas Mohammed Sajet Al-Oqaili

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APPROVED:

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Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Firas Mohammed Sajet Al-Oqaili, Author
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CONTRIBUTION OF AUTHORS

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1 General Introduction

Water is often a limiting factor for crop growth, particularly in arid and semi-arid regions and even in some humid areas. (Siebert et al., 2010). The hydrologic cycle has been changed by using intense irrigated agriculture and often has major environmental consequences (Foster et al., 2018).

Agriculture uses the greatest amount of water in the world: 70% for Agriculture, 20% for industry and 10% for municipalities (Molden, 2013; Rosegrant et al., 2009; Siebert et al., 2010). The largest consumer of fresh water resources is agriculture for its necessity in crop production (Mancosu et al., 2015) as it plays a major role in food security and food production (Calzadilla et al., 2011). It is clear that the intensity of irrigation in different countries varies with climate, cultivated crops and farming styles (Fisher et al., 2017; Morison et al., 2008). Biological water uses are closely related to ecosystem productivity and require knowledge of the amount of water lost by evaporation or transpiration (Morison et al., 2008). The intensity of irrigation water in the agricultural field can be outlined as direct evaporation from the soil surface, crop transpiration, and deep filtration under the crop root zone (Wang et al., 2012; Agam et al., 2012).

The number of water molecules that fracture from the water surface and move out into the atmosphere as gas is greater than the number that gets in the surface of the water and this is called operation 'Evaporation'. (Kumar et al., 2013), and evaporated water is either productive as transpiration or nonproductive (Falkenmark & Rockström, 2006). Productive evaporation is water that the plant uses to produce biomass whereas
nonproductive evaporation includes flows that are not used by plants (Van Emmerik et al., 2012). Therefore, it is necessary to determine the water loss by evaporation in order to optimize the use of water by different irrigation methods (Alvarez et al., 2008). Water is distributed over an irrigated area by spraying it through the air when the irrigation is applied by a sprinkler system (Zazueta, 2011). The nozzles might be fixed and equipped with reflectors, which break up the water stream and deflect the area to be irrigated or they shifted to cover circular or partial areas of the field (Zazueta, 2011). Through overlapping of spray designs from adjacent sprinklers can achieve high uniformity of water application. (Zazueta, 2011). “The amount of evaporation depends on three factors: (1) the climate (2) the time available for the evaporation to occur, (3) and the surface area of the water droplets” (Smajstrla & Zazueta, 1994).

The results found by (Chen et al., 2010) in row spacing of winter wheat (Triticum aestivum L.) and their effect on soil evaporation (E) and evapotranspiration (ET) showed that E increased with row spacing whereas interrow mulching affects the water use efficiency and crop productivity of furrow and drip-irrigated maize (Zea mays L.). Under both irrigation treatments, (two drip line sources spacing patterns 60 and 80 cm), when the irrigation dose or the distance between the line sources increases, the actual evaporation decreases (Elmaloglou et al., 2013). By contrast, when the irrigation dose or the distance between the line sources increases, the deep percolation increases. (Elmaloglou et al., 2013). Since the 1960s, the variation in isotopes of deuterium to hydrogen (D / H) ratio in water has been studied especially rain, as a tracking of the hydrological process. (Craig, 1961; Dansgaard, 1964; Craig and Gordon, 1965)
Water stable isotopes ($^2$H and $^{18}$O) are important tools for tracking the real usage of water (Springer et al., 2017). They were used to follow the partitioning of evapotranspiration (ET) under fully controlled conditions (climatic chamber) along the growth of a tall fescue cover into soil evaporation (E) and plant transpiration (T) by measuring their stable oxygen isotopic compositions ($\delta_{ET}$, $\delta_E$ and $\delta_T$) (Rothfuss et al., 2010).

This chapter is specified to a general introduction for all manuscripts, prepared during the doctoral research program. These were done in different fields that can give us real results of using stable water isotope ratios in monitoring the non-productive evaporation accompanied with three irrigation regimes. It discusses three main parts: all manuscripts discuss the efficiency of water irrigation through determining the evaporation loss from different irrigation regimes (the nozzle elevation of sprinkler irrigation, furrow irrigation and drip irrigation) by using the isotope compositions. We suggest that stable water isotopes provide a powerful technique for improving the management of water resources through the assessment of irrigation efficiency.

The first paper configures the evaporation losses from sprinkler irrigation in four center-pivot irrigation sites in the Pacific Northwest of the U.S.; three alfalfa fields and one corn field. All the four fields’ sites were located on the eastern side of the Cascade Mountains within the arid to semi-arid climate of eastern Oregon and Washington, as the soil water evaporation loss in sprinkler irrigation was affected by the height of the droplets. The study followed the nonproductive water loss from Sprinkler irrigation within Mid-elevation spray application (MESA) and Low elevation spray application (LESA) droplet heights by using hydrogen and oxygen stable water isotope ratios of
soil water and we found soil evaporative water losses under both LESA and MESA irrigation systems were distinctly characterized using δ^{18}O and δD. This isotopic based method revealed robustness in estimating evaporation under the MESA and LESA moving sprinkler irrigation systems. Our results were useful for understanding evaporative water loss dynamics for traditional center pivot irrigation (MESA) and more modern center pivot irrigation approaches, such as LESA.

The second paper, at Hermiston, Oregon, shows soil evaporation from the row and interrow positions within potato fields of contrasting irrigation timing (daytime vs nighttime), and it was estimated based on hydrogen and oxygen isotope ratios. On average, row positions were more enriched in heavy isotopes than inter-row positions, indicating that the evaporated fraction of applied irrigation (E/I) depends on the position. The results indicated that there is more evaporation from the row, as compared with inter-row positions. Larger non-productive soil evaporation losses from within inter-rows minimized evaporative soil water losses.

The third paper was based at a Hazelnut farm (Christensen farm, Amity) Willamette Valley, Oregon, Pacific Northwest. The soil evaporation at this hazelnut field was determined based on the isotopic compositions ratios of soil moisture to soil samples from the hazelnut field under two varying treatments of drip irrigation. The results showed an average deuterium and ^{18}O isotope ratios of the single line with drip irrigation that was higher than double line with drip irrigation. These results suggest that less soil evaporation occurred from the double line with drip irrigation, which also had higher soil moisture levels than the single line with drip irrigation that was irrigated during the day and was highly significant in E/I at surface layers. The general
hypotheses of our study quantifying the unproductive water losses as evaporation that is provided by the data analyses of stable water isotopes.

To conclude, three detailed studies under three various applications of irrigation with intensive irrigated agriculture have discussed the estimation of the variations in the fractionation of the dual stable water isotopes and quantifying the water losses via soil evaporation.
Using stable water isotopes to assess the influence of irrigation structural configurations on evaporation losses in semiarid agricultural systems

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2 Chapter 1: Using stable water isotopes to assess the influence of irrigation structural configurations on evaporation losses in semiarid agricultural systems

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2.1 Abstract

The arid areas east of the Cascade Mountains in the Pacific Northwest have high irrigation water use and changing the elevation of sprinkler nozzles in these systems has been proposed as a strategy to reduce evaporative losses in order to diminish the total irrigation water demand. Validation of any structural modifications requires techniques able to identify water losses from these systems that were non-productive, particularly soil evaporation. In this study, we quantified evaporation losses from soils under Mid Elevation Spray Application (MESA) and Low Elevation Spray Application (LESA) irrigation systems by using stable isotope tracers to estimate the fraction of non-productive water losses (i.e. the ratio of soil water evaporation to irrigation water applied, E/I). During mid-summer 2017 in eastern Oregon and southeast Washington, we collected soil samples at multiple positions and depths around the central irrigation tower from four different agricultural fields, each with both LESA and MESA configurations. We measured the hydrogen and oxygen stable isotope ratio of soil water at MESA and LESA field locations using H2O liquid – H2O vapor equilibration laser spectroscopy. Though soil moisture contents were similar, the average isotope ratio of soil water under LESA irrigation (δD = -114.5‰, δ18O = -14.5‰) had lower values
than under MESA irrigation ($\delta D = -108.2\‰$, $\delta^{18}O = -13.1\‰$). Calculated $E/I$ values demonstrated higher sprinkler and soil water evaporation occurring at the MESA irrigated locations ($E/I = 16.1\%$) compared to the LESA irrigated locations ($E/I = 9.0\%$). We find that LESA systems have lower non-productive water losses than MESA systems and are thereby more efficient users of applied water. Our results suggest that stable water isotopes provide a technique for improving the management of water resources through the assessment of irrigation efficiency.

2.2 Keywords

Irrigation, LESA, MESA, evaporation, isotope

2.3 Introduction

Over 70% of the world's freshwater withdrawals are used for irrigated agriculture (Siebert et al., 2010) and the USDA estimates over half of the irrigated acres in the U.S. are watered using center pivot and linear move systems (Sarwar et al., 2019). The typical water application efficiency of center pivot and linear move systems is 80-85%, which translates into 15-20% losses to wind drift and evaporation (Peters et al., 2016; Rajan et al., 2015). Wind drift and evaporation losses (WDELs) consist of water that is removed from the landscape through soil, plant surface, and atmospheric evaporation before it is taken up by roots. These losses can range from 0% (Faci et al., 2001; Ocampo et al., 2003) to 50% (Yacoubi et al., 2012) and are functions of irrigation system design and their operational parameters (Sheikhesmaeili et al., 2016; Tarjuelo et al., 2000). Studies have concluded that drop size is the defining parameter for quantifying the WDELs affecting these systems. Droplet sizes and irrigation efficiency
are a function of the riser height from the ground (Abo-Ghobar, 1992), operating pressure (Yazar, 1984a; Ali and Barefoot, 1981, 1980), nozzle size, spray plate type, and sprinkler type (Tarjuelo et al., 2000). Droplets are susceptible to evaporative losses under dynamic variations of wind, vapor pressure deficit and solar radiation (Rajan et al., 2015; Sadeghi et al., 2017). Thus, changes in the structural configuration of irrigation systems can result in more efficient use of limited water resources.

Typical moving sprinkler irrigation systems (center pivot and linear move) can have different configurations of impact sprinklers, including the common mid-elevation spray application (MESA) and more recently implemented low elevation spray application (LESA) (New and Fipps, 2000; Peters et al., 2016). MESA systems have sprinkler heights of 1.8-2.4 m from the ground, high pressure regulators, and larger nozzle sizes and wetted radii of application. This is compared to the sprinkler heights of 0.3 m for LESA, which have low pressure regulators, smaller nozzle sizes and wetted radii (Bordovsky, 2018). Decreased pressure in LESA systems allows for lower pumping costs per hectare and therefore energy savings (Peters et al., 2016; Reed, 2018). Overall, applying water closer to the ground is expected to result in less exposure to the ambient weather conditions and makes LESA systems more efficient than MESA. However, specific mechanisms associated with decreasing WDELs have not been properly studied.

The most common method for measuring WDELs is the standard catch can test, which is mostly used for sprinkler irrigation research (Playán et al., 2005). Catch efficiency
estimates are also influenced by the wind speed and evaporation from cans by direct
t solar radiation and high temperatures (Edling, 1985; Sadeghi et al., 2017). Sadeghi et
al. (2015) used the strip method to measure the percentage of water that arrived at the
ground surface and found the strip method increased the catching efficiency; however,
the experimental setup of this method is tedious. Studies have also used electrical
conductivity (Yazar et al., 1984b) and physical-mathematical approaches (Molle et al.,
2012; De Wrachien and Lorenzini, 2006) to measure the amount of evaporation during
droplet flight. These methodologies resulted in diverse results unable to characterize
differences in evaporation once water has infiltrated the soil. Lysimeter techniques
were able to measure soil evaporation losses using a simple water balance approach
and these field methods have proved to be accurate, however they can be tedious and
costly (Feltrin et al., 2011, Wang et al., 2012; Liu et al., 2002).

Due to the complex and dynamic interrelationships throughout the soil-plant-
atmosphere continuum, a robust, cost-effective, and generally-accepted technique is
needed to understand and measure various water losses (Fetter, 2018), both productive
and non-productive. In the last couple of decades, the stable isotopes of hydrogen and
oxygen have been used as tracers in a wide variety of fields related to hydrology, water
resources, agriculture, and climate change (Peng et al., 2015; Liu et al., 2010). Water
isotope methods have been robust, fast, and cost-effective methods for separating
evaporation from other hydrology processes (Wang 2000; Wang et al., 2012). Differences in the atomic mass of stable water isotopes cause fractionation (i.e. shifts
in the ratio of rate to abundant isotopes) during phase changes (Craig and Gordon 1965;
Horita et al., 2008) and when water evaporates from liquid to vapor, the heavy isotopes preferentially remain in the liquid. If water is removed from soil via evaporation, the isotope ratio will increase. If water is removed through root water uptake, this water loss will not alter the value of the isotope ratio as there is no associated phase change (Soderberg and Good 2012; Wang et al., 2012).

In this study, we evaluate the impact of different irrigation systems structural configurations on agriculture soil water loss mechanisms. Our aim is to separate productive root water uptake from non-productive atmospheric and soil evaporation. Our working hypothesis is that the water held in soils under LESA irrigation systems would be more depleted in heavy isotopes relative to MESA due to decreased evaporation. To test this, we measured the stable water isotope ratio of soil waters under two irrigation regimes during the mid-summer season in paired agriculture treatments. The objective of this study is to quantify differences in the volumetric water content and stable water isotope ratios of soil moisture under contrasting irrigation designs in order to identify non-productive water losses in semi-arid agriculture.

2.4 Material and methods

2.4.1 Study Locations and Sample Collection:

In this study, we examined four center-pivot irrigation sites in the Pacific Northwest of the U.S., three alfalfa fields and one corn field. All four field sites were located on the eastern side of the Cascade Mountain Range within the arid to semi-arid climate of eastern Oregon and Washington (Figure 2.1). The first alfalfa field was located near
Christmas Valley, OR, the second alfalfa field was located near Dufur, OR and the third alfalfa field was located near Maupin, OR. The corn field was located near Pasco, WA. For each site, the average meteorological conditions were determined using nearby AgriMet (https://www.usbr.gov/pn/agrimet/) stations (Table 2.1).

![Map of Oregon and Washington showing four field sites and four AgriMet stations](image)

Figure 2-1: Four field sites (x’s) and four AgriMet Stations (circles) used in this study. These included 3 alfalfa fields (Dufur, Maupin and Christmas Valley, OR) and 1 corn field (Pasco, WA) in North East Oregon and South East Washington, Cascadia.

Each field was irrigated with a center pivot irrigation system that was equipped with both LESA and MESA nozzle systems. Approximately half of the spans between towers were set with LESA nozzles and the other half with MESA nozzles. The irrigation systems consisted of ‘off the shelf’ modern agricultural equipment with irrigation amount controlled by sprinkler spacing and regulated pressure levels. While irrigation amount was not directly measured, each system sprinkler system was
configured to deliver approximately the same amount of water, with MESA sprinkler heads 3m (10 feet) apart operating at 15-20 psi and LESA sprinkler heads 1.5m (5 feet) apart operating at 6-10 psi (Peters 2015, 2016). All the fields were irrigated with groundwater from nearby wells.

At each site, 20 representative soils samples were collected from July to August of 2017 using a soil hand auger at 4 locations, with one of the sampling locations duplicated for quality assurance in each field. We sampled at two depths, 10 cm and 30 cm, which are both well within the effective rooting depths of corn (80cm-120cm) and alfalfa (100cm-200cm) (NRCS 2016). The sampling locations were selected in each cardinal direction and located in the center of the sections of the field irrigated by LESA and MESA systems. Thus, ten soil samples from each irrigation system type were collected (i.e. five soil cores collected from each of the LESA and MESA irrigation sections). Note, in the Dufur and Pasco fields, one quarter of each field was not planted so these fields only had 4 holes sampled instead of five. At the southern MESA sampling location in Maupin, no 30 cm sample was collected because the soil was too compacted for auguring. Each field was sampled once in the summer of 2017: Dufur, OR samples were collected from 9:30 to 10:30 am on the 28th August; Pasco, WA samples were collected 7:30 to 8:30 am on the 29th of August; Maupin, OR samples were collected from 12:00 to 2:00 pm on the 29th of August; and Christmas Valley, OR samples were collected from 9:30 to 11:30 am on the 8th September. With the exception of the field in Christmas Valley, which was being irrigated at the time of sampling, it is not known when the other fields were last irrigated.
Table 2-1: The location and average meteorological conditions on the day of sampling at the AgriMet station closest to each field site.

<table>
<thead>
<tr>
<th>Site Name (AgriMet Station ID)</th>
<th>Station Coordinates (latitude, longitude)</th>
<th>Station Elevation (m)</th>
<th>Air Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Vapor pressure (kPa)</th>
<th>Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christmas Valley, OR (CHVO)</td>
<td>43.24138 N, -120.72805E</td>
<td>1312.164</td>
<td>16.98</td>
<td>68.69</td>
<td>1.21</td>
<td>clay loam</td>
</tr>
<tr>
<td>Dufur, OR (PNGO)</td>
<td>45.65222 N, -121.50916E</td>
<td>188.976</td>
<td>22.13</td>
<td>63.12</td>
<td>1.68</td>
<td>clay loam</td>
</tr>
<tr>
<td>Maupin, OR (MWSO)</td>
<td>44.85424 N, -121.1479E</td>
<td>431.9016</td>
<td>23.84</td>
<td>33.85</td>
<td>0.87</td>
<td>clay loam</td>
</tr>
<tr>
<td>Pasco, WA (LEGW)</td>
<td>46.20527 N, -118.93611E</td>
<td>176.784</td>
<td>23.71</td>
<td>62.02</td>
<td>1.68</td>
<td>sandy loam</td>
</tr>
</tbody>
</table>

A bulk density soil auger (AMS, Inc., ID, USA) was used to extract intact soil cores, which were kept within their steel sleeves, sealed with plastic caps tightly on both ends and stored in two heavy duty 1500 mL plastic food industry freezer bags (Ziploc brand). The collected samples were stored in an insulated case under ambient temperature until they could be placed in the lab refrigerator at 4°C (maximum time of 12 hours between collection and refrigeration). In the lab, samples were divided into two, with half used for stable isotope analysis and the other half used to estimate volumetric water content (Dingman, 2015). Half of each sample was oven dried for 24 hours at 105°C. Then, the difference between wet and dry sub-samples masses was divided by the wet soil sub-sample mass to compute a gravimetric water content per unit wet soil basis. This was
then scaled by total sample wet mass and divided by the steel sleeve's known volume and the density of water to estimate volumetric water content. The mean bulk density of all soil samples was 1.20 g/cm³ for the field near Christmas Valley, 1.33 g/cm³ for the field near Dufur, 1.22 g/cm³ for field near Maupin, and 1.51 g/cm³ for field near Pasco.

2.4.2 Isotope Analysis and Post Processing:

The stable water isotopes \( \delta^{18}O \) and \( \delta D \) (deuterium, i.e. \( \delta^2H \)) were expressed in the unit of parts per thousand (‰), with the isotopic compositions calculated as

\[
\delta^{18}O \text{ or } \delta D = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000
\]  

(1)

Where the molar ratios of the sample, \( R_{\text{sample}} \), and standard water, \( R_{\text{standard}} \), were the \(^{18}O/^{16}O \) or D/H values. In addition, we examined the deuterium excess (\( \text{dex} \)), which was calculated as

\[
\text{dex} = \delta D - 8 \delta^{18}O.
\]  

(2)

For determining the stable water isotope ratio of the soil water, we used H₂O liquid - H₂O vapor equilibration following Wassenaar et al., (2008). This technique is faster and more cost effective than conventional isotope ratio mass spectroscopy and can measure isotopic ratios of \(^{18}O/^{16}O \) and D/H down to low water contents of ~5% without the need for cryogenic extraction of soil water (Wassenaar et al., 2008). Furthermore, Wassenaar et al., (2008) found the effective failure rate was lowered to 5% by double bagging all soil samples. This technique avoids stable water isotope contamination resulting from the atmosphere or the microclimate of the lab due to dry air creating headspace volume at equilibration within the bag (Wassenaar et al., 2008). In addition, a positive feature of this technique is that soil samples can be measured with less
processing and exposure to evaporation comparing with IRMS (Wassenaar et al., 2008). Though the technique of Wassenaar (2008) has potential biases (Orlowski et al., 2016), it also presents clear benefits for agricultural applications where rapid, low cost methods are desirable. Orlowski et al., (2016) notes that more traditional methods, such as cryogenic distillation, are also prone to large deviations from reference waters. A recent study (Wang et al., 2020) further investigated liquid-vapor equilibration methods and found when the spiked soils of the same texture as unknown samples were used (as followed here), errors decreased to levels comparable to what we report. Finally, in this study, we evaluate differences between LESA and MESA treatments with similar soils, using the same methods on both sets of samples, thus observed differences are attributable to the treatment and not laboratory methods.

To prepare the collected samples, we pushed approximately 1000 cm$^3$ of dry air into the plastic bags, thus creating a headspace sampling volume for water vapor to come into equilibrium with the soil water within the sample. For each day’s laboratory analysis of the soil samples, three replicates of three internal laboratory-working standards were created by wetting a set of dried soil samples of similar volumes as the unknown soil samples. Following the principle of identical treatment, the laboratory working standard spiked samples were prepared and systematically measured along with the soil samples (Werner et al., 2001) using soils specific to each field for each analysis. Internal lab standards were; EH2, from the Earth H$_2$O bottled water company (-115.22‰, -15.43‰), FJ2, from the FIJI bottled water company (-43.09 ‰, -6.63‰), and CT2, from filtered Corvallis, OR tap water (-65.02‰, -9.85‰), where the values
in parentheses are the $\delta D$ and $\delta^{18}O$ isotope ratios respectively, (the numbers in each standard abbreviation indicate the batch number). Note that the $d$-excess for our lab standards is 9.57‰ (EH2), 11.98‰ (FJ2) and 10.36‰ (CT2). For each internal laboratory-working standard, we placed approximately 0.2 Kg of dried soil in a bag and added the same amount of standard water needed to raise the gravimetric water content to 10 cm$^3$/cm$^3$. Then, the bag was sealed, and the water was mixed by hand evenly through the soil sample.

The isotope ratio of the headspace vapor of samples and standards was measured directly using off-axis integrated cavity output spectroscopy (OA-ICOS, Los Gatos Research, Inc. model 908-0004 OA-ICOS). All samples and standards were allowed to equilibrate for 24 h on an isothermal laboratory bench so that headspace vapor reached isotopic equilibrium with the soil moisture. To sample the headspace vapor, a small needle connected to the OA-ICOS used to puncture each bag and continuously extract vapor directly from the gas sampling bags. When the temperature and pressure were stable at 45 °C and 39 torr and the flow rate was at ~0.25 liter per minute (LPM), the instrument punctured each bag with a needle and all headspace vapor was extracted (about three minutes). The concentration and isotopologues of H$_2$O were measured using 10-second integration intervals. Similar to the methods from (Wassenaar et al., 2008), we dependably processed approximately 35 soil samples with 9 standards per day.

To obtain a soil water isotope value for each sample from the spectrometer files, we first converted the vapor isotope ratios to liquid isotope ratios assuming liquid-vapor
equilibrium. The equilibrium fractionation factors, $\alpha_{e,L/V} = R_L/R_V$ are calculated using as a function of equilibrium temperature, taken to be the laboratory bench temperature following (Horita and Wesolowski, 1994). Due to instrumental drift and other operational effects, there is inherent amount of uncertainty and bias in each measurement from this system. These were corrected for by referencing our estimated liquid values obtained from measured vapor isotope ratios and the equilibrium fractionation factors from Horita and Wesolowski (1994) to known lab primary standards (EH2, FJ2, and CT2) for each set of observations each day. We first calculated the differences between estimates of the laboratory standard values and their known values (i.e. measurement errors). Next, for each day’s set of measurements, a unique linear equation between the measured isotope ratios and measurement errors was fit using linear least squares regression to account for day-to-day variation in isotope analyzer performance. These equations were then applied to both known and unknown samples to calculate both known (for our lab standards) and expected measurement errors (for unknown samples). All three standards were used in the measurement error regression, and the standard deviation of our lab standards measurement errors is used to assess measurement precision. Measurement accuracy is not assessed because all three standards were used in our regression, however our study principally focuses on differences between LESA and MESA isotope ratios which are expected to remain distinct regardless of any systematic measurement biases. After the corrections, the average standard deviation of sample measurements errors was 2.3‰ for $\delta^D$ and 0.35‰ for $\delta^{18}O$ across all lab measurement days. No vapor concentration
corrections were applied because bag vapor concentrations showed little variability between samples.

### 2.4.3 Soil Evaporation Estimation

The measured soil water isotope ratios were used to examine the fraction of input water that evaporated before being able to be productively used by plants. The fraction of input water (I, in mm) that was lost from soil surface evaporation (E, in mm) can be calculated as

$$\frac{E}{I} = \frac{\delta_I - \delta_S}{\delta_E - \delta_S}. \quad (3)$$

Where subscripts $I$, $S$, and $E$ refer to the isotope ratio of irrigation water, soil liquid water and evaporation respectively. This approach is derived from other evapotranspiration partitioning methods (Gibson et al., 2002, Good et. al. 2014) however, it has been reframed with respect to evaporation losses. This is a steady-state mass-balance model of each agricultural field’s soil water, where inputs are assumed to be balanced by fractionated (E) and non-fractionated (transpiration and percolation downward) losses. In Eq. (3), the value of $\delta_S$ was obtained from the lab analysis described above. The value of $\delta_I$ was obtained based on the relationship between $\delta$D and $\delta$18O values for monthly precipitation values forming the Local Meteoric Water Line (LMWL) and between $\delta$D and $\delta$18O values for soil samples forming the Local Evaporation Line (LEL), with the source water estimated as the intersection of the LEL with the LMWL. The LMWL was derived using monthly precipitation estimates from the Online Isotopes In Precipitation Calculator (http://wateriso.utah.edu/waterisotopes/pages/data_access/oipc.html).
The value of $\delta_E$ was estimated based on the Craig and Gordon model (1965). The isotope ratio of evaporated water is calculated as

$$
\delta_E = \frac{\delta_S / \alpha_{e,L/V} - h_A' \delta_A - \epsilon^* - \epsilon_K}{(1-h_A') + \epsilon_K}
$$

(4)

Where $\delta_S$ is the isotope ratio of soil liquid, $\alpha_{e,L/V}$ is the kinetic isotopic fractionation factor between the liquid and the vapor (unitless), $h_A'$ is the relative humidity of the atmosphere normalized to the evaporating surface (unitless), $\delta_A$ is the isotope ratio of the atmosphere and $\epsilon_K$ is the kinetic isotopic fractionation (unitless) factor, and $\epsilon^* = (1 - 1/\alpha_{e,L/V})$.

Average daily AgriMet station data were used for temperature and relative humidity values, with humidity normalized to the evaporating surface based on the temperature and activity of water at the evaporating surface (Horita et al., 2008). This is calculated as

$$
h_A' = \frac{h_A e_{s,A}}{a_w e_{s0}},
$$

(5)

Where $e_{s0}$ is the saturation vapor pressure at the evaporating surface in kPa, $e_{s,A}$ is the saturation vapor pressure in the atmosphere kPa, $h_A$ is the relative humidity of the overlying air, and $a_w$ is the thermodynamic activity of water (unitless) which is assumed 1 here. Based on recorded soil temperature measurements at Christmas Valley, soils were all taken to be 3.68°C warmer than recorded air temperatures, though the effect of the humidity normalization is minor overall. We assume the isotopic composition of the local atmospheric moisture is in isotopic equilibrium with input water as:

$$
\delta_A = \frac{(\delta_I + 1000)}{\alpha_{e,L/V}} - 1000.
$$

(6)
Finally, the kinetic fractionation was incorporated using

$$\varepsilon_K = n(1-h_A)(D/D_i - 1)r_m/r,$$  \hspace{1cm} (7)

where $n$ is an aerodynamic parameter for adjusting diffusivity ratios, $D$ is the diffusion coefficient (with subscript $i$, indicating the minor isotopologues, m$^2$ s$^{-1}$) and $r_m/r$ is fraction of atmospheric resistance that is considered diffusive. Based on previous studies in arid environments, $n$ was set at 0.97, $D/D_i$ was set at 1.0251 and 1.0285 (for H and O respectively), and $r_m/r$ set at 1.0 (Soderberg and Good 2012; Horita et al., 2008). We calculate the values of $E/I$ based on both $\delta D$ and $\delta^{18}O$ isotope ratios. Finally, if an $E/I$ value was estimated with an unrealistic value less than zero, it was set at zero for further statistical analysis.

2.4.4 Statistical Analysis

A Linear Mixed Effects Model (LMEM) is used to analyze collected samples due to the hierarchically nested sample collection strategy employed here. LMEMs have the ability to control for higher similarities of our samples collected from two depths within a single core and similarities between multiple cores within the same site (Jashami et al., 2019; Barlow et al, 2019). Here, a set of LMEMs were used to determine whether there were any significant differences between 4 key response variables: soil water content, soil isotope ratios, and soil evaporation ratios in LESA and MESA irrigation systems. This analysis was simulated using the Statsmodels module (Seabold et al., 2010) in Python. Our LEME modeling script and required data are provided as supplementary files (‘Supplementary Data 1.csv’ and ‘Supplementary Scrip 1.csv’) as well as a figure summarizing model output (‘Supplementary Figure 1.csv’). We also
conduct a set of t-tests on the means of collected samples, with significance evaluated at the 0.1, .05, and .01 levels (marked as *, **, and *** in Figures).

LMEMs are used to test the relationship between irrigation type (LESA vs. MESA) and as well as the relationship between type and sample depth (10cm or 30) with each of the four investigated response variables. Two LMEMs were created for each response variable, with ‘Model 1’ of the form “RESPONSE ~ TYPE” and ‘Model 2’ of the form “RESPONSE ~ TYPE + DEPTH”, where response is either soil water content, soil isotope ratios, and soil evaporation ratios. Fixed effects are irrigation type (model 1 and model 2) and depth (model 2). Random effects are incorporated for each core, resulting in random intercepts for each core, with these processed separately for each top-level group (the site). Nesting of samples within cores within sites is handled by specifying the cores variance component.

This approach will properly account for variability in $E/I$ estimates within sites and between sites, however it does not account for uncertainty in environmental factors such as temperature and humidity as well as parametric factors. However, earlier sensitivity analysis (Wang et al., 2013) has demonstrated that local soil water isotope ratios are the dominate driver of evaporation flux partitioning uncertainty while environmental factors such as temperature errors are less relevant. Thus, variability in sample differences between $\delta_L$ and $\delta_I$ is the main factor driving variability in $E/I$ estimates, and this uncertainty is thereby incorporated into test of the $E/I$ significance tests of the LMEM.
2.5 Results

2.5.1 Soil Water Content

The volumetric water content of the soil samples at all sites for MESA irrigated soils ranged from 0.13 \( \text{cm}^3/\text{cm}^3 \) to 0.40 \( \text{cm}^3/\text{cm}^3 \) at 10 cm depth and 0.10 \( \text{cm}^3/\text{cm}^3 \) to 0.41 \( \text{cm}^3/\text{cm}^3 \) at 30 cm. The volumetric water content of the LESA irrigated soil samples ranged from 0.08 \( \text{cm}^3/\text{cm}^3 \) to 0.37 \( \text{cm}^3/\text{cm}^3 \) at 10 cm depth and 0.12 \( \text{cm}^3/\text{cm}^3 \) to 0.37 \( \text{cm}^3/\text{cm}^3 \) at 30 cm depth. The individual average of water contents within the soil profile at each site was given in the (Table 2.2) and shown in the (Figure 2.2). Figure 2.3 depicts the average water content at each site for each irrigation configuration. For the fields near Christmas Valley and Dufur, higher average soil water content values were estimated at the MESA irrigated locations for both depths. In contrast, lower average water content values were estimated for MESA irrigated locations at the 30cm depth at Maupin and Pasco, while the 10cm depths had higher MESA water contents. Based on a t-test analysis, the mean soil moisture contents at 10cm were significantly different between LESA and MESA samples at Dufur and Maupin. When averaging both depths, only Dufur had significantly different water contents between LESA and MESA samples.

2.5.2 Soil Isotope Ratios

Although we found that water content was similar between MESA and LESA soil samples, stable isotope ratios were found to be move divergent. Soil water isotope ratios are shown in figure 2.4 for each site. Overall, the soil isotope ratio measurements across all sites were found to be a significant potential indicator of irrigation type,
strengthening the hypothesis that stable water isotopes could supply insights into E/I losses or nonproductive water losses.

Across all sites, the isotope ratio of LESA irrigated soils was more negative than MESA irrigated soil (Figure 2.5). At the soils irrigated with MESA system, the soil water δD values at all four sites ranged from -85.4 ‰ to -124.4 ‰, and at the same depths of soil profile that irrigated with LESA systems, the stable water δD isotopes at all sites ranged from -96.7 ‰ to -128.3 ‰. Similarly, the δ¹⁸O of soils irrigated with MESA system ranged from -16.7 ‰ to -3.7 ‰ while LESA soils ranged from -17.1 ‰ to -10.3‰. Similarly, the mean values of δD and δ¹⁸O at MESA sites (-108.2‰ and -13.1‰ respectively) was less negative than that of LESA sites (-114.5‰ and -14.5‰ respectively). In addition, the average d-excess across all MESA fields was -3.6 ‰ while the average d-excess across all LESA fields was 1.4‰.

Local evaporation lines (LELs) were estimated at each site, using both MESA and LESA samples. With every site, there was a single distinct LEL fit because the LESA/MESA regions of the field have the same source water and atmospheric conditions (Figure 2.4). Relative distances along the LELs correspond to differences in evaporation, with evaporation expected to be largest for isotope values that were farther from the irrigation source water, estimated at the LEL intersection with the LMWL. In general, MESA points were farther the LEL than LESA points. However, there were clearly some LESA points that were larger than some MESA points.

Based on a t-test analysis, both the means of δD and δ¹⁸O were significantly different between LESA and MESA samples at Maupin and Pasco. The deuterium excess was typically larger at LESA sites compared with MESA sites; however, this was only
significant at Maupin. Our LMEM analysis of the differences between MESA and LESA soil isotope ratios found that differences between irrigation types were a statistically significant predictor of both $\delta D$ ($p = 0.001$) and $\delta^{18}O$ ($p = 0.01$). This held true when sample depth was also included, and depth was found to be a significant predictor of $\delta^{18}O$ ($p=0.000$) but not $\delta D$ ($p=0.289$).

### 2.5.3 Soil Evaporation Ratio

We calculated $E/I$ value based on both $\delta D$ and $\delta^{18}O$ isotopes ratios (Figure 2.6). The calculations of these ratios were computed by combining the delta liquid of soil ($\delta_s$), delta evaporation ($\delta_E$), and delta irrigation ($\delta_i$). The details of the parameters have been described in the Materials and Methods section of this paper (Equation 3). $E/I$ ratios form $\delta D$ were highly correlated with $\delta^{18}O$, however $\delta D$ values were generally higher. We calculated the average of $E/I$ ratios from both isotopes (Figure 2.7) and use this for subsequent analyses.

Based on our calculations, the average proportion of $E/I$ from the soils with LESA irrigation systems was lower than MESA irrigation systems. The column averaged estimated $E/I$ proportions (mean $\pm$ standard deviation) of LESA and MESA was 16.7 $\pm$ 7.3 % and 20.1 $\pm$ 6.7 % for the Christmas Valley field, 2.7 $\pm$ 3.3 % and 3.4 $\pm$ 3.7 % for the Dufur field, 12.6 $\pm$ 5.9 % and 21.1 $\pm$ 12.0 % for Maupin field, 4.0 $\pm$ 4.8 % and 19.6 $\pm$ 17.5 % for the Pasco field, respectively. Overall, the average evaporation ratio across all MESA fields was 16.1 %, with a standard deviation of 6.1 %. The average evaporation ratio across all LESA fields was 9.0 %, with a standard deviation of 1.7 %.

Based on a t-test analysis, the means $E/I$ were significantly different between LESA and MESA samples at Maupin and Pasco. Our LMEM analysis of the differences
between MESA and LESA E/I ratios found irrigation type a significant ($p=0.004$) predictor of $E/I$. This is was also true when depth was included ($p=0.004$), which was also found to be a significant predictor of $E/I$ ratios ($p=0.000$). All sites with LESA pivots experienced less evaporation, approximately 20 to 77% less, compared to MESA pivots (Table 1.2). This proportion of E was immediately lost from shallow surface soil based on our results. In summary, the evaporation loss of water from the soil surface, as a fraction of total water loss, was shown to vary consistently between MESA and LESA irrigation systems across the region.

2.6 Discussion

2.6.1 Soil moisture profile under different irrigation systems

We did not find that irrigation configuration was a statistically significant predictor of differences in the water content. However, Sarwar et. al. (2019) reported that on average 21% more water reached the ground with LESA compared with MESA systems. Peters et. al., (2016) suggested that the larger wetted radius of MESA compared to LESA may result in more water infiltrating into the soil (i.e. greater runoff potential for LESA systems) when the same water is applied over a shorter time period. Differences in the nozzle pressure and height change water droplet size and kinetic energy, and higher kinetic energy is associated with surface sealing and can reduce infiltration (NRCS 2016). A variety of physical factors may be partially responsible for variability in measured soil water contents, yet the 10 cm and 30 cm volumetric water contents measured here are not a complete record of the fate of all water released from sprinkler heads. We did not measure water delivered deeper into the rooting zone or percolation beyond it and it is possible that differences between MESA and LESA
changed volumetric water contents lower in the soil profile or the amount of bypass flows within macropores.
Table 2-2: Mean and standard deviation (in parentheses) of water content of the soil samples, stable water isotopes composition and the percent of the evaporation for irrigation systems for each field for LESA and MESA field locations.

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Irrigation System</th>
<th>Sample Count</th>
<th>Water Content (cm³/cm³)</th>
<th>Soil D/H (%)</th>
<th>Soil $^{18}$O/$^{16}$O (%)</th>
<th>d-excess (%)</th>
<th>E/I (%) D/H as function of evap.</th>
<th>E/I (%) ($^{18}$O) as function of evap.</th>
<th>E/I (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christmas</td>
<td>MESA</td>
<td>10</td>
<td>0.40</td>
<td>-119.50</td>
<td>-14.69</td>
<td>-1.96</td>
<td>26.8</td>
<td>13.5 (4.1)</td>
<td>20.1 (6.7)</td>
</tr>
<tr>
<td>Christmas</td>
<td>LESA</td>
<td>10</td>
<td>0.37</td>
<td>-122.54</td>
<td>-15.20</td>
<td>-0.97</td>
<td>21.6</td>
<td>11.8 (4.9)</td>
<td>16.7 (7.3)</td>
</tr>
<tr>
<td>Dufur</td>
<td>MESA</td>
<td>8</td>
<td>0.27</td>
<td>-102.07</td>
<td>-13.92</td>
<td>9.32</td>
<td>3.9</td>
<td>2.9 (3.7)</td>
<td>3.4 (3.7)</td>
</tr>
<tr>
<td>Dufur</td>
<td>LESA</td>
<td>8</td>
<td>0.21</td>
<td>-103.94</td>
<td>-13.97</td>
<td>7.83</td>
<td>3.1</td>
<td>2.4 (3.1)</td>
<td>2.7 (3.3)</td>
</tr>
<tr>
<td>Maupin</td>
<td>MESA</td>
<td>9</td>
<td>0.12</td>
<td>-103.67</td>
<td>-10.77</td>
<td>-17.49</td>
<td>23.3</td>
<td>18.9 (11.3)</td>
<td>21.1 (12.0)</td>
</tr>
<tr>
<td>Maupin</td>
<td>LESA</td>
<td>10</td>
<td>0.11</td>
<td>-110.74</td>
<td>-13.10</td>
<td>-5.96</td>
<td>13.9</td>
<td>11.4 (4.2)</td>
<td>12.6 (5.9)</td>
</tr>
<tr>
<td>Pasco</td>
<td>MESA</td>
<td>8</td>
<td>0.16</td>
<td>-107.61</td>
<td>-12.91</td>
<td>-4.30</td>
<td>26.2</td>
<td>13.1 (12.2)</td>
<td>19.6 (17.5)</td>
</tr>
<tr>
<td>Pasco</td>
<td>LESA</td>
<td>8</td>
<td>0.17</td>
<td>-120.95</td>
<td>-15.72</td>
<td>4.79</td>
<td>4.7</td>
<td>3.3 (3.2)</td>
<td>4.0 (4.8)</td>
</tr>
</tbody>
</table>
From Figure 2.2, the soil moisture values for the LESA soil samples appear more consistent than the values from the MESA soil samples (no statistical test was conducted of variance), which showed more fluctuations in observed soil moisture. The LESA soil moisture values show little differences and were more constant at all the different sample locations within a field, inferred from (Figure 2.2). It was possible that the LESA systems were more consistent due to the low elevation of a spray nozzle to the soil surface, which shows wind had a slight effect on the evaporation. Moreover, evaporation had minimal effects on the LESA irrigation application spray radius area and this resulted in less variation in the application efficiency in time (Peters et al., 2015; Peters et al., 2016).

Figure 2-2: The soil volumetric water content (VWC, cm\(^{3}\) cm\(^{-3}\)) at MESA and LESA irrigation locations for the two sampling depths, 10 cm and 30 cm, at A) Christmas Valley, OR, b) Dufur, OR, c) Maupin, OR, and d) Pasco, WA. Mean values are marked with as a diamond, while significant differences between means is marked with * for p<0.1, ** for p<0.05, and *** for p<0.01.
Though soil moisture amounts were similar between LESA and MESA treatments we observed distinct differences in the isotopic composition of soil water. Both evaporation from soils and root water uptake will decrease water amounts, but only evaporation and not root water uptake, will alter isotope ratios of soil waters (Soderberg et al., 2012; Wang et al., 2012; Wu et al., 2018). Any likely decreases in soil water amount occurring since the time of last watering did not create statistically different soil moisture levels three of four fields, but did create statistically different isotope ratios at two of four fields. Thus, although losses may have been similar, the loss mechanisms were likely different; i.e. more root water uptake from LESA and more evaporation from MESA.

Figure 2-3: Boxplots of soil volumetric water content (VWC, cm³cm⁻³) categorized by field site and LESA or MESA irrigation. Mean values are marked with as a diamond, while significant differences between means is marked with * for p<0.1, ** for p<0.05, and *** for p<0.01.
2.6.2 Stable isotope under different irrigation systems

In this study, we found the differences in stable isotope ratios between treatments were statistically significant at half of our study sites, and overall irrigation types as a statistically significant predictor of isotope ratios. This was attributed to differences in irrigation system designs, irrigation water management strategies, and the time of sampling in relation to the last date and amount of irrigation. Additional discrepancies were attributed to the effective conditions of evaporation and root systems irrigated by both designs.
We found the isotopic compositions of the soil water samples of both LESA and MESA generally fell below the local meteoric water line along characteristic evaporation lines (Figure 2.4). These results suggest a strong evaporation effect on soil water isotopes ratios between treatments were different. The soil samples from LESA and MESA locations, at both 10 cm and 30 cm depths, demonstrated isotopic enrichment across the 4 sites (Figure 2.4). However, for the LESA irrigation areas, the isotope compositions at the two depths were less variable compared to the MESA irrigation design. Differences in the pressure and elevation of sprinkler heads between LESA and
MESA systems are expected to result in differences in drop size distributions and fall times as well changes in infiltration dynamics and wetting front depths. These variations may have resulted in differences in the amount of evaporation and thus isotopic enrichment between treatments.

The comparison between δD values, δ¹⁸O values and the LEL at the four sites showed a high coefficient of regression ($R^2$) and provide reasonable slopes consistent with stable isotope literature, (e.g. Bowen, 2018). Our results from the stable isotope analyses estimated the isotopic composition of soil water, which were similar to (Craig and Gordon, 1965; Horita et al., 2008; Soderberg and Good 2012; and Wang et al., 2012). These results can be applied to additional studies to explore the influence of various factors and the detailed mechanisms involving stable water isotopes at different soil depths and to understand the relationships under different ecosystem root uptake conditions.

The Dufur, OR field had very steep slopes, which may have contributed to values falling above the LMWL due to unknown run-on or run-off influences. Additionally, water from a small creek (Fifteen Mile Creek, who’s source is high on Mount Hood) near the northwest of the field may have affected the isotope composition of the observed soil moisture when water table were higher in the spring (Figure 2.4). In general, the stable water isotopes in the four fields had similar behavioral distributions relative to their sources of irrigation water. The Dufur field values have different trends because the north direction of field has a steep downhill gradient, which leads the water
to accumulate in the soil surface and deeper layers. Thus, the site was not isotopically enriched in the north direction and the values were approximately similar to the isotope ratio of irrigation source. Such findings are consistent with earlier results showing that LESA irrigation systems likely generate more runoff on with high slope topography or soils with low infiltration rates (Peters, et al., 2015, 2016), which was assumed to be a result from reduced nozzle efficiency on the sloping terrain simulating high runoff.

2.6.3  **Evaporation from soil under different irrigation systems.**

Of the calculated $E/I$ ratios, 61 of 71 had positive (non-zero) estimates. Examining our soil isotope measurements (particularly figure 2.4), we see that there are a few points where the oxygen or hydrogen isotope was measured as more negative than the estimated irrigation source water. This was 9 $\delta^D$ samples and 7 $\delta^{18}O$ samples, of which 6 samples were more negative for both. In these cases, the $E/I$ valued was initially calculated as a negative value, and then set as zero. For these samples the average difference between irrigation water and measured soil water was 2.85‰ $\delta^D$ and 0.84 for $\delta^{18}O$, well within 2 to 3 times our estimate measurement precision (2.3‰ $\delta^D$ and 0.35 for $\delta^{18}O$). These zero $E/I$ values, thus represent points where $\delta I$ and $\delta S$ are not able to be distinguished, and likely little evaporative enrichment has occurred.

The evaporation of water from saturated or unsaturated soils was strongest at the surface of the soil. This results in a maximum isotopic enrichment that decreases with depth (Horita et al., 2008).
Figure 2-5: Boxplots of the four study site’s categorized by MESA or LESA irrigation with A) illustrating soil water δD values, B) illustrating soil water δ¹⁸O values, and C) illustrating d-excess values. Mean values are marked with as a diamond, while significant differences between means is marked with * for p<0.1, ** for p<0.05, and *** for p<0.01.
In the past decade, many researchers have developed models for soil δE based on local weather parameters at the soil surface and then used the isotopes compositions end-member to calculate the evaporation (Gibson et al., 2008; Soderberg et al., 2012; Brooks et al., 2014). As explained in the methodology section, the relationship between weather parameters needs to be used to estimate isotopic fractionation during evaporation from both a free surface water and soil that was first characterized by (Craig and Gordon 1965; Soderberg and Good, 2012). Meteorological differences between the LESA and MESA sections of each field were not considered in this study and only one set of meteorological conditions was used. While it was possible that local microclimate differences occurred, the open nature of these fields likely leads to well mixed atmospheric conditions. However, the leaf temperatures vary between crops and canopy geometry, and may have differed between treatments if transpiration rates if were much larger in one irrigation treatment than another. Finally, the time since last irrigation is not known for three of the study sites. It is possible that as the time from the last irrigation increases, larger differences between LESA and MESA may be evident. This is a possible reason for the variation in the estimated differences in $E/I$ between sites.
Figure 2-6: The values of $\delta^{18}O$ and $\delta^2H$ for all soil samples at the LESA and MESA in the 2017 of the four-study sites and the LWML is the line in the dual-isotope plot.

Figure 2-7: Boxplots of the E/I values at the LESA and MESA irrigation applications for the four study site locations. Mean values are marked with as a diamond, while significant differences between means is marked with * for $p<0.1$, ** for $p<0.05$, and *** for $p<0.01$. 
Our findings revealed characteristic evaporation fractionation in the soil water samples under both LESA and MESA irrigation systems (Table 2.2, Figure 2.7). In addition, the weather parameters had the same influence on both irrigation center pivot designs with the two soil depths 10 cm, 30 cm and the findings were showing us the minimum evaporation was in LESA design. (Table 2.1 and Table 2.2). As shown here, the isotopic composition can provide a valuable and excellent tool for approximating the proportion of the $E/I$ for LESA and MESA. LESA irrigation systems had an average 20-70 % less E loss from sprinkler application. This was caused by the different elevations from the nozzles and surface soils, while liquid phase partitioning was unequal from both systems based on the findings presented in this study.

### 2.7 Conclusions

Stable water isotopes can contain valuable information for estimating evaporative water loss from soil under varied agricultural practices. In this study, we evaluated the $\delta D$ and $\delta^{18}O$ dual soil stable isotopes to determine the variations in evaporation under different irrigation treatments during the summer of 2017 in the eastern Cascade Range, USA. The isotope analysis results quantified the differences between the two irrigation designs supplying water to crops. Significantly high variations were recorded in $\delta D$ and $\delta^{18}O$ distributions between the LESA and MESA systems near the soil surface, with LESA systems indicating less E loss. The soil’s surface water amount demonstrated greater fluctuations under MESA systems at all sites.

The soil evaporative water losses for both the LESA and MESA irrigation systems were distinctly characterized using $\delta^{18}O$ and $\delta D$. The average evaporative losses at the soil
profile for Christmas Valley, OR were 20 % for LESA and 30 % for MESA, Dufur, OR were 3 % for LESA and 4 % for MESA, Maupin, OR were 21 % for LESA and 35 % for MESA, and Pasco, WA were 21 % for LESA and 48 % for MESA. Interestingly, the evaporation was decreased within the top 30 cm of the soil profile indicating the importance of the spatial scale in fractionation for the first 10 cm of surface soil. This isotopic based method revealed robustness in estimating evaporation under the MESA and LESA moving sprinkler irrigation systems. Our results were useful for understanding evaporative water loss dynamics for traditional center pivot irrigation (MESA) and more modern center pivot irrigation approaches, such as LESA. In addition, this study provides guidance on optimal irrigation strategies for decreasing water consumption and thereby improving the water use efficiency at the field/territorial scale irrigation systems in the Eastern Cascade region.

2.8 Acknowledgements

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Chapter 2: Differences in soil evaporation between row and interrow positions in furrowed agricultural fields

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3.1 Abstract

Though large-scale surface irrigation has replaced center pivot sprinkler irrigation systems in many locations, the agricultural practice of growing crops in furrows remains common. Yet how the presence of elevated soil rows influences evaporation losses remains unclear, even while quantifying non-productive water losses becomes increasingly important for informing new water conservation and irrigation strategies.

At Hermiston city, Oregon, soil evaporation from the row and interrow positions within potato fields of contrasting irrigation timing (daytime vs nighttime) was estimated based on hydrogen and oxygen isotope ratios. Samples collected throughout the 2016 growing season were measured and used to calculate soil evaporation ($E$) losses relative to applied irrigation ($I$). On average, row positions were more enriched in heavy isotopes than interrow positions, indicating that the evaporated fraction of applied irrigation ($E/I$) depends on the position. Within the day irrigated field the estimated (mean ± standard deviation) $E/I$ ratios determined from both stable isotopes for May, July, and September were 18±8%, 10±3% and 19±5% for row samples and 15±6%,
7±2% and 12±4% for interrow samples. Within the night irrigated field during these same months, the \( E/I \) ratios were 13±12%, 16±7% and 13±5% for row samples and 12±7%, 9±2% and 6±2% for interrow samples, respectively. These results reveal that there is more evaporation from the row, as compared with interrow, positions. Therefore, management strategies and practices for water conservation should take into account larger non-productive soil evaporation losses from within rows to minimize evaporative soil water losses.

3.2 Keywords
Isotope, Irrigation, Row, Interrow, Evaporation

3.3 Introduction
Furrowed planting systems, wherein plants are rooted into soil that is mounded into rows with lower interrow spaces, are one of the oldest methods used to convey supplied water throughout irrigated agriculture fields. Sprinkler irrigation has now supplanted surface irrigation for many crops in the western United States, and yet many important field crops, such as potatoes, are still planted in raised rows (Taberna et al., 2009; Tarkalson et al., 2010). The benefits and drawbacks of the continued use of raised rows have led to considerable research on their effects on infiltration and soil water redistribution (Saffigna et al., 1967, Robinson et al., 1999, Timlin et al., 2001, Hupet and Vanclooster 2005). Because furrows are no longer necessary for water delivery, other planting configurations have been explored (Tarkalson et al., 2010), and yet furrows are still the dominant agricultural approach throughout much of the western United States. Given the continued use of furrowed agriculture, one important question
that remains unanswered is how the three-dimensional form of rows influences soil moisture dynamics, particularly the evaporative losses of water from the soil.

Irrigation water has three principle exit pathways from the soil within a crop’s rooting zone: direct evaporation ($E$) from the soil surface, transpiration ($T$) from crops, and deep percolation ($L$) below the crop root zone (Wang, et al., 2012; Agam et al., 2012). Evaporation can be an important component of the water balance especially under the arid and semi-arid conditions, as well as when agricultural fields are planted with sparse canopies and/or in rows (Eastham et al., 1999; Smajstrla and Zazueta, 1994; Burt et al., 2005). While $E$ may indirectly benefit crop growth by maintaining a micro-climate within the canopy favorable to the productivity of the plants (Burt et al., 2005) it has often been considered a water loss that does not directly contribute to agriculture production (Jensen et al., 1971; Chen et al., 2010; Keller and Bliesner, 1990; McLean et al., 2000; Melloulı et al., 2000; Zhang et al., 2005; Zhang et al., 2010; Zegada-Lizarazu et al., 2011). Evaporation losses are a concern for crops planted in furrowed fields because the elevated soil rows where plants are rooted might be exposed to conditions that are dissimilar from the lower interrow space. Timlin et al., (2001) found that there were small but consistent differences in water losses from the row and interrow zones. Furthermore, they suggested that the surface boundary conditions of the soil changed with the presence of the crop canopy and, as a result, the volume of infiltrating water can be altered. Hupet and Vanclooster (2005) found that throughout long drying periods, total evapotranspiration ($ET=E+T$) from maize was less variable across the rows than root water uptake, even as root water uptake progressively moves downwards and towards the interrow space. Additionally, soil water content in the
maize interrow was consistently higher than in the rows at the end of the considered
dry period (Hupet and Vanclooster, 2005). In wheat and soybeans, both yield and water
use efficiency were found to be negatively correlated with row spacing (Zhou et al.,
2015). Through fall and sprinkler irrigation, redistribution has also been shown to be
influenced by the canopy structure and position across rows in cornfields (Paltineanu
higher row positions is dryer for fine sandy loam soils. Additionally, the aerodynamic
resistance to $E$ was found to increase when the wind direction was perpendicular to the
row orientation (Timlin et al., 2001; Agam et al., 2012). Overall, it remains unanswered
how transpiration and evaporation vary between row and interrow positions.

Stable isotopes ($^2$H and $^{18}$O) in soil water are a sensitive indicator of water loss by
evaporation because evaporation enriches soil water in heavy isotopes while root water
uptake and subsurface leakage do not (Wang et al., 2012; Soderberg et al., 2012; Al-
Oqaili et al., 2020). This property has propelled stable isotopes to be an established
method for soil water flux monitoring (Busari et al., 2013) and the partitioning of
moisture losses (Al-Oqaili et al., 2020). Van den Akker et al., (2011) found differences
in isotope enrichment among irrigation bays due to evaporation losses driving isotope
enrichment within the local pan at different stages of irrigation. The determination of
temporal variations in $ET$ partitioning has also been demonstrated with the isotope
techniques (Ma and Song, 2019; Soderberg et al., 2012; Wang et al., 2012; Wu et al.,
2016; Wu et al., 2018). Lu et al., (2017) found the stable isotopic composition of
evaporation increased initially as soil water was depleted following irrigation in
different fields of crops (e.g. wheat, grass, etc) but after the mid- to late-irrigation cycle,
it decreased when the soil became dry. Han et al., (2019) reported a significant change in the hydrogen isotope ratio of the water content at the surface, and the variation of hydrogen isotopes was found to decrease with the depth. Mahindawansha et al., (2018) found that the stable water isotope composition of groundwater responded rapidly to irrigation during the dry season of maize through a process that indicated preferential flow via cracks and deep roots. Recently, Al-Oqaili et al., (2020) were able to demonstrate differences in stable isotope ratios as a result of changes in irrigation structural configurations.

The aim of this study was to assess the contribution of soil evaporation to soil moisture losses from the row and interrow positions of the planting line within potato fields. Two irrigation schedule treatments: day- and night-time irrigation, are examined to broaden the range of experimental microclimate conditions. The hypothesis of our study is that the soil water losses from row locations at both schedules (day and night) would be larger due to increased evaporation, and thus these soils would be more enriched in heavy isotopes relative to interrow locations. To test this hypothesis, the soil water and its associated losses were assessed via measurements of stable isotope ratios of hydrogen and oxygen in soil waters ($^{2}$H/$^{1}$H and $^{18}$O/$^{16}$O) under day and night irrigated fields during May, July and September. The objectives of this project were to: (1) quantify differences in isotope fractionation from three soil layers under contrasting position (row and interrow) and irrigation schedule (day and night), and (2) compare and identify the variations of evaporation resulting from these contrasts.
3.4 MATERIAL AND METHODS

3.4.1 Experimental Setup and Sample Collection

This study took place at the Hermiston Agricultural Research and Extension Center (HAREC) in Hermiston, Oregon. HAREC is located in eastern Oregon, Latitude: 45.81944 N and Longitude: 119.28333 W, at an elevation of 607 ft. (185m). Observations were conducted between April and September, during which the total precipitation was 2.89 inches (73.41 mm), the mean temperature was 66°F (18.9 °C), and the mean of relative humidity was 51% based on an AgriMet (https://www.usbr.gov/pn/agrimet/agrimetmap/hrmoda.html) station located at the HAREC. Potato (cv. ‘Ranger Russet’) was planted on 21 April in two adjacent and independently irrigated 0.27 acre (0.11 ha) fields. Seed pieces were spaced 30.5 cm apart within rows, and rows were spaced 86.4 cm apart. After planting, the potato crop was maintained according to commercial practices typical for the region with respect to nutrient and pest management. The two potato fields were irrigated with the same water quantity, but at altered timings: daytime (pivot started the irrigation at 11:00 am) vs. nighttime (pivot started the irrigation at 11:00 pm). The monthly irrigation applied to for each pivot for the five months from May to September was 12.20, 22.10, 22.86, 16.51, and 1.27 cm, respectively.

Soil samples were collected from each field during the summer of 2016 from two positions in the planting line: row and interrow. Sixty samples (two treatments: day and night; two locations: row and interrow; at five of location; and at three depths: 5cm, 15cm, 25cm) were collected during each monthly sampling campaign. We extracted soil samples using a bulk density soil auger, and soil samples were left within their steel sleeves (90.59 cm³), sealed on both sides with plastic caps, and then placed within two
heavy-duty plastic bags (1500 mL, Ziploc trademark). Double bagged soil samples were transported within an insulated case from the field to laboratory. During laboratory processing, the soil samples were divided into two equal parts, one utilized to assess the soil moisture and the other part for analyzing the stable water isotope ratios.

The volumetric water content was computed from the difference between the wet and dry sample weights and the known sample volume (Dingman, 2015). Samples were dried for at least 24 hours at 105 °C. The average bulk density for each soil was 1.386 g/cm³ within the day irrigation field and 1.364 g/cm³ within the night irrigation field.

**Table 3-1: The location and meteorological conditions at HAREC AgriMet station nearby**

<table>
<thead>
<tr>
<th>Site Name (AgriMet Station ID) &amp; months</th>
<th>Station Coordinates (Lat/Long)</th>
<th>Station Elevation (Meters)</th>
<th>Air Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Saturated Vapor pressure (kpa)</th>
<th>Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAREC (May)</td>
<td>45.81944 N, 119.28333 W</td>
<td>185</td>
<td>12.5</td>
<td>61.24</td>
<td>1.60</td>
<td>Loam</td>
</tr>
<tr>
<td>HAREC (July)</td>
<td>45.81944 N, 119.28333 W</td>
<td>185</td>
<td>24.9</td>
<td>37.18</td>
<td>3.29</td>
<td>Loam</td>
</tr>
<tr>
<td>HAREC (September)</td>
<td>45.81944 N, 119.28333 W</td>
<td>185</td>
<td>15.24</td>
<td>36.47</td>
<td>1.81</td>
<td>Loam</td>
</tr>
</tbody>
</table>
3.4.2 Laboratory Analysis and Post Processing

The isotopic compositions, $\delta^{18}O$ and $\delta D$, are calculated as:

$$\delta^{18}O \text{ (or } \delta D) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000,$$  \hspace{1cm} (1)

Where the standard water, $R_{\text{standard}}$, and sample water, $R_{\text{sample}}$, molar ratios are the $^{18}O/^{16}O$ or $^2H/^1H$ values. Isotopic compositions are expressed in parts per thousand ($‰$). We calculated the deuterium excess (dex) as:

$$\text{dex} = \delta D - 8 \delta^{18}O.$$  \hspace{1cm} (2)

The stable isotope ratio of the soil water was assessed with the H$_2$O liquid - H$_2$O vapor equilibration method (Wassenaar et al., 2008). The advantages of this technique are that it does not require cryogenic extraction of soil water to measure isotopic ratios of $^{18}O/^{16}O$ and $^2H/^1H$, and that this process is quicker and more cost-efficient than the typical isotope ratio mass spectroscopy down to water contents as low as ~5%. The effective failure rate is at or below 5% when soil samples are double bagged (Wassenaar et al., 2008), which also avoids inter-lab isotope contamination (Mueller et al., 2014; Orlowski et al., 2016) and allows the soil samples to be processed with less laying open to evaporate compared to isotope-ratio mass spectrometry methods (Wassenaar et al., 2008). Work by Orlowski et al., (2016) found that conventional methods, such as cryogenic distillation, may be prone to big offsets between measurements and reference waters, and assessments of the errors within our data show our approach is consistent with a recent methodological assessment study (Wang et al., 2020) which reported measurement errors on spiked samples of known isotopic composition. Sample handling and analysis was maintained consistent across all
treatments and locations, thus differences between samples are expected to be caused by field conditions and not normal laboratory procedures.

Three replicate standards were created daily by wetting approximately 200g of oven-dried soil (of similar composition specific to each field) to approximately 10% as volume of water content with internal laboratory-working water standards. The bag was tightly closed and the water was mixed by hand into the soil until evenly spread. Internal lab water standards were EH, from the Earth H₂O bottled water company (-114.51‰ -15.51‰); FJ, from the FIJI bottled water company (-41.3‰ -6.66‰), and CT, from filtered tap water Corvallis, Oregon (-67.53‰ -9.74‰), with values of the δD and δ¹⁸O isotope ratios respectively for lab water standards given in parentheses. Prior to sample analysis, approximately 1000 cm³ of dry air was pushed into the plastic sample and standard bags. After 24 hours in the lab on an isothermal laboratory bench, all standards and samples were equilibrated with the dry air that was pushed into plastic bags. This period allowed the headspace water vapor to reach isotopic equilibrium with soil water content. A small needle punctured each bag and then continuously withdrew vapor directly from the headspace in each bag and delivered the vapor to an off-axis integrated cavity output spectrometer (OA-ICOS, Los Gatos Research, Inc. model 908-0004 OA-ICOS). Each punctured bag was sampled for approximately three minutes until all the gas in the headspace was extracted. Within the OA-ICOS system, the temperature and pressure were stable at about 45°C and 39 torr, and the flow rate through the system was 0.25L/min (LPM). The water vapor concentration and
isotopologues were measured using 10-second integration intervals. Within the lab, we processed approximately 35-soil samples and 9 internal lab water standards each day.

The vapor isotope ratios were converted to liquid isotope ratios assuming liquid-vapor equilibrium, and uncalibrated soil water isotope values were obtained for each sample from the spectrometer. Following Horita and Wesolowski (1994), we calculated the equilibrium fractionation factors, \( \alpha_{e,L/V} = \frac{R_L}{R_V} \), as a function of equilibrium temperature which was assumed to be the laboratory bench temperature. Because of uncertainty arising from different steps within this approach (Wassenaar et al., 2008), isotope ratios were corrected following the methods used in Al-Oqaili et al., (2020). The un-corrected liquid water values calculated from the measured vapor isotope ratios were converted to liquid isotope ratios using equilibrium fractionation factors from Horita and Wesolowski (1994) for the internal lab water standards (EH1, FJ1, and CT1) for each set of soil samples each day. We then quantified the measurement errors by calculating the difference between estimates of the lab standard values with their known values. Subsequently, a unique linear equation between the measured isotope ratio and measurement errors was fit with linear regression to account for day-to-day variation in isotope analyzer performance. The linear equations were used for soil samples to compute (and then subtract) the expected measurement errors for unknown samples. Each of the 3 lab standards were included in the measurement error regression, and we take the standard deviation of the post-correction errors of our lab standards as an estimate of measurement precision. The bag vapor concentrations showed only small differences between samples and therefore we did do a secondary correction.
based on the vapor concentration. Averaged across all laboratory measurements days, the standard deviations of errors for known standards were 2.22‰ for δD and 0.36 ‰ for δ^{18}O after the corrections were applied. Samples collected in June and August showed anomalous fluctuations in the stable water isotope ratios. This may be attributed to improper standards, calibration methods, and unstable instrument performance. Nevertheless, we exclude these two months from analysis and discussion.

3.4.3 Soil Evaporation Estimation

The relative concentration of the water isotopologues is not altered when plant take up soil water with their roots, but the heavier isotope will become enriched in soils during evaporation (Craig and Gordon 1965; Horita et al., 2008; Wang et al., 2012; Soderberg et al., 2012). Soil water isotope ratios can therefore be used to quantify the how much input water that was lost through nonproductive soil evaporation. The fraction of water lost from soil surface evaporation (E, in mm), relative to the total input water (I, in mm) can be calculated as:

$$\frac{E}{I} = \frac{\delta_I - \delta_S}{\delta_E - \delta_S},$$

(3)

where subscripts E, I, and S refer to the isotope ratio of evaporation, irrigation water, and soil liquid water respectively. This approach follows that developed in Al-Oqaili et al., (2020), which used similar methods to evaluate evaporative losses from irrigation sprinkler configurations. In equation 3, water inputs are assumed to be removed by either fractionated (evaporation E) and non-fractionated (transpiration T and infiltration downward L) losses, based on a mass-balance model (steady state) of each agricultural field’s soil water. The value of δS was provided from the laboratory analysis of the
soils. The value of $\delta_I$ was attained based on where the local evaporation line (LEL) crossed the local meteoric water line (LMWL). The values of $\delta D$ and $\delta^{18}O$ of these source waters were -103.57‰ and -14.19‰ for May, -120.18‰ and -16.27‰ for July, and -123.87‰ and -16.73‰ for September. The local meteoric water line was determined using the Online Isotopes in Precipitation Calculator (http://wateriso.utah.edu/waterisotopes/pages/data_access/oipc.html) using monthly precipitation estimates.

We have quantified the value of $\delta_E$ using the Craig and Gordon model (1965). This was computed as:

$$
\delta_E = \frac{\delta_S}{\alpha_e L/V - h_A' \delta_A - \epsilon_k} (1 - h_A') + \epsilon_k.
$$

(4)

Here, $\delta_S$ is the isotope ratio of soil liquid, $\alpha_e$, $L/V$ is the kinetic isotopic fractionation factor between the liquid and the vapor (unitless), $h_A'$ is the relative humidity of the atmosphere expressed based on conditions at the evaporating surface (unitless), $\delta_A$ is the isotope ratio of the atmosphere, $\epsilon_k$ is the kinetic isotopic fractionation (unitless).

Weather station data from AgriMet were used for the temperature and relative humidity values. Following Horita et al., (2008) the relative humidity is adjusted based on the temperature and water activity at the evaporating surface as:

$$
h_A' = h_A e_{sA} A_{aw} e_{s0},
$$

(5)

where $h_A$ is the relative humidity of the overlying air, $e_{sA}$ is the saturation vapor pressure in the atmosphere kPa, $a_{w}$ thermodynamic activity of water (unitless), (assumed 1 here), $e_{s0}$ is the saturation vapor pressure at the evaporating surface in kPa.

We assumed that the stable water isotopes of the local atmospheric moisture were in isotopic equilibrium with input water as:
\[
(\delta_A) = \frac{(\delta_I + 1000 - (\alpha e_{L/v}) \times 1000)}{\alpha e_{L/v}}.
\] (6)

The kinetic isotopic fractionation was estimated by using:

\[
\epsilon_{K,L/v} = n(1 - h_A) \left( \frac{D}{D_i} - 1 \right) \frac{r_m}{r},
\] (7)

where \(n\) is an aerodynamic parameter for modifying diffusivity ratios, \(D\) is the diffusion coefficient, (with subscript \(i\), indicates the minor isotopologues, \(\text{m}^2\text{s}^{-1}\)) and \(r_m/r\) is a fraction of atmospheric resistance that is considered diffusive. Based on previous studies in arid ecosystems, \(n\) was set at 0.97, \(D/D_i\) was set at 1.0251 and 1.0285 (for hydrogen and oxygen respectively), and \(r_m/r\) set at 1.0 (Soderberg et al., 2012; Horita et al., 2008). We have calculated the values of \(E/I\) based on each of the \(\delta D\) and \(\delta^{18}O\) ratios as well as taking their average. When an \(E/I\) value of less than zero was found, it was set at zero for the subsequent statistical analysis.

### 3.4.4 Statistical Analysis

Following Al-Oqaili et al., (2020), a Linear Mixed Effects Model (LMEM) was applied to evaluate the relationship between irrigation location and timing with the soil moisture and its isotopic composition. Higher similarities of soil samples that were collected during the same month from three different depths at a single core as well as similarities between numerous cores collected at the same location or field results i hierarchically nested samples that can be controlled for within LMEMs (Jashami et al., 2019; Barlow et al., 2019). A set of LMEM was applied to determine whether there were any significant variations between treatments and four key response variables: the soil moisture; the stable water isotopes, and \(E/I\) ratios in a row and interrow irrigated fields. We have utilized the Statsmodels module in Python for simulating these analyses.
(Seabold et al., 2010). In addition, we evaluate the differences between means of collected groups of samples via a set of t-tests at different significance levels (0.1, .05, and .01) with labeling as (*, **, and ***) in figures.

LMEM was utilized to assess the relationship between sample location (row vs. interrow) and irrigation field (day and night). A single LMEM was formed for every response variable of the form “RESPONSE ~ FIELD + LOCATION”, where response is either soil moisture; the stable water isotopes, and $E/I$ ratios. The fixed effects were irrigated field and location. Random effects were integrated for every core, resulting in random intercepts for every core for every month, with these addressed independently for every top-level group (the month). Nesting of samples within cores within sites was treated by specifying the variance component.

Uncertainty in ecosystem factors such as temperature, relative humidity, and other atmospheric factors is not directly included in this computation. Previously, a detailed sensitivity analysis has demonstrated that local soil water isotope ratios were the dominant driver of $E/I$ flux partitioning uncertainty, while ecosystem factors such as temperature errors were less relevant (Wang et. al., 2013). Therefore, variability in sample variations between the $\delta_S$ and $\delta_I$ was the main factor driving variability in $E/I$ estimates, and the uncertainty was thereby integrated into the test of the $E/I$ significance tests of the LMEM.
3.5 RESULTS

3.5.1 Soil Water Content

The soil moisture was influenced by position, irrigation timing, depth, and month (Figure 3.1). The soil samples in the row and interrow locations had volumetric water contents that ranged from 0.05 cm$^3$/cm$^3$ to 0.29 cm$^3$/cm$^3$ and from 0.04 cm$^3$/cm$^3$ to 0.33 cm$^3$/cm$^3$, respectively. Interrow positions were typically wetter than the row positions. Differences between day and night fields were less clear. Generally, soil water content decreased with depth and the 25 cm has low fluctuation in average values of the soil moisture during irrigation months. We focus our analysis on May, July and September to coincide with isotopic data availability.

In May, the daytime irrigated plots were wetter than nighttime irrigated plots and the interrow locations were wetter than row locations. Within the daytime irrigated field, the average water content in rows was 0.15 cm$^3$/cm$^3$, with a standard deviation of 0.05 cm$^3$/cm$^3$, while the average water content in interrow locations was 0.16 cm$^3$/cm$^3$, with a standard deviation of 0.02 cm$^3$/cm$^3$. Within the nighttime irrigated field, the average water content in rows was 0.13 cm$^3$/cm$^3$, with a standard deviation of 0.03 cm$^3$/cm$^3$ while the average water content in interrow locations was 0.15 cm$^3$/cm$^3$, with a standard deviation of 0.01 cm$^3$/cm$^3$. The highest average soil water content values were found at the surface of interrow fields. The average water contents at 5cm were significantly drier at row locations as compared with interrow locations for each day and night irrigated fields based on a t-test analysis.
Figure 3-1: The soil volumetric water content (VWC, cm³/cm³) at row and interrow locations for the three sampling depths, 5cm, 15cm, 25cm, at Day- Night irrigated fields during May, July and September. The significant differences between means are marked with * for \( p<0.1 \), ** for \( p<0.05 \), and *** for \( p<0.01 \), however, the mean values are marked with X.

During July, the daytime irrigated plots were drier than the nighttime irrigated plots and the interrow locations were again wetter than row locations. Within the daytime irrigated field, the average water content across all row locations was 0.17 cm³/cm³, with a standard deviation of 0.05 cm³/cm³ while the average water content across all interrow locations was 0.19 cm³/cm³, with a standard deviation of 0.03 cm³/cm³. Within the nighttime irrigated field, the average water content across all row locations was 0.19 cm³/cm³, with a standard deviation of 0.03 cm³/cm³ while the average water content across all interrow locations was 0.21 cm³/cm³, with a standard deviation of 0.03 cm³/cm³. The mean water content of the entire columns were not significantly different between day and night fields. However, significant differences were found at the near surface between row and interrow locations.
Figure 3-2: The δD and δ\textsuperscript{18}O stable water isotopes composition for independent soil samples during (A) May, (B) July, and (C) September. The 95% confidence intervals for the regression displayed as a shaded area around the Local Meteoric Water Line (LMWL) and Local Evaporation Line (LEL). Error bars denote soil isotopes ratio measurement precision.

3.5.2 Soil Isotope Ratios

During May, July, and September of this project, we measured the δD and δ\textsuperscript{18}O in soil waters at row and interrow locations in the daytime and nighttime irrigated fields (Figure 3.2). The lowest value of the soil δD (and δ\textsuperscript{18}O) values were estimated at 25 cm depth under interrow locations during September with values of -122.72‰ (and -15.88‰). The highest value of the soil δD (and δ\textsuperscript{18}O) values were estimated at 5cm depth in the surface soil under row locations during May with values of -52.77‰ (and -0.99‰). The mean values of the soil isotope ratios with the different depths are given in (Table 2.1). The highest mean and standard deviation of the δD (and δ\textsuperscript{18}O) values were estimated in rows locations with the values -83.35‰ (4.93‰) and -8.03‰ (1.38‰), while the lowest mean of the δD (and δ\textsuperscript{18}O) values were estimated at the interrow locations with the values -116.17‰ (2.90‰) and -13.56‰ (0.53‰), respectively.

In May, there was no clear isotope trend between row locations and interrow locations. The average isotopic ratio, for both δD and δ\textsuperscript{18}O, were larger in row locations in the day irrigated field but also larger in interrow locations in the night irrigated field (Figure 3.3). The average soil isotope ratios across all the soil samples from the day irrigation field at row and interrow locations were -83.35‰ and -85.11‰ with a standard deviation of 7.09‰ and 6.76‰ for δD and were -8.03‰ and -8.73‰ with a standard deviation of 2.16‰ and 1.47‰ for δ\textsuperscript{18}O, respectively. The average soil isotope ratios
across all the soil samples from the night irrigation field at row and interrow locations were -84.75‰ and -84.46‰ with a standard deviation of 14.50‰ and 9.04‰ for δD and were -10.95‰ and -11.19‰ with a standard deviation of 3.39‰ and 2.10‰ for δ¹⁸O, respectively.

In July, row locations in both the night and day irrigated files generally had larger isotope ratios than interrow locations. The average soil isotope ratios across all the soil samples from the day irrigation field at row and interrow locations were -105.94‰ and -109.74‰ with a standard deviation of 3.47‰ and 2.64‰ for δD and were -12.49‰ and -13.14‰ with a standard deviation of 0.65‰ and 0.34‰ for δ¹⁸O, respectively.

The average soil isotope ratios across all the soil samples from the night irrigation field at row and interrow locations were -99.65‰ and -107.02‰ with a standard deviation of 7.14‰ and 2.44‰ for δD and were -11.32‰ and -12.58‰ with a standard deviation of 1.77‰ and 0.51‰ for δ¹⁸O, respectively.

In September, row locations in both the night and day irrigated fields generally had larger isotope ratios than interrow locations, similar to July. The average soil isotope ratios across all the soil samples from the day irrigation field in September at the row and interrow locations were -101.28‰ and -107.37‰ with a standard deviation of 4.25‰ and 4.59‰ for δD and were -11.32‰ and -12.58‰ with a standard deviation of 1.33‰ and 0.73‰ for δ¹⁸O, respectively. In the night irrigated field, the average of isotope ratios at row and interrow locations were -109.21‰ and -116.17‰ with a standard deviation of 5.26‰ and 2.90‰ for δD and -11.29‰ and -13.56‰ with a standard deviation of 1.71‰ and 0.53‰ for δ¹⁸O, respectively.
For each month, both scheduled irrigation treatments were assumed to be drawn from the same source water and exposed microclimate, thus resulting in a single distinct local evaporation line (LEL) that was fit using both day and night field samples (Figure 3.2). Relative distances along these LELs are determined by variations in the amount of water lost as evaporation. During the month of May, the values of δD and δ¹⁸O in the night treatment (both row and interrow) field were closer to LMWL line than the values on Day treatment of irrigation (row and interrow) at 5 cm, 15 cm, and 25 cm depths. In addition, May samples were farther along the local evaporation line than July or September samples. During July and August, samples were more tightly clustered around the LEL and spanned a smaller range closer to the inferred irrigation source.
Figure 3-3: The average values of the stable water isotope compositions in the soil profile of the months and for the day and night irrigated fields. Boxplots of the three months are categorized by row or interrow irrigation with A) illustrating soil water $\delta^{2}D$ values at day, B) illustrating soil water $\delta^{2}D$ values at night, C) illustrating soil water $\delta^{18}O$ values at day, D) illustrating soil water $\delta^{18}O$ values at night, E) illustrating d-excess values at day and E) illustrating d-excess values at night. The mean values are marked with X, While significant differences between means are marked with * for p<0.1, ** for p<0.05, and *** for p<0.01.
Table 3-2: Mean and standard deviation (in parentheses) of water content of the soil samples, stable water isotopes composition for day and night fields at row (R) and interrow (IR) locations

<table>
<thead>
<tr>
<th>Month Name</th>
<th>5 cm Depth</th>
<th>15 cm Depth</th>
<th>25 cm Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Content (cm³/cm³)</td>
<td>Soil Water (^{2}H/^{1}H) (%)</td>
<td>Soil Water (^{18}O/^{16}O) (%)</td>
</tr>
<tr>
<td>May-Day (R)</td>
<td>0.15 (0.06)</td>
<td>-62.23 (9.09)</td>
<td>-3.78 (2.82)</td>
</tr>
<tr>
<td>May-Night (R)</td>
<td>0.11 (0.03)</td>
<td>-74.43 (13.01)</td>
<td>-7.93 (4.23)</td>
</tr>
<tr>
<td>Jul-Day (R)</td>
<td>0.17 (0.06)</td>
<td>-103.08 (5.35)</td>
<td>-11.69 (0.91)</td>
</tr>
<tr>
<td>Jul-Night (R)</td>
<td>0.24 (0.03)</td>
<td>-100.07 (6.81)</td>
<td>-11.72 (0.82)</td>
</tr>
<tr>
<td>Sep-Day (R)</td>
<td>0.11 (0.01)</td>
<td>-94.08 (5.77)</td>
<td>-8.54 (1.94)</td>
</tr>
<tr>
<td>Sep-Night (R)</td>
<td>0.10 (0.03)</td>
<td>-101.52 (7.65)</td>
<td>-8.30 (2.36)</td>
</tr>
<tr>
<td>May-Day (IR)</td>
<td>0.21 (0.02)</td>
<td>-68.31 (7.70)</td>
<td>-5.66 (2.38)</td>
</tr>
<tr>
<td>May-Night (IR)</td>
<td>0.17 (0.02)</td>
<td>-65.80 (8.06)</td>
<td>-7.38 (2.63)</td>
</tr>
<tr>
<td>Jul-Day (IR)</td>
<td>0.24 (0.03)</td>
<td>-106.96 (1.85)</td>
<td>-12.68 (0.34)</td>
</tr>
<tr>
<td>Jul-Night (IR)</td>
<td>0.30 (0.02)</td>
<td>-108.31 (2.49)</td>
<td>-12.67 (0.48)</td>
</tr>
<tr>
<td>Sep-Day (IR)</td>
<td>0.17 (0.00)</td>
<td>-103.87 (4.28)</td>
<td>-12.16 (0.66)</td>
</tr>
<tr>
<td>Sep-Night (IR)</td>
<td>0.15 (0.02)</td>
<td>-114.27 (1.59)</td>
<td>-13.05 (0.81)</td>
</tr>
</tbody>
</table>

$^{18}$O/$_{16}$O (‰)
Table 3-3: The average of E/I percentage for day and night at row (R) and interrow (IR) locations

<table>
<thead>
<tr>
<th>Month name of the treatments by sprinkler irrigation</th>
<th>5 cm Depth</th>
<th>15 cm Depth</th>
<th>25 cm Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E/I % (O¹⁸) as function of evap.</td>
<td>E/I % (D/H) as function of evap.</td>
<td>E/I% (O¹⁸&amp;D/H) as function of evap.</td>
</tr>
<tr>
<td>May-Day (R)</td>
<td>33.21 (12.54)</td>
<td>48.63 (16.70)</td>
<td>40.92 (14.30)</td>
</tr>
<tr>
<td>May-Night (R)</td>
<td>17.22 (14.92)</td>
<td>28.88 (18.37)</td>
<td>23.05 (16.08)</td>
</tr>
<tr>
<td>Jul-Day (R)</td>
<td>10.94 (2.79)</td>
<td>15.29 (7.05)</td>
<td>13.11 (4.83)</td>
</tr>
<tr>
<td>Jul-Night (R)</td>
<td>10.86 (2.50)</td>
<td>19.30 (9.06)</td>
<td>15.08 (4.92)</td>
</tr>
<tr>
<td>Sep-Day (R)</td>
<td>22.49 (6.10)</td>
<td>30.93 (7.32)</td>
<td>26.71 (6.49)</td>
</tr>
<tr>
<td>Sep-Night (R)</td>
<td>23.30 (7.66)</td>
<td>21.78 (9.35)</td>
<td>22.54 (8.21)</td>
</tr>
<tr>
<td>May-Day (IR)</td>
<td>24.90 (9.70)</td>
<td>37.48 (12.55)</td>
<td>31.91 (10.76)</td>
</tr>
<tr>
<td>May-Night (IR)</td>
<td>18.37 (9.96)</td>
<td>41.91 (14.72)</td>
<td>30.14 (12.32)</td>
</tr>
<tr>
<td>Jul-Day (IR)</td>
<td>7.93 (1.03)</td>
<td>10.24 (2.32)</td>
<td>9.09 (1.49)</td>
</tr>
<tr>
<td>Jul-Night (IR)</td>
<td>7.96 (1.43)</td>
<td>8.55 (2.97)</td>
<td>8.26 (2.23)</td>
</tr>
<tr>
<td>Sep-Day (IR)</td>
<td>11.16 (1.95)</td>
<td>18.83 (5.12)</td>
<td>14.99 (3.28)</td>
</tr>
<tr>
<td>Sep-Night (IR)</td>
<td>8.52 (2.36)</td>
<td>6.70 (1.80)</td>
<td>7.61 (1.54)</td>
</tr>
</tbody>
</table>
3.5.3 Soil Evaporation Ratio

The fraction of soil evaporation losses \((E/I)\) was estimated with both \(\delta D\) and \(\delta^{18}O\) isotope ratios (Figure 3.5), with results highly correlated between isotopes \((r^2=0.74)\) and \(E/I\) estimated with \(\delta D\) generally larger than that estimated from \(\delta^{18}O\). During the crop-growing season, the amount of evaporation that occurs from soils depends on the time available for evaporation between irrigation, atmospheric demand (via temperature and relative humidity) and the surface properties of the soil (Burt et al., 2005; Soderberg et al., 2012; Good et al., 2014). In general, more isotopic fractionation occurred due to the evaporation at surface soil layer compared with lower soil depths across all months. Our findings show there were distinct changes in fraction of water lost as evaporation between the row and interrow positions, and these differences were significant (Figure 3.5, Table 3.3). The soil samples from the rows and interrow had the \(E/I\) values that ranged from 0% to 56.43% and 0% to 48.42% for May, 5.32% to 35.22% and 2.53% to 13.21% for July and 2.66% to 34.07% and 2.84% to 38.53% for September, respectively when we used the average of \(\delta D\) and \(\delta^{18}O\) isotope compositions to estimate the evaporation.

In May, the average of the evaporation fraction from the day irrigation field across all the row soil samples was 18.11% with a standard deviation of 7.87% and for interrow field locations was 15.01% with a standard deviation of 6.19%, respectively. For the night irrigation field, the average of the evaporation fraction across all the soil samples for row locations using the average of \(\delta D\) and \(\delta^{18}O\) was 13% with a standard deviation of 12.47% and for interrow field locations and was 12.55% with a standard deviation of 6.58% and respectively. The average difference in the evaporation fractions during
May was insignificant between row and interrow, based on t-test analyses (Figure 3.4).

In July, the mean of evaporation fraction across all the soil samples from the day irrigation for row locations was 10.05% with a standard deviation of 3.16% and for interrow locations was 6.69% and 8% with a standard deviation of 1.97%, respectively. For the night irrigation field, the mean of the evaporation fraction across all the soil samples from row locations using the average of isotopic compositions were 16.06% with a standard deviation of 6.85% and for interrow locations was 9.21% with a standard deviation of 2.07%, respectively. Based on a t-test analysis, the mean of the evaporation fraction at July was significantly different between row and interrow locations (Figure 3.4).

Figure 3-4: The average of E/I % in (A) and (B) when used the stable water isotope composition as a function of evaporation in the soil profile at row and interrow locations in Day- Night irrigated fields during May, July and September. However, the average of E/I in (C) and (D) at day-night irrigated fields under row and interrow locations during May, July and September. The mean values are
marked with X, While significant differences between means are marked with * for $p<0.1$, ** for $p<0.05$, and *** for $p<0.01$.

Figure 3-5: The values of $\delta^{18}O$ and $\delta D$ for all soil samples at the row and interrow in 2016 of the three months in the study site (HAREC) semiarid region, and the LWML is the line in the dual-isotope plot.

In September, the mean of the evaporation fractions across all the soil samples at the day irrigation field for row locations was 18.53% with a standard deviation of 4.52% and for interrow locations was 11.94% with a standard deviation of 3.52%, respectively. In the night irrigation field, the mean of the evaporation fractions across all row locations was 13.34% with a standard deviation of 5.54% and for interrow locations was 5.9% with a standard deviation of 1.57%, respectively. Based on our analyses of a t-test of the differences between row and interrow locations the evaporation fraction during September was strongly significant at both irrigated treatments. All positions of the depths soil (5cm, 15cm and 25cm) with interrow
planting lines experienced less evaporation at Night irrigation treatment (Figure3.4, Table 3.3).

3.5.4 Linear Mixed Effects Modeling

Combining all samples within the LMEM analysis demonstrated that the volumetric water content could be reasonably predicted ($r^2=0.51$) based on the fixed effects of field and location when allowing for random effects of month and core (Figure 3.6A). The timing of irrigation (day and night) was not a statistically significant predictor of volumetric soil moisture at a 95% C.I. ($p=0.189$). However, the locations of a sample (row and interrow) was a statistically significant predictor of volumetric soil moisture ($p=0.001$). The LMEM for the both isotopes ratios demonstrated improved predictive ability, with $\delta D$ ($r^2=0.81$) and $\delta ^{18}O$ ($r^2=0.60$) both accurately estimating observed values. The timing of irrigation was of mixed importance, as it was a significant predictor of isotope ratios for $\delta ^{18}O$ ($p=0.01$) but not for and $\delta D$ ($p=0.182$). However the location within a field was found to be highly significant for $\delta D$ ($p=0.000$) and $\delta ^{18}O$ ($p=0.000$). Similar to the other response variables, the evaporation ratio was able to be predicted ($r^2=0.60$) based on the fixed and random effects within the LMEM. Again, the timing of irrigation (day and night) was not a statistically significant predictor of the evaporation ratio at 95% C.I. ($p=0.113$). However, the locations of a sample (row and interrow) was a statistically significant predictor of the evaporation ratio ($p=0.000$).
Figure 3-6: Linear Mixed Effects Model (LMEM) used to determine whether there were any significant differences between four key response variables: the soil water content; the soil isotope ratios and soil evaporation ratios in row and interrow irrigated fields.
3.6 DISCUSSION

Although we observed some fluctuation in the average of the water contents between the row and interrow locations in both day and night irrigated fields, these differences proved insignificant beyond the surface layer. In contrast, consistent statistically significant differences were found in stable isotope ratios and evaporation fractions during the middle and end of the growing season (July and September). This suggests that soil moisture alone may not be a useful indicator of evaporation losses during the growing season. The soil isotope ratio measurements across both treatments’ fields was found to be a useful indicator of evaporation due to significant differences in isotope ratios.

3.6.1 The Soil Moisture Profile

At both the day and night irrigated fields in May, July, and September the water content in the interrow soil locations was higher than the row soil locations and this difference was statistically different at 5cm. We found in this study that the difference between measurements of water content was inconsistent during both treatments the day and the night irrigated fields and at locations, this is consistent with prior studies (Cavero et al., 2008; Yacoubi et al., 2010; Agam et al., 2012). These studies found that evaporation was affected by the time of irrigation, solar radiation reaching the soil, air temperature, and soil temperature; however, in our study the treatment with larger evaporative losses changed as the growing season progressed (nighttime in July and daytime in September). Cavero et al., (2008) found lower soil matric potential during daytime irrigation late in the season, which we observed in July, but not September. In addition, Cavero et al., (2008) claim that the water stress that occurs due to less water availability was caused by the higher wind drift and evaporation losses for daytime irrigation, while
Playán et al., (2005) suggested that using nighttime irrigation during episodes of high wind can help reduce evaporation losses.

The small magnitude of difference in water content at the depth of 30 cm from both irrigation treatments has been attributed to capillary action in the soil that recharged the root zone (Wang et al., 2012; Wu et al., 2018). The influence of the canopy (expected to decrease evaporation) was not sustained later in the season as surface soil water contents declined, consistent with Eastham et al., (1999). Although the isotopic compositions of soil moisture changes during evaporation from soil and not from root water uptake, the soil water content decreases by both evaporation from soil and transpiration from plants (Soderberg et al., 2012; Wang et al., 2012; Wu et al., 2016; Wu et al., 2017; Wu et al., 2018).

### 3.6.2 Stable Isotope Tracers

Stable isotope techniques have been used to estimate the evaporation through both natural landscapes and agricultural practices (Craig and Gordon 1965; Horita et al., 2008; Werner et al., 2001; Wassenaar et al., 2008; Good et al., 2014; Good et al., 2015; Price et al., 2015; Wu et al., 2016; Wu et al., 2018). During our study, the variations in the isotopic compositions were statistically significant. This was ascribed to differences in planting lines form and accentuated by the time of sampling in relation to the last date and amount of irrigation, as well as the scheduling the irrigation water management strategies. Moreover, there is potentially a local speed up of the wind due to the micro-topography. This extra exposure creates a local condition that is more desiccating.
Figure (3.2) shows the soil water samples of both day irrigation and night irrigation fields had mostly lower values of isotopic composition at all depths than the values of the local meteoric water lines (LMWL) during all three months May, July and September. These findings indicate a strong evaporation effect on the soil water isotopes when the crops were irrigated during the summer season. However, during May, our results suggested the relatively low early season proportion cover of the plant decreased the consequences of the location or treatments, and samples had more behavior that is similar in the stable water isotopes composition. The higher canopy cover during July happened over all locations (row and interrow) during the summer months in both treatments, which caused a lower evaporation rates overall. The soil profile at row and interrow positions experienced isotopic enrichment across both irrigation treatments (Figures 3.2 and 3.3). However, for the rows at both irrigation fields, the stable water isotopes at the three depths were highly variable compared to the interrow. Based on our results, we estimate that interrow locations experienced less kinetic fractionation of water during and after irrigation because of the smaller surface area of soil exposed to wind drift and solar radiation effects subjected these soils to less evaporation compared to rows locations.

Both treatments started irrigation in early May, the combination of irrigation water with the last wet season precipitation, may have contributed to the wider scatter in May isotope values as well as those falling beyond the LMWL with night irrigation. Wu et al. (2017) and Youjie et al. (2017) found the heavy isotopes depleted and enriched alternately along with the processes of condensation and distillation, which is similar to what happened in our study during the night (Figures 3.2A and 3.2B). Overall, the
isotopic compositions in both treatments had similar distributions relative to their sources of irrigation water. The above-mentioned discrepancy may also be attributed to the difference between rows and interrow locations leading to water entering the soil surface at different times and varying evaporation before reaching the root zone (Timlin et al., 2001; Chen et al., 2010; Nurit et al., 2012).

3.6.3 Evaporative Losses

Our results show that stable water isotopes ratios become less enriched in heavy isotopes with increases in depth, thus and the surface of the soil has a strong water loss as evaporation. In the last few years, numerous scientists have used stable isotope information with local atmosphere factors for developing the models to calculate the soil evaporation from the soil surface (Soderberg et al., 2012). Our results displayed distinctive $E/I$ partitioning in the soil moisture samples within row and interrow locations for both irrigation times. (Table 3.2, 3.3, Figure 3.2, 3.3 and 3.4). We found the evaporative enrichment process for positions (row and interrow) of treatments fields was very sensitive to changes in kinetic fractionation (Horita et al., 2008; Braud et al., 2009a; Soderberg et al., 2012). Changes in the ratio of $E/I$ for rows and interrow is driven primarily by variations in the structural form of the soil-plant-atmosphere continuum. Furthermore, the atmosphere variables had a similar effect on each irrigation treatment design under the three soil depths 5 cm, 15 cm, and 25 cm. These results demonstrate that the minimum evaporation was at interrow locations within both treatments (Figures, 3.3, 3.4 and 3.5 and Table 3.3). The isotopic compositions provided a informative technique for evaluating evaporation dynamics for row and
interrow locations. Moreover, interrow planting lines design had 27 to 90% less $E/I$ that loss from both treatments day and night (Timlin et al., 2001; Agam et al., 2012).

### 3.7 Conclusion

These analyses provide estimates of the evaporation as a fraction of water applied from different locations within a furrowed agricultural system. From our study, we quantified the variations in evaporation under two irrigation schedule treatments by evaluating the $\delta$D and $\delta^{18}$O dual soil stable isotopes during the summer of 2016 at potato fields in the Hermiston area. Within each treatment, we also assessed the positional and depth dependence. The results of this dual soil stable isotope analysis quantified the variations between the row and interrow field locations. The findings showed highly significant variations in $\delta$D and $\delta^{18}$O distributions between the row and interrow locations within the upper layer of the soil, with interrow locations having on average fewer evaporation losses. The upper layer of the soil demonstrated larger variations on the soil moisture within rows at both treatments during the summer season.

Water losses from both interrow and rows planting lines as evaporation were characterized using stable isotope ratios. The mean of evaporation under the soil profile within the day irrigated field for row and interrow estimated $E/I$ (mean ± standard deviation) when combined the three months were 15.56% ± 5.19%, and 11.21% ± 3.89%, and for the night irrigated field the rows and interrows were estimated $E/I$ were 14.14% ± 8.29% and 9.22% ± 3.41%, respectively. Thus, in both fields the rows experiences more evaporation relative to inputs. The findings are useful for the quantifying the dynamics of water losses through evaporation for scheduling
conventional irrigation (day) and shifting time of irrigation to (night) beneath interrow and row irrigation designs. Furthermore, our study supplies key values of irrigation efficiencies, which have utility for optimizing agricultural management for decreasing water consumption.

3.8 ACKNOWLEDGEMENTS

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3.9 References


4 Chapter 3: Estimating soil evaporation losses from single- and double-line drip irrigation treatments within a hazelnut farm in the US Pacific Northwest using stable water isotopes.

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4.1 Abstract

Drip irrigation is often considered an efficient means of water delivery, however how the efficiency changes as more emitted are added to a system is unclear as additional water may be lost to evaporation before it can be taken up by roots. In this study, non-productive soil evaporation losses are estimated based on the hydrogen and oxygen isotope ratios of soil moisture for a hazelnut field in the Willamette Valley of the Pacific Northwest. Soil samples from the hazelnut field under single-line and double-line drip irrigation treatments were collected in summer 2018 at multiple depths from different positions in the tree rows. The stable isotope ratio of soil water in these samples was measured using H₂O liquid - H₂O Vapor equilibration laser spectroscopy. Our results show average $^2$H/$^1$H and $^{18}$O/$^{16}$O isotope ratios of the single line with drip irrigation were higher than double line with drip irrigation. These results suggest that less soil evaporation occurred from the double-line drip irrigation ($E/I = 17.33 \pm 6\%$) when compared to the single-line treatment ($E/I = 20.93 \pm 6.5\%$), which also had higher soil moisture levels than the single line with drip irrigation that irrigated during the day. This suggests that increasing the number of drip emitters can lead to an increase in the
efficiency of drip irrigation when efficiency is defined as the fraction applied that is used productively by plants.

4.2 Keywords

Single-line drip irrigation, Double-lie drip irrigation Isotope, Hazelnut, Evaporation

4.3 Introduction

As the global population increases, so too does demand for water resources, with irrigation water demand having more than tripled from the 1960s through 2000 (Fereres, 2008; Wada et al., 2012). Furthermore, competition for water resources has increased due to the development of industrial and other non-agricultural uses in recent decades. During recent years, freshwater shortages are becoming more prevalent in arid and semiarid areas of the world as water resources are used across agricultural, industrial and urban consumers (Chai et al., 2016), and yet agriculture use constitutes approximately 70% of freshwater withdrawals per year globally (Saccon, 2018). Because irrigation water is an essential element for crop production in many locations (Howell, 2001), numerous new technological and management strategies have been developed in order to increase food production and gain food security when water resources are limited (Reddy, 2016). This insufficiency in water availability and the gradual increase in irrigation costs have focused attention on improving the productivity of crop production (Bessembinder et al., 2005; Fereres and Soriano, 2007; Reddy, 2016) and has led to the expansion of drip irrigation in recent decades (Burney et al., 2010; Barnes, 2012).

Drip irrigation can raise the efficiency of irrigation because there is little-to-no runoff generated, less evaporation or deep infiltration from within soil column, and more
applied water reaches crop leaves, stems and fruit (Shock, 2006). The combination of mulching and fertigation with drip irrigation has demonstrated further improvements in agricultural productivity (Jayakumar et al., 2017). In addition to being advantageous when water is costly or scarce, drip irrigation is readily adaptable to oddly shaped fields or those with irregular slopes, and those particular conditions have to be considered when designing drip irrigation systems (Shock et al., 2002; Jayakumar et al., 2017). Drip systems can also work well where other irrigation systems are inefficient because parts of the field have excessive infiltration, water puddling, or runoff (Ali, 2011). Drip irrigation management based on the water balance analysis has been used to improve fruit tree growth and production (Dias et al., 2004; Bignami et al., 2008, Bignami et al., 2010) and farmers have realized areca nut, coconut, and nutmeg increases from 13% to 47% through drip irrigation when compared to the surface method of irrigation (Madhava & Surendran, 2016). Given these benefits of drip irrigation systems, growers have also experimented with different drip irrigation configurations. One potential option is to double, or triple, the number of emitters by adding additional drip lines throughout planted fields. Double-line drip irrigation can increase crop yield by more than 10% when compared to the single-line drip treatments (WANG et al., 2012; Roncucci et al., 2014), demonstrating that yields can respond positively to increasing volumes of water supplied. How increasing drip emitters influences overall irrigation efficiency is unclear because additional water may either be up taken by rooting systems or it may evaporate off before uptake. In particular, the amount of soil evaporation losses associated with single (and double) drip irrigation lines has not been
assessed at this point. This is a critical metric of irrigation efficiency as soil evaporation constitutes a non-productive loss of water resources.

As an important global nut crop, commercial cultivation of Hazelnut (*Corylus avellana*) occurs in Asia (principally Turkey), Europe (principally Italy and Spain), and North America (principally the in the Pacific Northwest of the United States) (Boccacci et al., 2008) resulting in total nut production that is second after almonds (Shahidi et al., 2007). Hazelnut trees have a low capacity for stomatal regulation which makes them sensitive to water stress, and are estimated to need about 800 millimeters of water during the season (Cristofori et al., 2012). Hazelnut trees also have shallow root systems which are typically less than ~60cm deep that cannot reach deeper soil moisture reservoirs, and thus draw moisture from the upper soil layers more rapidly than from lower depths (Olsen, 2013; Pscheidt et al., 2016). As hazelnut trees are sensitive to water stress, their yield is heavily dependent on the trees receiving adequate amounts of irrigation (Mingeau & Rousseau, 1992; Cristofori et al., 2012). From 1982 to 1989, the evapotranspiration (ET) and transpiration was measured in hazelnut trees using lysimeters to determine crop coefficients, and irrigation-warning systems based on potential evapotranspiration PET values (Mingeau & Rousseau, 1992). Drip irrigation has been used for hazelnut production because it is a highly efficient water saving irrigation system that is widely utilized in the cultivation of orchards around the world (Shock et al., 2002; Xi et al., 2014; He et al., 2015; Paris et al., 2018; Yan et al., 2018). The growing demand for hazelnuts is inducing increasing numbers of farmers to expand production, particularly in the Pacific Northwest of the United States, and drip irrigation systems likely represent the best tool for efficiently managing fam water,
energy, fertilizer and labor resources (Dias et al., 2004). However, given the increasing scarcity of water resources it is important to identify how different irrigation configurations influence the efficiency of drip lines and within hazelnut orchards.

Stable isotopes of hydrogen and oxygen ($^2$H or $^{18}$O) have been used in many experimental settings to examine water uptake patterns by plants in natural and agricultural ecosystems (Ehleringer and Dawson, 1992). Stable isotopes are widely used to separate evapotranspiration into the transpiration and evaporation components, (Yakir and Wang, 1996; Gibson et al., 1993; Wang et al., 2013) and these tools to partition water fluxes have been used to understand agricultural productivity and efficiency (Kool et al., 2014; Al-Oqaili et al., 2020). Hydrogen and oxygen isotopes are illustrative of uptake of soil water by plants relative to evaporation of soil water because roots do not fractionate (i.e. change the ratio of heavy to light isotopes) water during uptake from the soil as it enters the plant xylem stream (Ehleringer & Dawson, 1992) whereas evaporation from top layer of soil does fractionate waters (Mahindawansha et al., 2020; Al-Oqaili et al., 2020). Accordingly, isotope ratios serve as useful tracers, with established applications in hydrology, ecology and agricultural systems (Good et al., 2014; Al-Oqaili et al., 2020).

The aim of this study was to use stable isotope measurements to identify the fate of water applied to a hazelnut field as a metric of irrigation efficiency. Specifically, this work is an integrated study using stable ratios $^2$H/$^1$H and $^{18}$O/$^{16}$O to detect what fraction of applied water was lost to surface evaporation in contrasting drip irrigation treatments within a hazelnut farm in the Willamette Valley of Oregon. Our hypothesis is that drip irrigation efficiently moves water downward into the rooting zone thereby leaving
relatively limited water exposed to surface evaporation. Thus, increasing the number
of drip lines may not necessarily lead to a doubling of surface evaporation because only
a limited amount of water remains at the surface. In this case soils under double-line drip
irrigation should be less depleted in heavy isotope ratios relative to soils under single-
line drip irrigation. To test this, the soil evaporation was estimated by measuring the
stable water isotope ratios in the soil profile under single-line and double-line drip
irrigation during the middle of the hazelnut growing season. The objectives of this study
are to 1) estimate the differences in the fractionation of stable water isotopes from
different drip irrigation treatments, and 2) to quantify the variations in water lost as soil
evaporation from different drip irrigation treatments.

4.4 Material and Methods

4.4.1 Experimental Setup and Sample Collection

This study was carried out at the Hazelnut farm near Amity, Oregon in the Pacific
Northwest of the United States. The elevation of this farm is 193.01 ft. (58.83 m) and
coordinates of 45.108725 N latitude and 123.280781 W longitude. The observations
were conducted during 2018, which had a total annual precipitation was 30.72 inches
(780.29 mm), a mean annual temperature was 53.5 °F (11.9 °C), and the mean of
relative humidity was 76.60 %. Samples were collected in August, during which the
average temperature was 62.76 °F (17.08°C), the average of the relative humidity was
67.59%, based on the CRVO AgriMet weather station (https://www.usbr.gov/pn/agrimet/agrimetmap/hrmoda.html). The baseline single-drip
irrigation rate was 5 gallons per minute (300 gallons per hour) per acre. The field was
irrigated for 10hrs a day 5 days a week, corresponding to 150,000 gallons per acre per
week. Hazelnut trees were planted into rows spaced 20 feet apart, with trees 10 feet
apart within rows. Throughout the orchard, specific sets of rows were configured with single-line, double-line and triple-line irrigation treatments, with each line having the same flowrate so that double-line treatments received double applied water and triple-line treatments received triple applied water. Within each drip line the distance between emitters was 42 inches (106.68 cm).

Soil samples were collected from each drip irrigation treatment during August 2018. In total 225 samples were collected: three treatments of drip irrigation (single-, double-, and triple-line); five replicate rows per treatment, five soil cores per row; and three depths per core (10cm, 30cm, 45cm). We extracted the soil sample by using a bulk density soil auger, and soil samples were kept within their steel sleeves (90.59 cm$^3$), sealed with plastic caps on both ends and stored in two heavy-duty plastic bags (1500 mL, Ziploc brand). Soil collection sample points were selected randomly along each line, and the distance from each soil core to the nearest tree and nearest emitter were recoded. The collected samples were stored in an insulated case under ambient temperature until they could be placed in the lab refrigerator at 4 °C (maximum time of 12 hours between collection and refrigeration). In the lab, samples were divided into two, with half used for stable isotope analysis and the other half used to estimate volumetric water content (Dingman, 2015). Half of each sample was oven dried for 24 hours at 105°C. Then, the dry weight was subtracted from the wet soil sample’s mass to compute a gravimetric water content per unit wet soil basis. This was scaled by total sample wet mass and divided by the steel sleeve's known volume. The mean bulk
density of all soil samples was 1.311 g/cm$^3$ for a single line water treatment, 1.342 g/cm$^3$ a double line water treatment, 1.335 g/cm$^3$ for a triple line water treatment.

4.4.2 Laboratory Analysis and Post Processing

The isotopic compositions, $\delta^{18}$O and $\delta^2$H, were calculated as

$$\delta^{18}$O (or $\delta^2$H) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000$$ (1)

where both standard water, $R_{\text{standard}}$ and the sample, $R_{\text{sample}}$, molar proportions are the $^{18}$O/$^{16}$O or $^2$H/$^1$H values. Isotopic compositions are conveyed in parts per thousand ($‰$). The deuterium excess ($dex$) was computed as:

$$dex = \delta D - 8 \delta^{18}O.$$ (2)

The isotopic compositions of the soil liquid was estimated with the H$_2$O liquid - H$_2$O vapor equilibration methodology (Wassenaar et al., 2008) following the methods detailed in Al-Oqaili et al., (2020), a measurement technique that is low cost and relatively quick. In brief, soils were placed into a plastic bag which was then inflated with dry air and set on the lab bench for 24hrs. We then measured the stable isotope ratio of the water vapor after which isotopic equilibrium between the air gas and the soil sample inside the headspace of a plastic bag. This technique had less exposure to evaporation compared with conventional cryogenic methods (Wassenaar et al., 2008) and uses soil samples from the same field that are oven dried and then spiked with known standards for calibration. This step simplifies calibration and reduces contamination with the lab (Mueller et al., 2014; Orlowski et al., 2016). Wang et al., (2020) and Al-Oqaili et al., (2020) noted that measurement errors were lowered if standard spiked soils have the same properties as unknown soils when estimating
isotopic compositions with liquid-vapor equilibration. For each day of sample analysis in the laboratory, we used 3 replicates of 3 internal lab standards with soil from the same field and followed the calibration procedure of Al-Oqaili et al., (2020). The $\delta^{2}H$ and $\delta^{18}O$ isotope values of internal labs standards were -113.77‰ and -15.45‰ (EH4), -40.44‰ - 6.75‰ (FJ2) and -61.90‰ -11.51‰ (CT3).

We transformed measured water vapor isotope ratios to liquid water isotope ratios presuming liquid-vapor equilibrium and attained uncalibrated values of isotopic compositions of soil water from an off-axis integrated cavity output spectrometer (OA-ICOS, Los Gatos Research, Inc. model 908-0004 OA-ICOS). The equilibrium fractionation factors were calculated based on the temperature of air around plastic bags in the lab (Horita et al., 2008: Horita and Wesolowski (1994). Calculated soil water isotope ratios were corrected following Al-Oqaili et al., (2020) based on the measurements of spiked lab standards. Day-specific corrections were assessed by computing the difference between transformed liquid soil isotope ratio measurements of the internal lab standard values with their known values, with each day’s set of lab standard measurements was used to create a linear calibration equation that was then applied to both known and unknown samples. This leads to an unbiased estimate for measured samples and accounts for day to day differences in isotope analyzer performance. Bag vapor concentrations showed a little variability between samples and we did not apply any modifications based on vapor dependence. The averages of the standard deviation for measurements errors on lab standards was 7.32‰ for $\delta^{2}H$ and 2.11‰ for $\delta^{18}O$. 
4.4.3 Soil Evaporation Fraction Estimation

Plants do not alter the concentration of the water isotopic compositions are not changed by plants when they take out water from the soil, but evaporation will do this (Ehleringer & Dawson, 1992; Wu et al., 2018; Al-Oqaili et al., 2020). Thus, differences between measured soil water isotope ratios and input soil water are attributed to fractionation occurring when water evaporates from soil surfaces only. The fraction of input drip irrigation ($I$, in mm) that was lost from soil surface as evaporation ($E$, in mm) can be computed as

$$\frac{E}{I} = \frac{\delta_I - \delta_S}{\delta_E - \delta_S},$$

where subscripts $E$, $S$ and $I$ refer to the isotope ratio of evaporation, soil liquid, and irrigation water respectively. This approach was developed by Al-Oqaili et al., (2020) to quantify evaporative losses from various sprinkler irrigation configuration based on a mass balance of the rare and abundant stable isotopes of water in the soil column.

We obtain the value of $\delta_S$ for use in equation (3) from the lab analysis of soil samples. The value of $\delta_E$ was calculated based on the model of Craig and Gordon (1965) as

$$\delta_E = \frac{\delta_S/a_{s,L/V} - h_A \delta_A - \varepsilon - \varepsilon_K}{(1-h_A') + \varepsilon_K},$$

Where $a_{s,L/V}$ is the equilibrium fractionation between phases (liquid and vapor), $h_A'$ is the relative humidity standardized to the evaporating surface, $\delta_A$ is the isotopic compositions on atmospheric vapor, $\varepsilon$ is the kinetic isotopic fractionation. Microclimate parameters such as air temperature and relative humidity were taken from the CRVO AgriMet weather station. Monthly precipitation isotope ratio estimates from the Online Isotopes In Precipitation Calculator
were used to determine the local meteoric water line and atmospheric water vapor was assumed in isotopic equilibrium with the average of monthly precipitation isotope estimates. The value of $\delta_E$ was estimated as the intersection of the local meteoric water line and the line connecting the average value of $\delta_S$ and $\delta_E$ across all soil samples (Bowen 2018), with $\delta_I$ values found to be -135.67‰ and -18.08‰ for $\delta^2H$ and $\delta^{18}O$.

4.4.4 Statistical Analysis and Modeling

For collected samples from the single- and double-line drip irrigation treatments we evaluated the response of four variables: soil volumetric water content, soil water $\delta^2H$, soil water $\delta^{18}O$, and $E/I$ ratios in to landscape position and treatment by using a Linear Mixed Effects Model (LMEM). Through this LMEM approach, the expected change in the response variable per change in forcing variable is expressed as fitted slope parameter with an associated significance (Al-Oqaili 2020). In this analysis a separate LMEM was developed for each response variable as a function of 4 fixed effects: the irrigation treatment (single vs. double), sample depth, the distance to the nearest tree, and the distance to the nearest drip nozzle. Samples were nested with cores by specifying these a variance component. Models were fit using Python’s (V.2.7) Statsmodels module (Seabold et al., 2010). Additionally, we assessed the similarly of means of collected samples with significance at the 0.1, .05, and .01 levels (labeled as *, **, and *** in Figures) based on standard t-tests.

4.5 Results

4.5.1 The distribution of soil water content variations
In general, the soils were wetter under the double-line drip irrigation treatments, with an average water content of 0.31 cm³/cm³ in the double-line treatments as compared with 0.28 cm³/cm³ in the single-line treatments. Throughout the soil profile, the soil water content ranged from 0.08 cm³/cm³ - 0.68 cm³/cm³ for the single-line treatments and from 0.10 cm³/cm³ - 0.46 cm³/cm³ within the double-line treatments. Based on the results in Table (4.1) and shown Figure (4.1), the soil water content differences between the single and double drip irrigation treatments strongly significant at depths 10 cm and 30 cm, and we found the soils from the double-lines were generally more moist than the single line at all three layers, including 45cm.

**Figure 4-1: The boxplots for the median and average of the soil volumetric water content (VWC, cm³/cm³) at the single and double irrigation lines designs, under three layers of the depths (10cm, 30cm and 45cm). The average of the value was marked by square, however, the differences between means were pointed with * for p<0.1, ** for p<0.05 and *** for p<0.01 as significant.**

The LMEM model was able to reasonably describe the variability in observed soil moisture (r²=0.51) with root mean squared error of 0.06 cm³/cm³. Based on the LMEM,
shifting from double-line to single-line drip irrigation designs resulted in a statistically significant expected decrease in soil moisture of 0.037 cm³/cm³ ($p > 0.00$). Depth was not found to be significant predictor of volumetric water content ($p = 0.34$), suggesting that there was little vertical variation in the total amount of water relative to variation across samples. As sample collection locations were father from nozzles, the volumetric water content decreased ($p=0.00$). Similarly, as sample collections were farther from the nearest tree, the volumetric water content increased ($p = 0.03$).

Table 4-1: Mean and standard deviation (in parentheses) of the water content of the soil samples, stable water isotopes composition for Single Drip Irrigation and Double Drip Irrigation at three depths.

<table>
<thead>
<tr>
<th>Drip Irrigation designs</th>
<th>10 cm Depth</th>
<th>30 cm Depth</th>
<th>45 cm Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Content (cm³/cm³)</td>
<td>Soil Water $^2$H/$^1$H (%o)</td>
<td>Soil Water $^18$O/$^16$O (%o)</td>
</tr>
<tr>
<td>Single Drip Irr.</td>
<td>0.27 (0.08)</td>
<td>-90.51 (15.26)</td>
<td>-9.05 (2.96)</td>
</tr>
<tr>
<td>Double Drip Irr.</td>
<td>0.32 (0.06)</td>
<td>-87.33 (8.18)</td>
<td>-7.69 (1.51)</td>
</tr>
</tbody>
</table>

4.5.2 Isotope ratios distribution within the soil layers

Soil water samples collected from the study area fell along a general local evaporation line (LEL, Figure 4.2) though there was variation in measured isotope ratios between treatments and with sample location. Tables 4.1 and Figure 4.3 show the findings of the isotopic compositions of the soil by layer and treatment. Differences between measurements were found to be significant at all depths except at 10cm for $\delta^2$H, which broadly confirms the hypothesis that isotopic compositions might provide an insight
into the fraction of water inputs lost as nonproductive soil evaporation. In general, the single-line treatments had waters that were more enriched in heavy isotopes, with an average value $\delta^{2}H$ and $\delta^{18}O$ value of $-104.41‰$ and $-10.46‰$ in the single line and an average value of $-112.47‰$ and $-11.22‰$ in the double-line. At 10 cm in the soils within single-line drip irrigation, the highest value of the $\delta^{2}H$ isotopic compositions $-47.63‰$ was found (and $-0.74‰$ for $\delta^{18}O$) while the lowest value of the same soil variables was $-144.49‰$ (and $-15.26‰$) was under double-line drip irrigation at 45 cm.

Within all observations of the soil samples at the study area, there was one unique LEL fit because a single water source was used and the drip irrigation of both single and double lines had the same environmental factors (Figure 4.2). Changes in the magnitude of water lost as evaporation shifts the proportional distances along the LEL. The values of the water isotopic compositions in the double drip irrigation at depth 45 cm were nearest to the source water on the LMWL line than all values of the single drip irrigation at depth 45 cm or other depths. Overall, the soil samples of single drip irrigation were farther off the LEL than soil samples of double drip irrigation design (Figure 4.2).
The Linear Mixed Effects Model was able to capture variation in $\delta^2$H and $\delta^{18}$O well, with $r^2$ values of 0.61 and 0.55, respectively. Again, treatment was a highly significant predictor of soil water isotope ratios, with changing from double- to single-line treatment associated with an increase of 8‰ ($p=0.00$) and 0.74‰ ($p=0.01$) for $\delta^2$H and $\delta^{18}$O, respectively. Unlike the volumetric water content, depth was also a significant predictor of soil water isotope ratios, with a decrease of 9.8‰ ($p=0.00$) and 1.3‰ ($P=0.00$) associated with each 10cm increase in depth. Distance to the nearest nozzle or distance to the nearest tree was not a statistically significant predictors of $\delta^{18}$O ($p = 0.81$) and ($p = 0.51$), respectively. However, distance to the nearest nozzle was a statistically significant predictors of $\delta$D ($p = 0.07$) though distance to the nearest tree was not ($p= 0.13$).

4.5.3 The variations of evaporation ratio through the soil layers
We used both water isotopes ratios to calculate $E/I$, and found their resulting estimates highly correlated (Figure 4.4), with $E/I$ from $\delta^{2}$H generally larger than $E/I$ from $\delta^{18}$O. The average $E/I$ ratios were then calculated from both stable water isotopes, which will be used for the next analysis. The results from the computations showed the mean ratios of the evaporation from the soil samples under single drip irrigation was higher than double drip irrigation, with the average $E/I$ in the single drip irrigation being 20.93%, ±6.49% and the average $E/I$ in the double irrigation being 17.33%, ±5.97%. $E/I$ ratios values ranged from 5.14% to 75.67% for single drip irrigation and 3.12% to 53.05% for double drip irrigation. Across all samples, as well as at 30 and 45 cm deep, the mean of $E/I$ within soil samples had strongly significantly variation between the single drip irrigation line and double drip irrigation lines based on the t-test (Figure 4.5). The Linear Mixed Effects Model was able to represent the variability in sample $E/I$ well, with an $r^2$ value of 0.58 and a root mean squared error of 7.57%. Treatment and depth were a highly significant predictor of the fraction of irrigation water lost as evaporation, with changing from double- to single-line treatment associated with an increase in $E/I$ of 3.6% with treatment ($p=0.00$) and a decrease 6.0% per 10 cm of depth ($p=0.00$). Neither distance to the nearest nozzle nor distance to the nearest tree was not a statistically significant predictors of $E/I$ ($p = 0.43$) and ($p = 0.36$).
Figure 4-3: Boxplots for comparing between the single and double irrigation design through clarifying A) the δD values of the soil liquid, B) the δ¹⁸O values of the soil liquid, C) the d-excess values of the soil liquid. The means of the values were labeled with a diamond and the differences between means were pointed with * for p<0.1, ** for p<0.05 and *** for p<0.01 as significant.
4.6 Discussion

4.6.1 Soil moisture profile

There were significant differences in the average of the water contents between the single and double drip irrigation designs under both depths 10cm and 30cm, although we noticed more consistent water content between treatments at a depth of 45cm. Earlier work (WANG et al., 2012; Roncucci et al., 2014) found that double-line drip spacing, when compared to the single-line treatments, resulted in an increase of more than 10% of crop yield, with this increase in yield a response to rising volumes of water provided. It is clear that adding more drip lines changes the supplied water volume and the water in the root zone available to roots.

Our results showed the differences between calculations of water content were consistent under double drip irrigation at all depths (10cm, 30cm and 45cm), however, within the same treatments there was little fluctuation in water content under depths (Figure 4.1). The distribution of water content indicated through the soil column to the transfer of soil water content within depths affected by irrigation and root uptake (Han et al., 2019). Furthermore, the author did not assess the water transferred far off under the rooting zone and the percolation although the variations in soil water content that occurred between the single and double drip lines, it might change volumetric water contents in the soil column. (WANG et al., 2012) found the soil matric potential of both the single and double line designs was mostly nearer to threshold value of soil matric potential. Both the evaporation of water from the soil surface and the plant root uptake decrease the volumetric water content of soils, even though the stable water isotope ratios of soil liquid are altered during evaporation from the soil and not from root water
uptake duration of the transpiration. (Soderberg et al., 2012; Wang et al., 2012; Wu et al., 2016; Wu et al., 2017; Wu et al., 2018). Therefore, our finding that the soil water content in the single-line drip irrigation was less than the double-line treatment suggest that the single line cannot supply sufficient water for all transpiration and evaporation demand. This is also supported by noting that the double drip irrigation had increased yields (the yield from Single 2742 lbs./ac and from Double 2856 lbs./ac).

Figure 4-4: The distribution of the stable water isotopes for all soil observations within the single and double irrigation lines at the Hazelnut farm area in 2018 and the line in the dual-isotope plot was the local water metallic line LWML.

4.6.2 Stable isotope Tracers
At both drip irrigation designs, the stable water isotopes displayed distinctly decreasing (i.e. more negative) isotope ratios with depths (Figure 4.3). In our research, drip irrigation designs as a statistically significant indicator of isotopic composition ratios; this was attributed to variations in drip irrigation designs and the magnitude of irrigation. Furthermore, both drip irrigation designs were influenced by microclimate such as a local of the wind, which generates a local dry condition. All the soil observations of the stable water isotopes values within soil profile for this study were mainly further down the local meteoric water lines (LMWL); therefore, we conclude that there is a robust fractionation of evaporation impact on soil water isotopic compositions during the summer season between the drip irrigation designs (Figure 4.2). At both 30cm and 45cm depths, the soil samples from the single drip and double drip displayed higher variations in enrichment (Figure 4.3). The differences in a water volume of distributions and the water amount of drip irrigation between single line and double line designs altered the magnitude of evaporation and consequently, stable water isotopes were enriched within the root zone. Our findings might be used for additional scientific research to investigate the impact of distinct variables and the detailed mechanisms including the isotopic compositions under different soil layers and to understand the nexuses at the different microenvironment root uptake conditions (Al-Oqaili et al., 2020).
Figure 4-5: The E/I value within the single and double drip irrigation design under both soil profile and three layers, which was represented in boxplots for hazelnut farm area. In addition, the mean values were pointed with as a diamond, while the differences between means were pointed with * for p<0.1, ** for p<0.05 and *** for p<0.01 as significant.

4.6.3 Evaporative Losses

Figure 4.5 shows the results of using the isotopic composition measurements to calculate evaporation ratios. E/I ratios are largest at the soil surface and decrease with depths, with these ratios caused by having soil moisture more depleted in heavy the oxygen or hydrogen isotopes (Horita et al., 2008; Al-Oqaili et al., 2020). During this decade (Soderberg et al., 2012; Al-Oqaili et al., 2020) have used isotopic composition in combination with local weather factors such as relative humidity and temperature at
the soil surface for adjusting the models to compute the soil water loss as evaporation. In this study, we used only one combination of meteorological conditions that covered both drip irrigation designs throughout the entire field. Although this study carried out in an open field that drives fully mix the atmospheric parameters, it was possible that local microclimate differences occurred. Unfortunately, we did not measure the temperature of the hazelnut leaf to calculate the differences between crops and canopy, which might differ between drip irrigation designs whether the transpiration rates higher at any drip irrigation design.

Table 4-2: The average of E/I percentage for Single Drip Irrigation and Double Drip Irrigation at three depths and soil profile.

<table>
<thead>
<tr>
<th>Drip Irrigation designs</th>
<th>10cm Depth</th>
<th>30cm Depth</th>
<th>45cm Depth</th>
<th>All Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E/I % (O¹⁸) of evap.</td>
<td>E/I % (D/H) of evap.</td>
<td>E/I % (O¹⁸ &amp; D/H) of evap.</td>
<td>E/I % (O¹⁸) of evap.</td>
</tr>
<tr>
<td>Single Drip Irr.</td>
<td>24.33 (10.49)</td>
<td>34.98 (16.57)</td>
<td>29.65 (13.26)</td>
<td>17.99 (1.95)</td>
</tr>
<tr>
<td>Double Drip Irr.</td>
<td>28.34 (5.47)</td>
<td>36.95 (8.54)</td>
<td>32.65 (6.76)</td>
<td>14.97 (2.29)</td>
</tr>
</tbody>
</table>

From (Table 4.2, Figure 4.5), the results of this study show that E/I is greater in the single-line treatment compared with the double-line drip irrigation treatment. As we mentioned above, the atmosphere factors had the same impact on all drip irrigation designs, and accordingly each location was likely exposed to similar evaporation demand at the surface. The addition of more water with double-line treatments resulted in more water overall throughout the soil profile. Because more soil evaporation occurred at the surface relative to deeper depths, the increase in evaporation at the surface was offset by even larger increases in root uptake at lower depths. Thus, in the
case of drip irrigation in this hazelnut field increasing the number of drip lines increased 
the overall efficiency of the system, when efficiency is defined as the amount of applied 
water taken up by the hazelnut trees.

Figure 4-6: Linear Mixed-Effects Model (LMEM) used to identify the significant 
differences between the soil water content; the soil isotopic compositions and soil 
E/I under the single and double drip irrigation designs
4.7 Conclusions

During the summer of 2018 at a Hazelnut farm in the Willamette Valley of Oregon, US, we used measurements of stable water isotope ratios in soil water to quantify the differences in the fraction of applied water that evaporated from within different drip irrigation designs. The analysis found differences in the volumetric water content as well as the $\delta^2$H and $\delta^{18}$O isotope ratios between the drip irrigation designs and quantified the evaporation under depths. The findings were indicated that there were less evaporation losses as a fraction of total water applied occur from double-line drip irrigation treatments. This conclusion is based on highly significant differences in isotopic compositions distributions between the single and double drip irrigation designs within the top layer of the soil. Moreover, the drip irrigation efficiencies in our study were provided via the supervision values of optimum irrigation practices.

4.8 Acknowledgements

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5 General Conclusion

The aim of our work that estimated the variations for stable water isotopes and quantified the differences of the evaporation under various irrigation designs. Our work in this dissertation has modified the computation of the quantification of the evaporation based on the steady state through three projects for three years. The differences between the two irrigation designs that supplied water to crops were quantified via using the isotopes analysis results. Significantly, high variations were recorded in δD and δ¹⁸O distributions between the LESA and MESA systems near the soil surface, with MEAS systems indicating higher E loss. Under MESA systems at all sites, the soil’s surface water amount demonstrated greater fluctuations. The average evaporative losses at the soil profile for Christmas Valley, OR were 20 % for LESA and 30 % for MESA, Dufur, OR were 3 % for LESA and 4 % for MESA, Maupin, OR were 21 % for LESA and 35 % for MESA, and Pasco, WA were 21 % for LESA and 48 % for MESA. Our results were useful for understanding evaporative water loss dynamics for traditional center pivot irrigation (MESA) and more modern center pivot irrigation approaches, such as LESA. Additionally, this work supplies guidance on optimizing the irrigation strategies for reducing water consumption and herewith improving the water use efficiency under different crop areas that irrigated with sprinkler irrigation systems in the Eastern Cascade region. In the second study, the evaporation as a fraction of water applied from different locations within a furrowed agricultural system, which is estimated by using the same technique used in first study. The findings showed highly significant variations in δD and δ¹⁸O distributions between the row and interrow locations within the upper layer of the soil, with interrow locations
having on average fewer evaporation losses. The mean of evaporation under the soil profile within the day irrigated field for row and interrow estimated $E/I$ (mean ± standard deviation) when combined the three months were 15.56% ± 5.19%, and 11.21% ± 3.89%, and for the night irrigated field the rows and interrows were estimated $E/I$ were 14.14% ± 8.29% and 9.22% ± 3.41%, respectively. Thus, in both fields the rows experiences more evaporation relative to inputs. The results are useful for scheduling classic irrigation (day) and shifting time of irrigation to (night) under interrow and row irrigation designs through quantifying the dynamics of water losses from the soil surface as evaporation. Moreover, this study provides core values of irrigation efficiencies that have an advantage for optimizing agricultural management for reducing water consumption. Finally, in the third study, the analysis found differences in the volumetric water content as well as the $\delta^2$H and $\delta^{18}$O isotope ratios between the drip irrigation designs and quantified the evaporation under depths. Our results were indicated that there were less evaporation losses as a fraction of total water applied occur from double-line drip irrigation treatments. The conclusion of this study was based on highly significant differences in isotopic compositions distributions between the single and double drip irrigation designs within the top layer of the soil. Furthermore, the drip irrigation efficiencies in our study were provided via the supervision values of optimum irrigation practices.
6 Bibliography


