

May 2018

Evaluating Ecohydrological Separation with Geochemical Tracers, $\Delta 2\text{H}$ and $\Delta 18\text{O}$, from Northern California in an Irrigated and Semi-arid Setting

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EVALUATING ECOHYDROLOGICAL SEPARATION
WITH GEOCHEMICAL TRACERS, $\delta^2\text{H}$ AND $\delta^{18}\text{O}$,
FROM NORTHERN CALIFORNIA IN AN IRRIGATED AND SEMI-ARID SETTING

by
Erin Emily Bulson

A Thesis Submitted in
Partial Fulfillment of the
Requirements for the Degree of

Master of Sciences
in Geosciences

at
The University of Wisconsin-Milwaukee
May 2018

ABSTRACT

EVALUATING ECOHYDROLOGICAL SEPARATION WITH GEOCHEMICAL TRACERS, $\delta^2\text{H}$ AND $\delta^{18}\text{O}$, FROM NORTHERN CALIFORNIA IN AN IRRIGATED AND SEMI-ARID SETTING by

Erin Emily Bulson

The University of Wisconsin-Milwaukee, 2018
Under the Supervision of Professor Erik Gulbranson

The two water worlds hypothesis challenges the widely accepted ecohydrology tenet that plant roots access a single, homogeneous reservoir of soil water (McDonnell, 2014). This project aspired to advance the understanding of the two water worlds, or ecohydrological separation (ES) of soil water reservoirs, applied to an irrigated agricultural setting. This study also aimed to correlate plant root morphology with plant water uptake. Using geochemical tracers, $\delta^2\text{H}$ and $\delta^{18}\text{O}$, isotopic analysis of soil and plant tissue was used to evaluate irrigated plant water acquisition. Field work was conducted on two irrigated farms, Full Belly Farm and Riverdog Farm, in the Capay Valley of northern California, where the Mediterranean climate best exhibits ES. The fact that northern California is both an agricultural hub and drought-prone region makes this location a particularly interesting area to conduct precision agriculture research.

Overall, results for the original objectives of this project were inconclusive due to a lack of method development. Taking on a new direction, the redirected focus of this project aimed to use soil water isotopes to determine the pre-evaporative isotopic composition of soil water. The intersection between the local meteoric water line (LMWL) and linear regression through soil water isotopes for a given location was inferred to be the pre-evaporative soil water isotopic signature.

This research serves as a platform for future agriculture-based ES experimental designs using water isotopes. Future work can improve upon sample collection, sample processing, and isotopic analysis methods discussed in this project. With improved methodologies, future iterations of this project can work towards refining precision irrigation practices based on new understandings of soil water storage and transport in the soil-plant-atmosphere system.

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To
My family, a super support system
particularly my husband, Dave

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LIST OF ABBREVIATIONS

A.S.L.	Above sea level
ES	Ecohydrological separation
FB	Full Belly Farm
H	Hydrogen
IAEA	International Atomic Energy Agency
MESA	Medium elevation spray application
O	Oxygen
RD	Riverdog Farm
SD	Standard deviation
SDI	Subsurface drip irrigation
USDA	United States Department of Agriculture
VWC	Volumetric water content
WF	Water fraction

ACKNOWLEDGEMENTS

A big thank you to Dr. Gulbranson for introducing me to a very interesting topic and allowing me to be the first graduate student at UWM to work on this forward-thinking project. Thank you to my entire committee—Dr. Grundle, Dr. Cameron, Dr. Xu, and Dr. Gulbranson, for helping me work through a complicated topic. Also, many thanks to Dr. Fraiser and Dr. Czeck for always being so supportive.

This project would not have been possible without Full Belly Farm and Riverdog Farm allowing me to conduct field work at their properties. Thanks for facilitating a great learning experience, and a bit of an adventure.

INTRODUCTION

Global food security relies on modern farming practices such as irrigation, while the need to increase crop yields intensifies with a growing population (Cassman, 1999). For example, increased water withdrawal for irrigation will be necessary in drought-prone areas, accelerating the need to manage agricultural water resources more efficiently. Whereas technology such as drip irrigation and integration of geospatial soil maps and irrigation patterns are thought to reduce water usage, these models and applications are underpinned by standard hydrologic models of water movement and storage in soils. The classic perception of piston flow movement of water through soil has recently been challenged by isotopic approaches that demonstrate distinct geochemical separation of soil water from ambient rainfall, deemed as ecohydrological separation (ES) (Brooks, et al., 2010, Good, et al., 2015, Goldsmith, et al., 2012, Evaristo, et al., 2015). ES models suggest that distinct reservoirs of water exist within soil, with climate dictating the extent of ES. This partitioning of water confounds expectations that plants simply access a general reservoir of soil water.

Previous Work

Hydrologic connectivity research heavily relies on stable isotope analysis of H and O to distinguish between the “pools” of water utilized by plants (Gat, 1996). Previous studies on root water uptake from subsurface compartmentalized pools of water have largely focused on non-agricultural settings, absent of irrigation water as an input to the soil-plant system.

Using hydrogen isotope ratios analyses at natural abundance levels, Dawson & Ehleringer (1991) demonstrated that mature streamside trees may acquire water from more constant deeper pools as opposed to upper soil-layer water sources. Brooks et al., (2010) expanded on Dawson & Ehleringer’s study, using water-isotope data to show that trees in a

Mediterranean climate utilize water from a “tightly bound” water pool that does not engage in translatory flow or mix with “mobile” water (Figure 1). Goldsmith et al., (2011) similarly demonstrated a partitioning of soil water pools as “highly mobile” or “less mobile” in a seasonally dry tropical montane cloud forest (indicated through stable isotope analysis). Evaristo et al., (2015) increased the scope of ES research by assembling a global ecohydrological isotope database comprised of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for plant xylem water, soil water, stream water, groundwater, and precipitation on the global scale, showing global ubiquity of ES to varying degrees. Zhang et al., (2016) explored soil water residence times using tritium to suggest the possibility that apple trees access decades-old water.

ES research incorporating engineered models is in its infancy. Most recently, Oerter et al., (2017) observed partitioning of soil water into distinct pools in a seasonally drip-irrigated ornamental garden, suggesting ES is not exclusively limited to natural landscapes. Further analysis of plant water acquisition in irrigated settings is needed to better understand how crop plants consume soil water, specifically irrigation water.

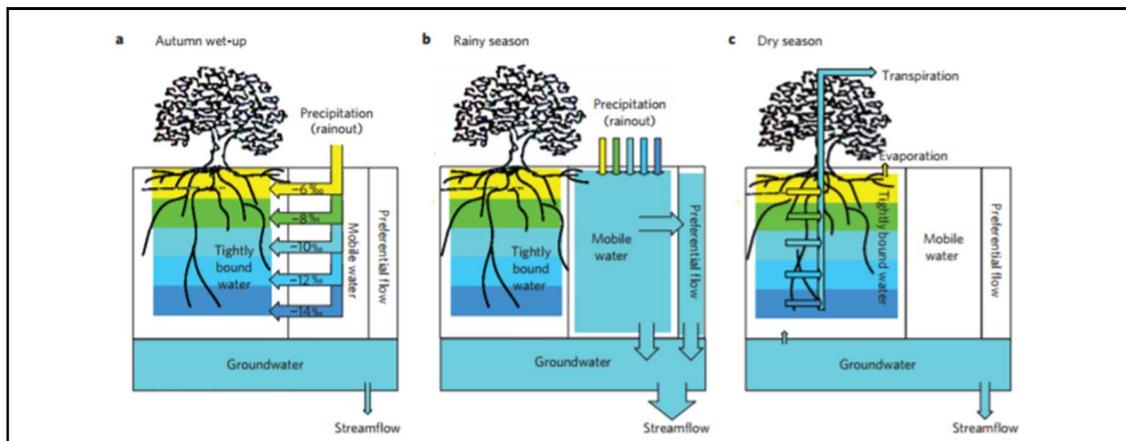


Figure 1. a. During autumn wet-up, pores within soil layers fill sequentially with progressively more isotopically depleted water as the wetting front moves to depth ($\delta^{18}\text{O}$ values shown) and the rainout process occurs during a large soil-wetting event. b. During the winter rainy season, precipitation moves through the soil profile through larger pores and preferential flow paths. c. During the dry summer, large pores drain, emptying mobile and preferential flow paths. The remaining soil water is tightly bound within small pores and used by plants for transpiration (Brooks, et al., 2010).

Hypotheses

The objective of this study is to evaluate whether plant water acquisition can be precisely determined for specific crops. The intention of this study was to address four hypotheses:

- 1) Plants access distinct reservoirs of water within soil based upon age-dependent growth needs.
- 2) Plant water acquisition is influenced by the unique hydrology of soils that are governed by soil texture and landscape position.
- 3) The loci of plant water uptake cannot be predicted from measurement of soil moisture status in soil surface horizons.
- 4) Plant root morphology has a direct impact on the loci of plant water uptake.

To test these hypotheses, several crops with different root morphologies and phenologies were selected from a study region hosting similar soil types (relatively young, fertile soils lacking horizon development) under a Mediterranean climate (warm, dry summers and cool, wet winters). Samples of soil water at consistent depth intervals and water extracted from root tissue, or suberized tissue of woody plants, were used to determine if the isotopic composition of the soil moisture and xylem water can indicate precise soil depth intervals where plant water uptake is maximized. These results are worth considering for precision agriculture applications in regions prone to drought and water stress.

BACKGROUND

Two neighboring farms, Full Belly Farm and Riverdog Farm, were selected for this study. The farms are situated in Guinda, California, in the Capay Valley within the southeastern region of the northern California Coast ranges (38.8292° N and 122.1929° W; ~ 110 m a.s.l.) (Fig. 2).

Capay Valley is part of the Cache Creek Drainage Basin, and both farms are located along the meandering portion of Cache Creek (Fig. 3). Fully Belly Farm and Riverdog Farm are mid-size, organic farm operations, covering 400 acres and 450 acres, respectively.

Capay Valley primarily consisted of a thick oak forest prior to agricultural development (Andrews, 1972). Presently, agricultural use dominates the valley, which hosts twenty-three farms and ranches. The varying soil fertility of the valley segregates land use. The rich, creek-bottom floodplain soil areas are covered by nut-tree orchards and row crops, while livestock is allocated to the less fertile segments of the valley.

A mix of stream water and well water is used for irrigation. Crop (asparagus, chard) samples evaluated in this study were subject to subsurface drip irrigation (SDI), while the orchard (almond) samples considered were irrigated using medium elevation spray application (MESA) (Fig. 4). The SDI systems at FB and RD were buried at roughly one-foot depth, while the MESA systems at FB and RD consisted of hoses with spray nozzles suspended roughly six feet high above the ground.



Figure 2. Aerial photograph of Capay Valley.

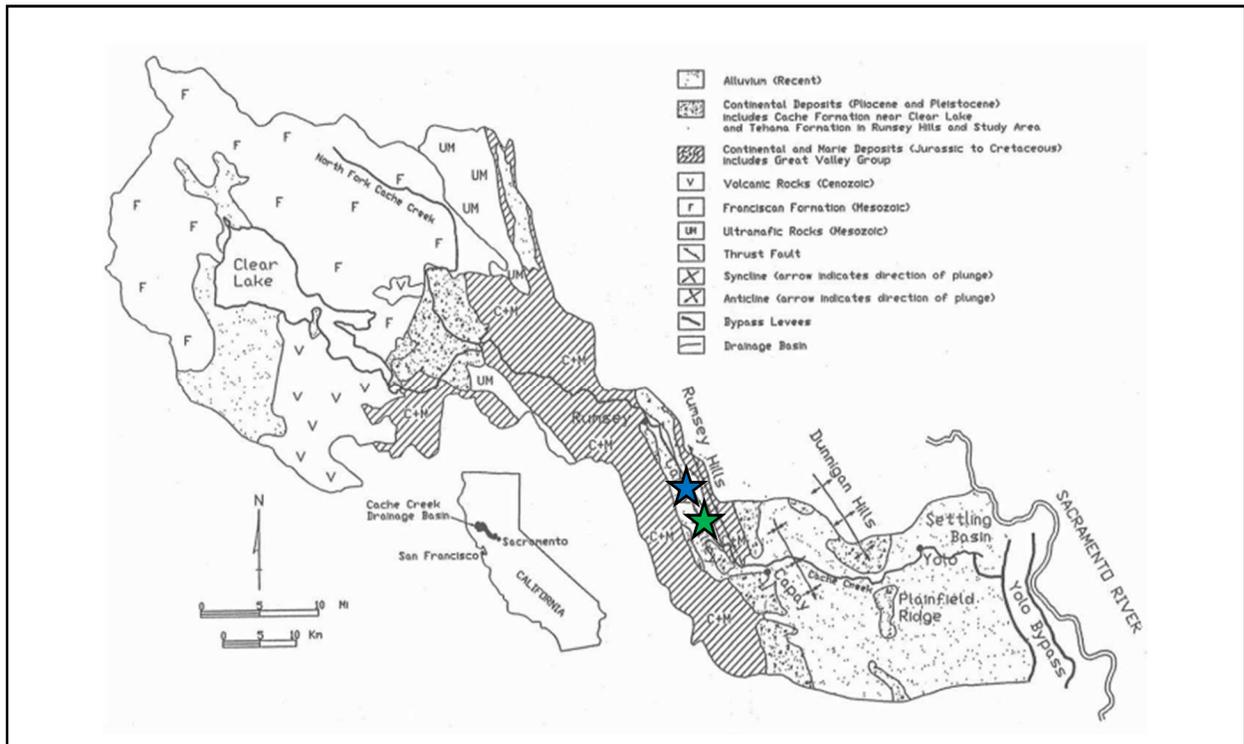


Figure 3. Geologic map of location of research within the Cache Creek Drainage Basin. Blue and green stars denote Full Belly Farm and Riverdog Farm, respectively. (Modified from YCRCD, 2010)



a.



b.

Figure 4. Irrigation systems used at Full Belly Farm and Riverdog Farm. a. Subsurface drip irrigation system used in asparagus crop, buried one foot below surface. b. Medium elevation spray application irrigation system used in almond orchard, hung roughly six feet above ground.

Soils

The soils considered in this study are derived from the fluvial processes of Cache Creek, which experiences periodic flooding of varying severities (Harmon, 1989). The many faults and folds associated with the San Andreas Fault System dictate the morphology and migrating path of Cache Creek (YCRCD, 2010). The Capay Valley hosts a series of Pleistocene-age terraces and alluvial fans (Yolo County 2030 Countywide General Plan). The segment of Cache Creek within the Capay Valley primarily functions as an agent of sediment transport, and thus presents soils derived from relatively recent alluvium (Fig. 1). The alluvial deposits are responsible for the rich soil fertility central to Capay Valley's ability to flourish as an agricultural community. The soil types sampled for this study are speculated to be Yolo and Soboba Soil Series. Both soil series are classified under the United State Department of Agriculture (USDA) soil classification system as xerofluvents—fluvial soils that are relatively young, fertile, and undergo warm, dry summers and cool, wet winters. Soil texture is the most notable difference between the two soils. The Yolo series has a fine-silty texture, while the Soboba series is much coarser (>35% coarse fragments) (Soil Survey Staff, 2017).

Climate

The Mediterranean climate of the Capay Valley is distinguished by cool, rainy winters (November-March) and warm, dry summers (April-October). The average monthly high temperature peaks in July at 97°F, with a low of 57°, while the average monthly high bottoms in January at 56°F, with a low of 35°F (NOAA, 2018). The mean annual precipitation in Capay Valley is roughly 17 inches. Precipitation at this location is strongly influenced by storms originating from the Pacific Ocean that are subject to orographic lift as they move east (YCRCD, 2010).

METHODS

Soil Analysis

Soil analysis consisted of field work to assess soil morphology and classification, comprised of digging trenches and assessing texture, color, and horizon, including depth and boundary. USDA soils maps were used as a general guide, but recognized as interpolation and not fact. Water fraction (WF) tests were carried out in the lab using the muffle furnace and scale, using Equation 1. Grain size was determined using the Malvern Mastersizer 2000 particle size analyzer in the UWM Geosciences Department.

$$\text{Eq. 1: } WF = \left(\frac{\text{Moist Soil Weight} - \text{Dry Soil Weight}}{\text{Dry Soil Weight}} \right)$$

Sample Collection

Water-isotope data was evaluated from various pools located in two farms situated in Capay Valley in the Cache Creek Watershed in northern California. Sampling consisted of soil, plant, and water samples from each sampling site for isotopic analysis. Samples were obtained from several crop locations within the two farms. Sample collection began in September 2016 and continued through June 2017. Soil was collected from 3 depths—10, 20, and 30 cm. Four crop types were collected; corn, chard, asparagus, and almond trees were selected for their varying root morphologies. Root system architectures considered are: tap roots (corn), lateral roots (chard), horizontal, vertical and somewhat fibrous roots (asparagus), and [annual] fibrous roots (almond trees). Three sites were sampled at each corn, chard, and asparagus crop. The almond orchards cover more acreage than the other crops, so we increased the number of sampling sites to six for each of the orchards. Site locations for each crop were selected to best represent any variabilities between sample sites due to changes in geomorphology and soil, such

as slope and texture. Water samples were collected from Cache Creek and irrigation water. A complete list of sample names and locations is described in Appendix A.

Samples were transported from California to the University of Wisconsin - Milwaukee in coolers filled with a combination of freezer ice packs and bagged ice. Soil and plant tissue samples were stored in sealed quart and gallon-size plastic bags at room temperature. Water samples were refrigerated and stored in 500 mL plastic media bottles.

Geochemistry

Water was obtained from plant and soil samples for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopic analysis using cryogenic vacuum water extraction, using modifications to the method described by Ehleringer, et al., (2010). The distillation modifications included increased temperature achieved through use of a heat gun (versus a hot plate), shortened extraction time (generally 15-20 minutes), and custom-designed glassware. All water samples were processed for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis via the Picarro Cavity Ring Down Spectroscopy (L2130-i) analyzer at the School of Freshwater Sciences at University of Wisconsin-Milwaukee. All $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are expressed relative to Vienna Standard Mean Ocean Water (VSMOW) in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ ‰

$$\text{Eq. 2: } \delta^2\text{H or } \delta^{18}\text{O} = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) 1,000$$

where R is the ratio of deuterium to hydrogen atoms or ^{18}O to ^{16}O atoms of the sample and VSMOW. Quality assurance was intended by following reference sample guidelines described by Jardine and Cunjak (2005). Quality control was assessed through international references VSMOW, GISP, and SLAP2.

The goal was to use a mass balance approach to determine the percentage of each soil water component (groundwater, rainwater, and drip irrigation water) derived from the equations:

$$\text{Eq. 3: } X_S \delta_S = X_R \delta_R + X_G \delta_G + X_D \delta_D$$

$$\mathbf{Eq. 4: } X_S = X_R + X_G + X_D$$

where δ_i is the stable isotopic composition, X_i is the fraction of the cryogenically extracted sample volume contributed by water source i , and S = soil water, G = groundwater, R = rainwater, and D = drip irrigation water. A linear regression can be constructed from this mass balance form, where $y = \delta_S$, $x = 1/X_S$, $m = [X_G(\delta_G - \delta_D) + X_R(\delta_R - \delta_D)]$ is the slope, and $b = \delta_D$ is the intercept (Equation 5).

$$\mathbf{Eq. 5: } \delta_S = [X_G(\delta_G - \delta_D) + X_R(\delta_R - \delta_D)] (1/X_S) + \delta_D$$

This mass balance model can be used to set up a ternary diagram depicting the isotopic composition and mole fraction of water for each of the three end-members. Plant water data can then be plotted on the ternary diagram to depict the percentage contribution of each soil water input.

RESULTS

Water Isotopes

The GMWL and soil linear regression intersection values for May 2017 range from $\delta^{18}\text{O}$ of -14.6 per mil to -9.21 per mil and $\delta^2\text{H}$ of -106.8 per mil to -63.69 per mil. The intersection values for June 2017 range from $\delta^{18}\text{O}$ of -18.09 per mil to -11.7 per mil and $\delta^2\text{H}$ of -134.72 per mil to -83.6 per mil. However, the average isotopic values for precipitation near the study site for May and June is -5.70 per mil for $\delta^{18}\text{O}$ and -35.56 per mil for $\delta^2\text{H}$, and 7.57 per mil for $\delta^{18}\text{O}$ and 50.53 per mil for $\delta^2\text{H}$, respectively. It is fair to scrutinize these results as the Lapham reference water isotope values yielded from cryogenic vacuum distillation exhibited poor precision (reported as mean \pm 1 standard deviation), as reported in Table 1. These precision values void the validity of drawing meaningful conclusions regarding source precipitation isotope values and plant water acquisition. Important to note, the reference samples were introduced to this study very late in the lab work, so reference data is limited. VSMOW, GISP, and SLAP references exhibited high precision. Precision issues are addressed in the Discussion and Future Work sections.

	n	Mean of isotope value ($\delta^{18}\text{O}$)	Precision ($\delta^{18}\text{O}$)	Mean of isotope value ($\delta^2\text{H}$)	Precision ($\delta^2\text{H}$)
Lapham Soil Water Reference	7	2.09	± 7.76	-45.86	± 30.27
VSMOW	11	0.01	± 0.046	0.12	± 0.62
GISP	11	-24.78	± 0.09	-188.69	± 0.53
SLAP2	11	-55.58	± 0.23	-428.24	± 1.23

Table 1. Precision values reported for reference waters, where n = number of replicate samples and precision is reported as \pm 1 standard deviation from the mean.

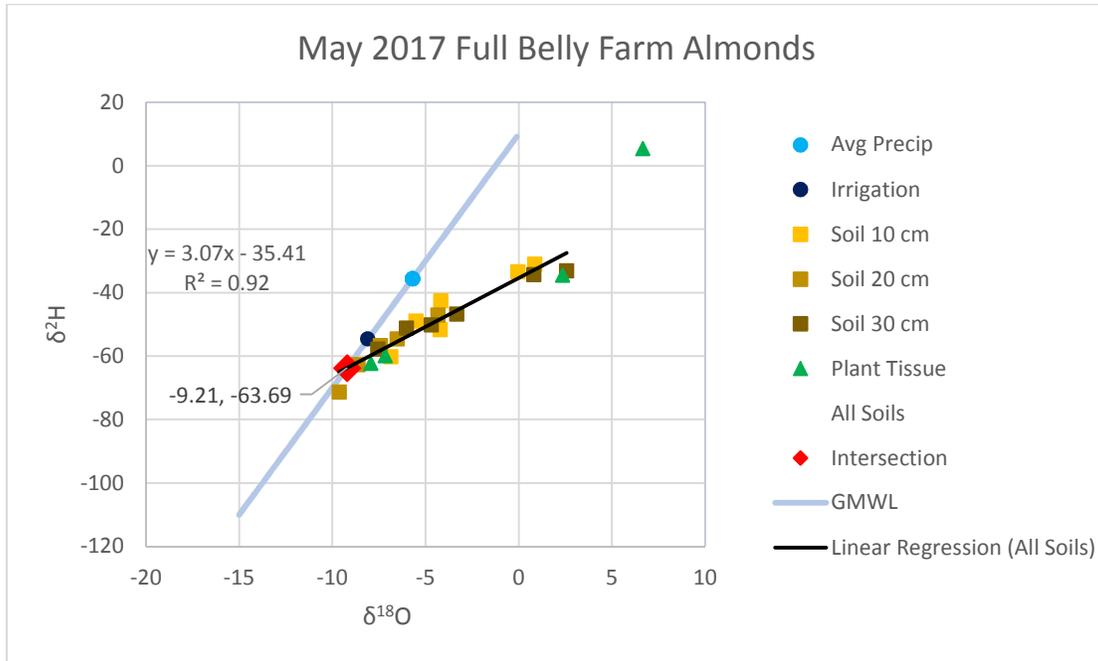


Figure 5. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Full Belly almond orchard in May 2017.

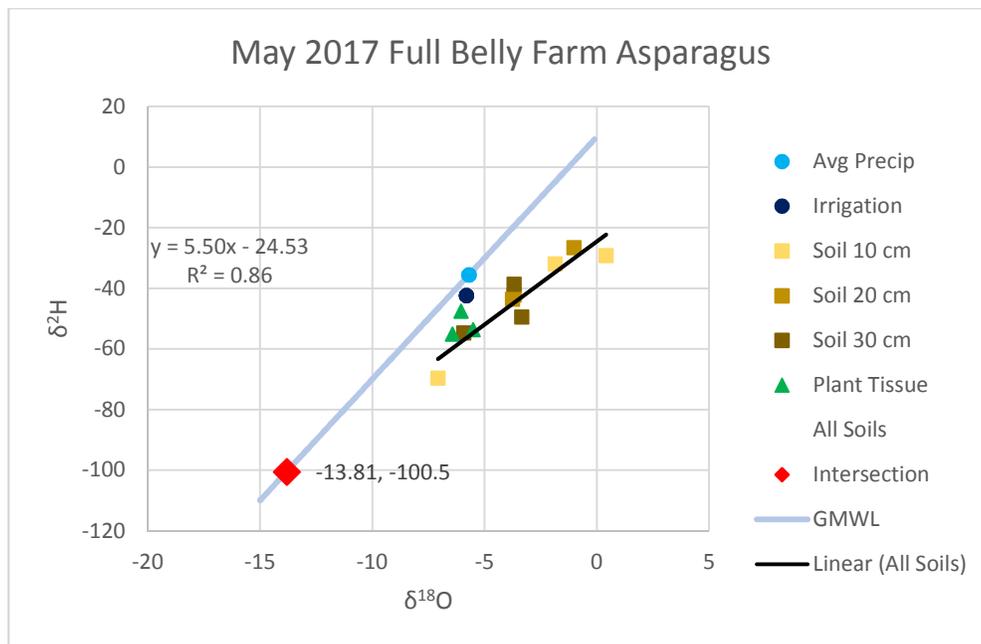


Figure 6. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from three locations within the Full Belly asparagus crop in May 2017.

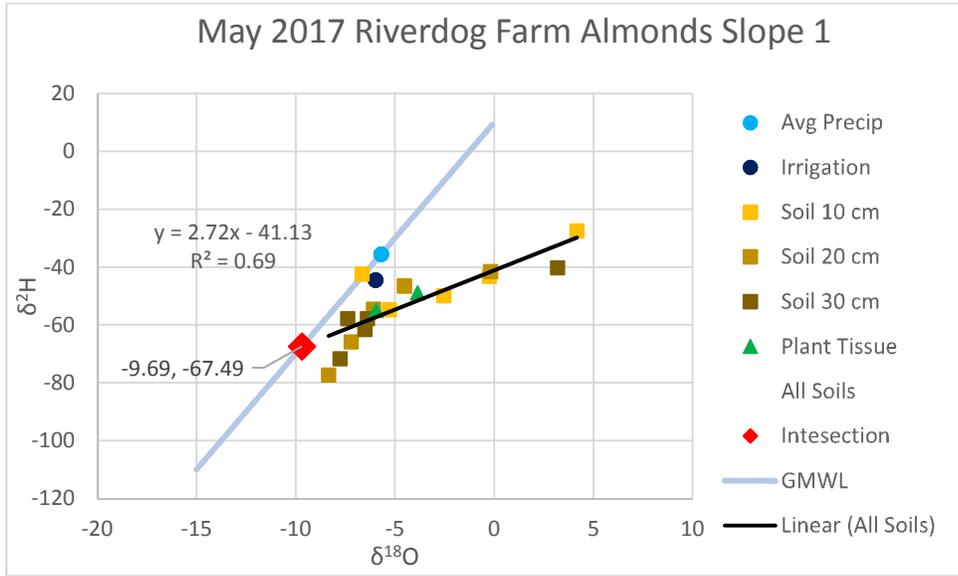


Figure 7. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Riverdog Farm almond orchard in May 2017.

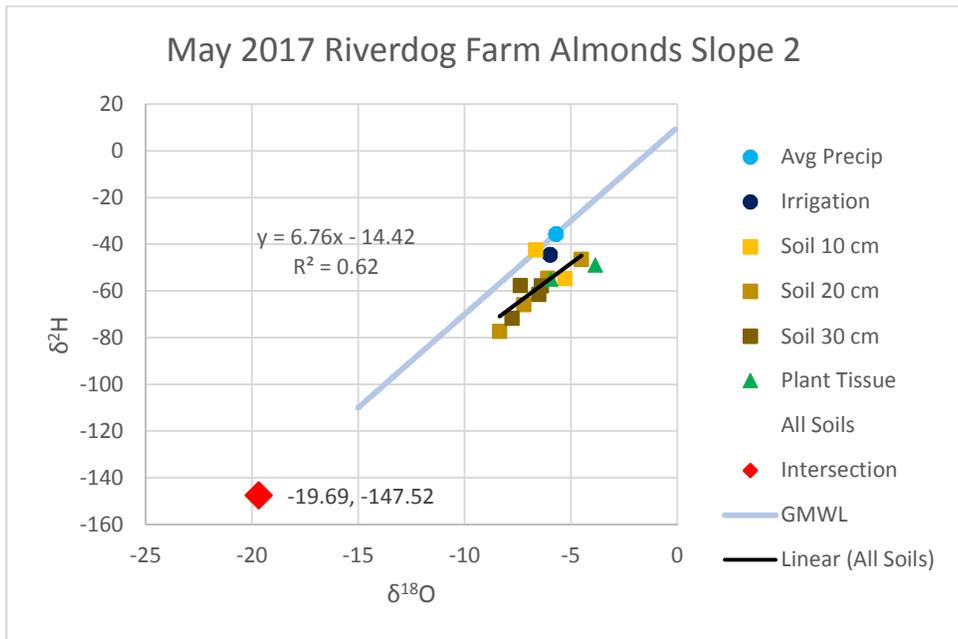


Figure 8. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Riverdog Farm almond orchard in May 2017. $\delta^{18}\text{O}$ soil water values > -4.50 per mil were excluded to exhibit a second trend in the data.

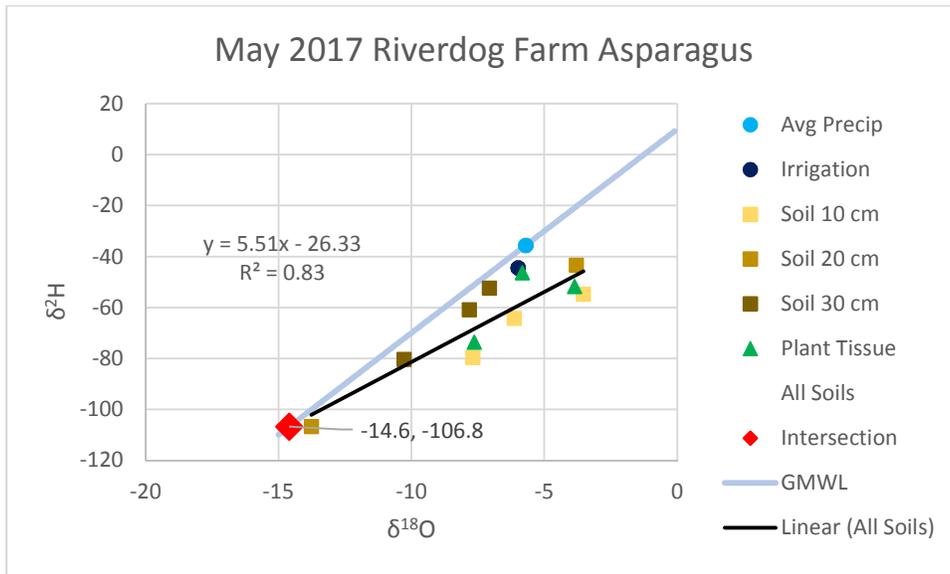


Figure 9. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Riverdog Farm asparagus crop in May 2017.

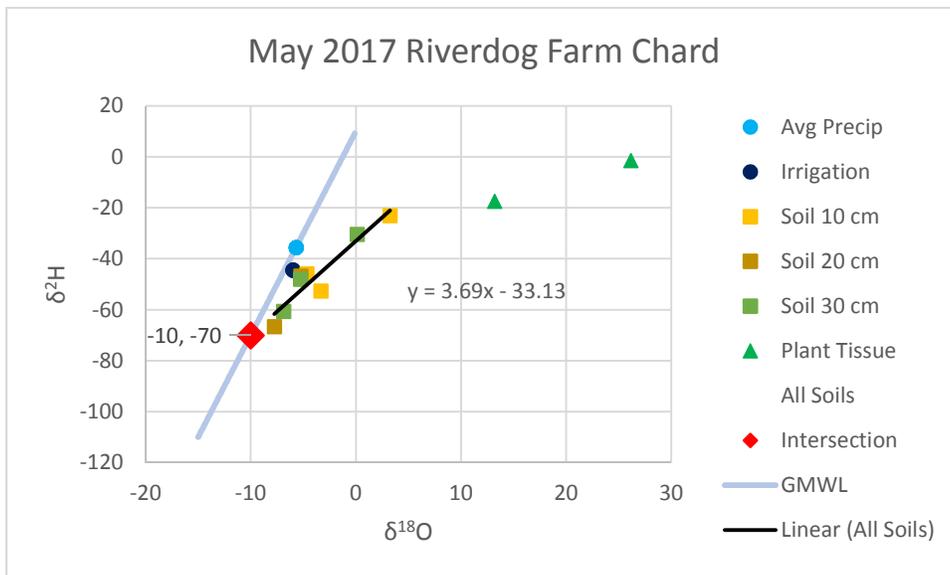


Figure 10. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from three locations within the Riverdog Farm chard crop in May 2017.

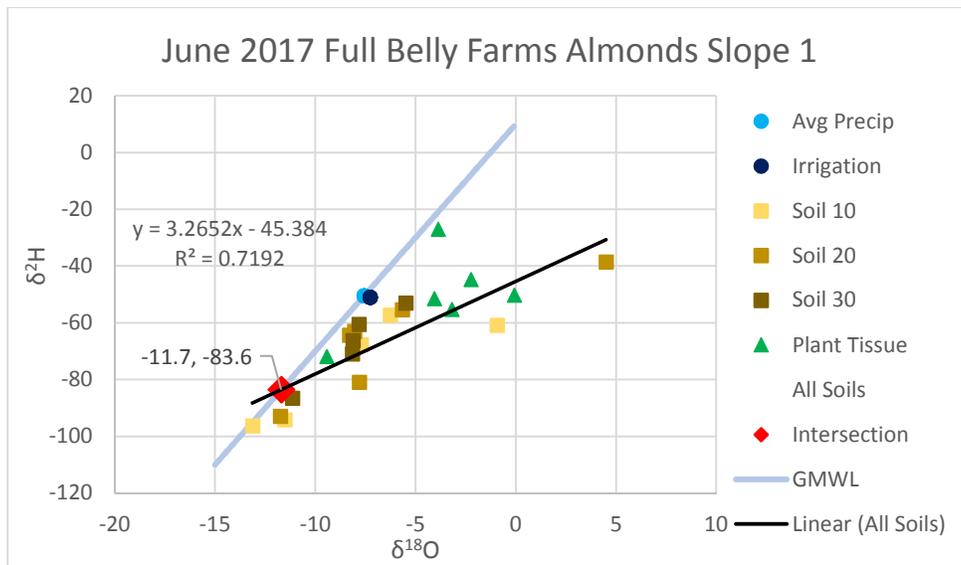


Figure 11. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Full Belly Farm almond orchard in June 2017.

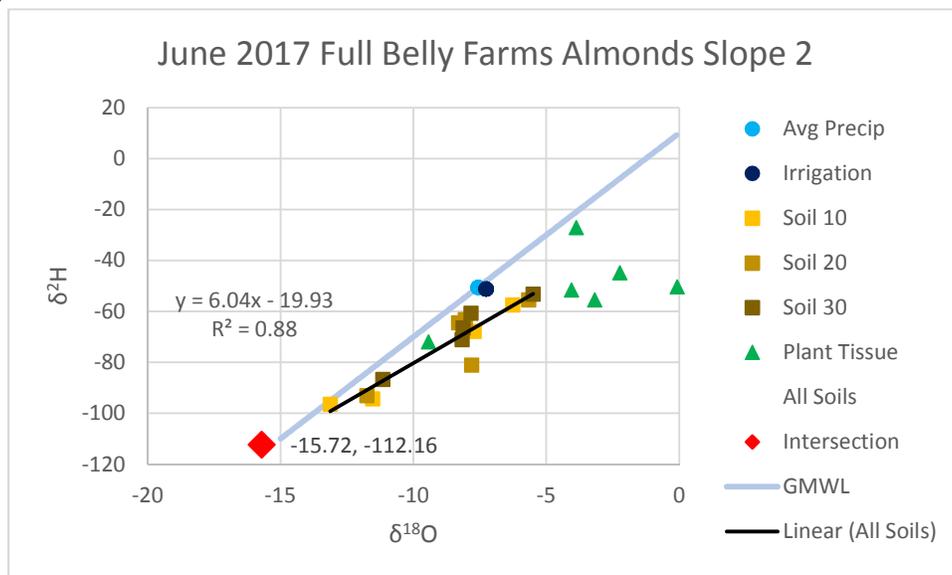


Figure 12. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Full Belly almond orchard in June 2017. $\delta^{18}\text{O}$ soil water values > -5.00 per mil were excluded to exhibit a second trend in the data.

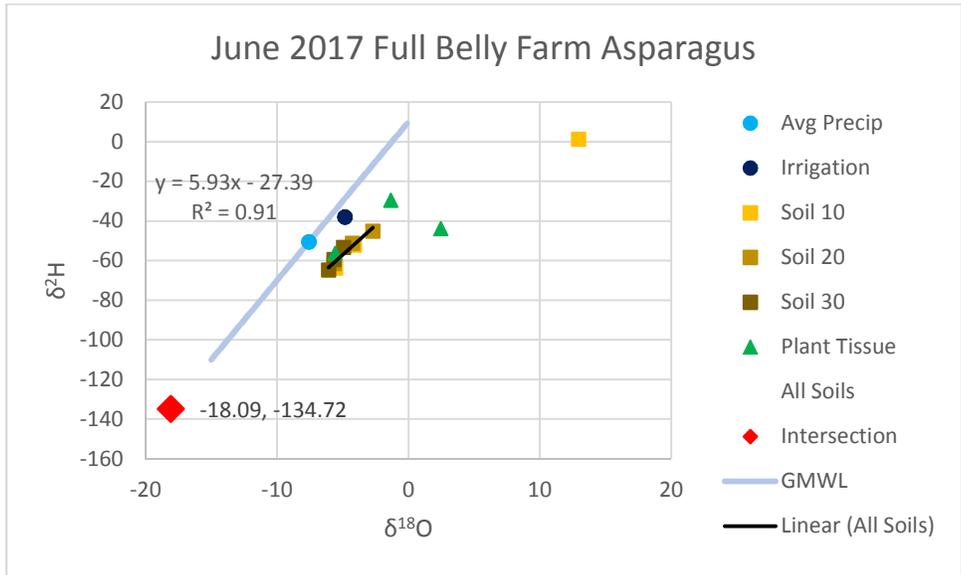


Figure 13. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from three locations within the Full Belly Farm asparagus crop in June 2017.

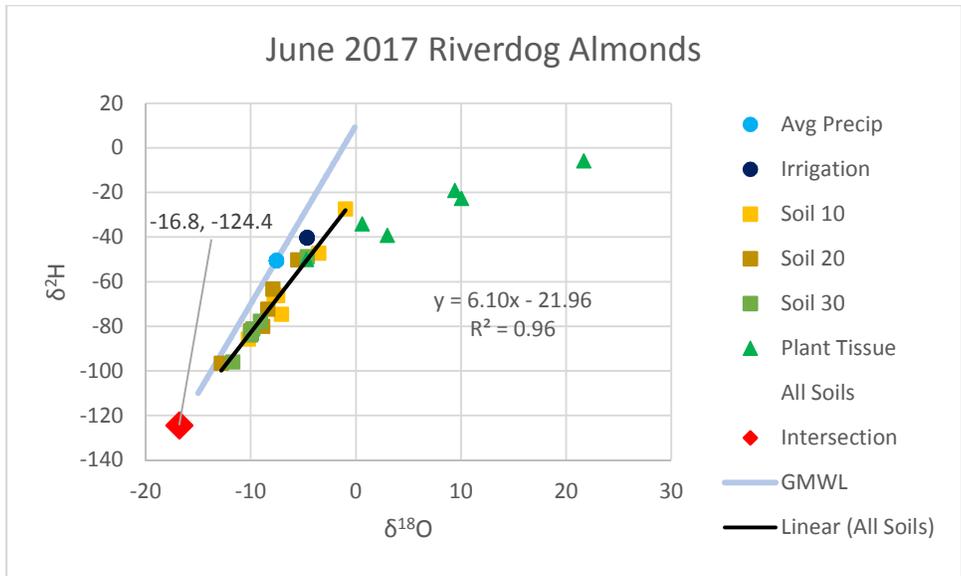


Figure 14. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Riverdog Farm almond orchard in June 2017.

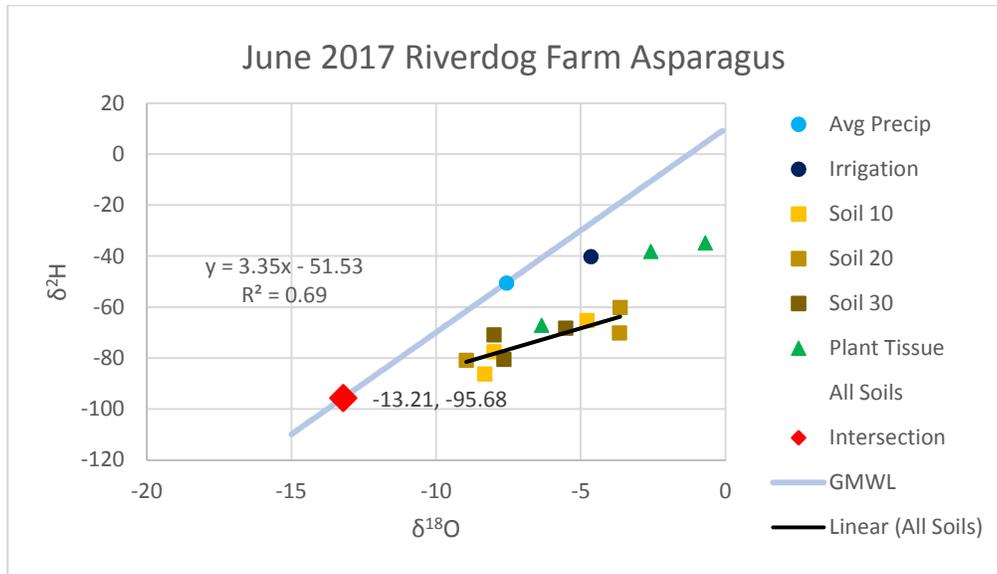


Figure 15. Water isotope values for precipitation, irrigation, soil at various depths, and plant tissue. Samples were taken from six locations within the Riverdog Farm asparagus crop in June 2017.

Crop/Orchard	Intersection of GMWL and Soil Linear Regression	Slope
May FB Almonds	(-9.21, -63.69)	3.07
May FB Asparagus	(-13.81, -100.5)	5.5
May RD Almonds 1	(-9.69, -67.49)	2.72
May RD Almonds 2	(-19.69, -147.52)	6.76
May RD Asparagus	(-14.6, -106.8)	5.51
May RD Chard	(-10.00, -70.00)	3.69
June FB Almonds 1	(-11.7, -83.6)	3.27
June FB Almonds 2	(-15.72, -112.16)	6.04
June FB Asparagus	(-18.09, -134.72)	5.93
June RD Almonds	(-16.8, -124.4)	6.1
June RD Asparagus	(-13.21, -95.68)	3.35

Table 2. Intersection of GMWL and soil linear regression, as well as slope, for all crops samples

Water Fraction

Soil water fraction range for each crop at all depths is reported in Table 2 and Table 3.

May 2017 Soil Water Fraction Ranges		
Crop	Minimum	Maximum
FB almonds	0.04	0.15
FB asparagus	0.13	0.18
RD almonds	0.08	0.20
RD asparagus	0.06	0.19

Table 3. May 2017 minimum and maximum soil water fraction values for each crop at all depths.

June 2017 Soil Water Fraction Ranges		
Crop	Minimum	Maximum
FB almonds	0.02	0.31
FB asparagus	0.11	0.17
FB corn	0.11	0.19
RD almonds	0.09	0.19
RD asparagus	0.08	0.15

Table 4. June 2017 minimum and maximum soil water fraction values for each crop at all depths.

Important to note, reported water fraction values are questionable due to sample storage methods (further considered in Discussion section).

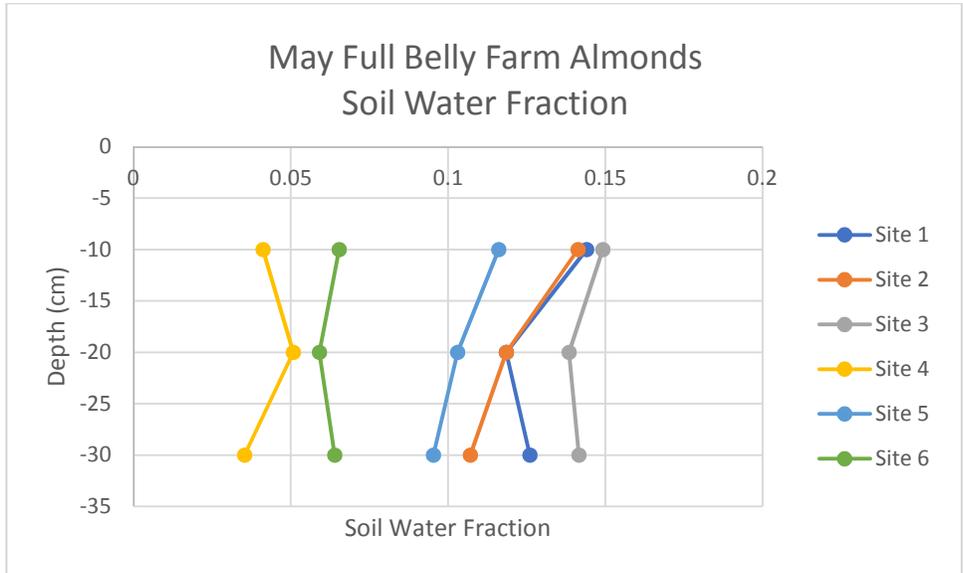


Figure 16. May 2017 soil water fractions for six locations within the Full Belly Farm almond orchard.

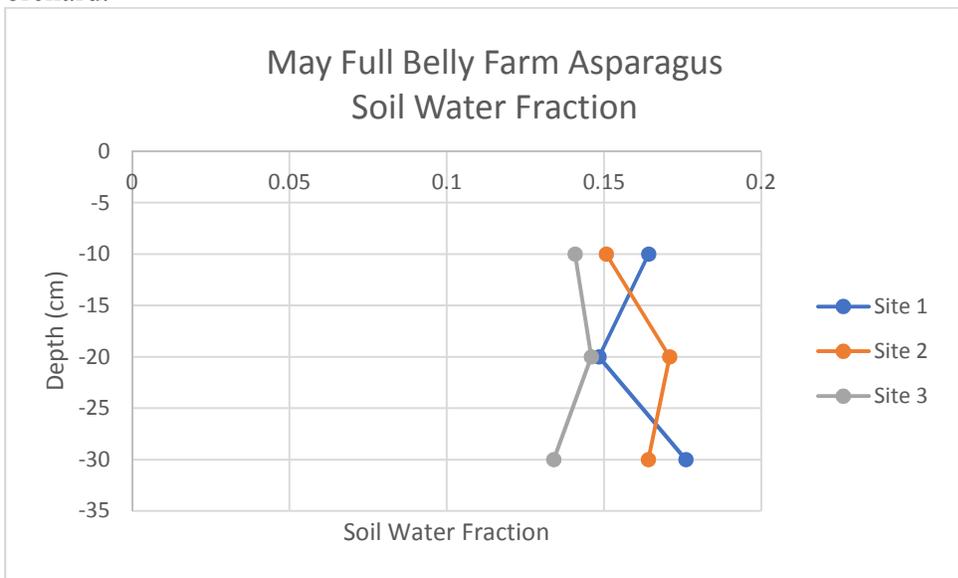


Figure 17. May 2017 soil water fractions for three locations within the Full Belly Farm asparagus crop.

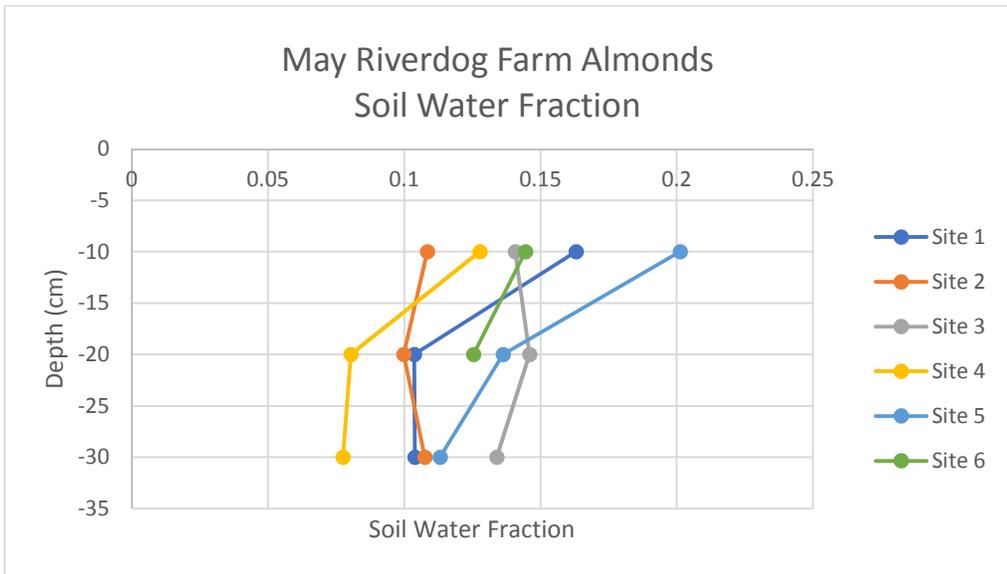


Figure 18. May 2017 soil water fractions for six locations within the Riverdog Farm almond orchard.

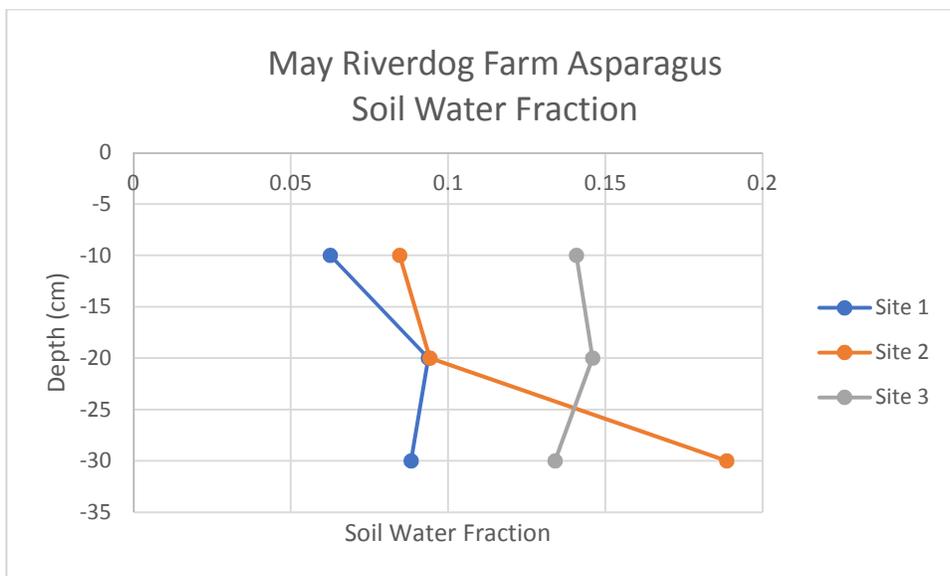


Figure 19 May 2017 soil water fractions for three locations within the Riverdog Farm asparagus crop.

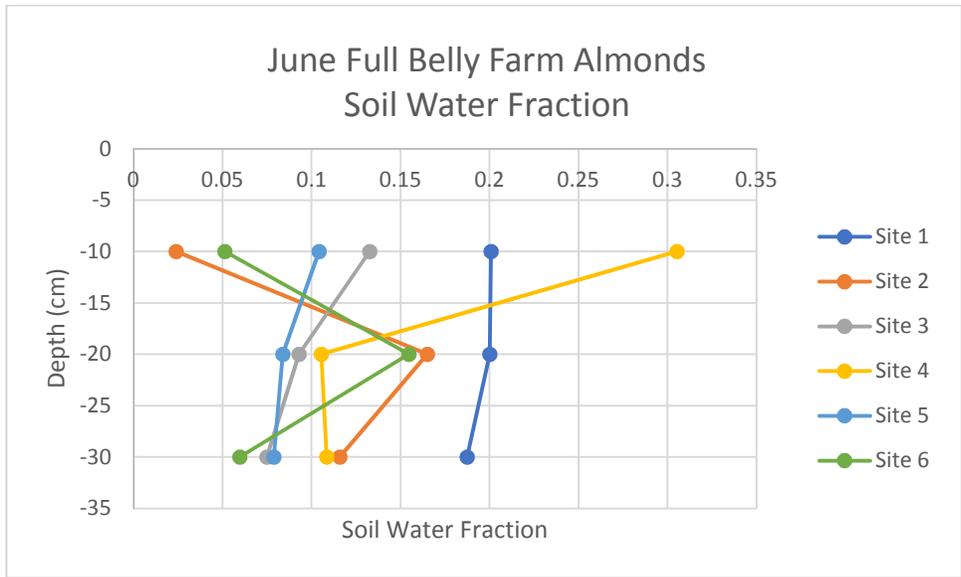


Figure 20. June 2017 soil water fractions for six locations within the Full Belly Farm almond orchard.

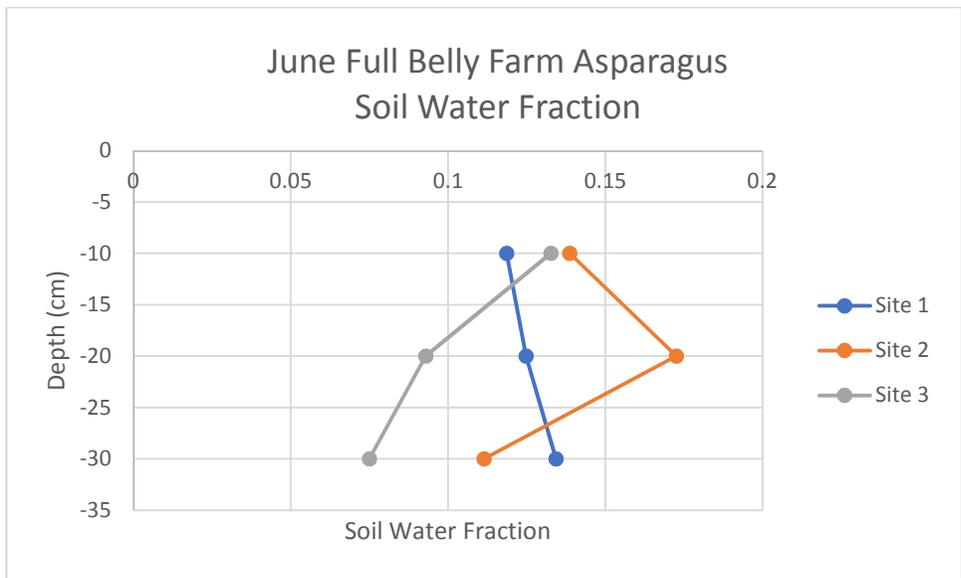


Figure 21. June 2017 soil water fractions for three locations within the Full Belly Farm asparagus crop.

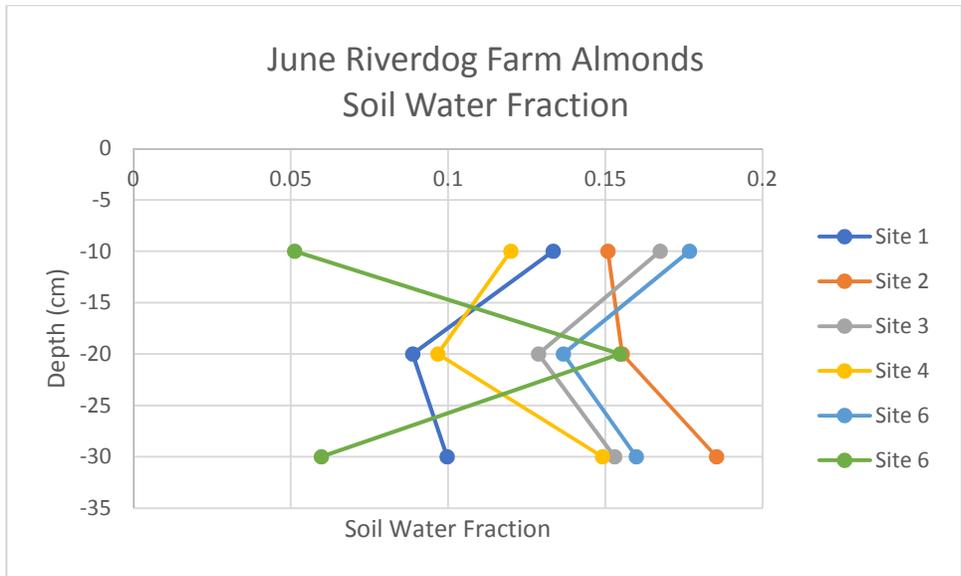


Figure 22. June 2017 soil water fractions for six locations within the Riverdog Farm almond orchard.

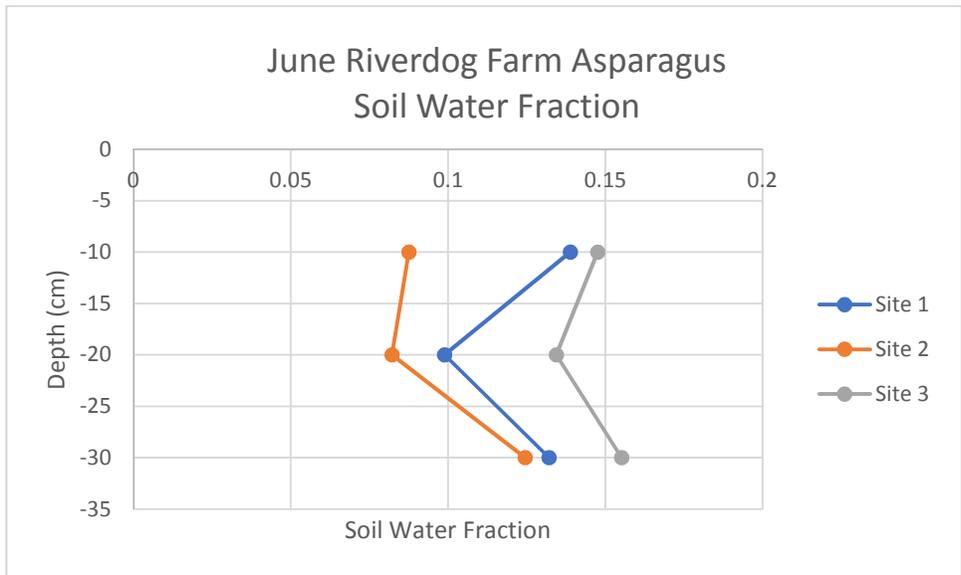


Figure 23. June 2017 soil water fractions for three locations within the Riverdog Farm asparagus crop.

Soil Textures

Soil texture analysis was completed for a limited number of sampling locations. Soil texture analysis results indicate that three Full Belly almond locations and two Full Belly asparagus locations host silt loams (**Appendices G-K**). This silt loam texture is consistent with the anticipated Yolo soils series, and further validated through visual observation on site. There was no evidence of the Soboba soil series (>35% coarse fragments) from the [limited] Malvern data. However, a coarser soil (\approx 25% coarse fragments) was observed in the field at the Riverdog Farm asparagus crop location (unable to validate % coarse fragments due to lack of Malvern data).

DISCUSSION

Water Isotopes

As expected, evaporative trends are isotopically demonstrated for all soil waters evaluated in this study (Figs. 2-12, Table 1). Extrapolating the evaporative trend to the GMWL provides a suggestion for the local rain signature for the time of year, and that the plants contain water that lies along this trend of evaporated rain. Plant tissue isotope values were generally enriched relative to soil samples, indicating greater evaporation in plant tissue than soil. The enriched isotopic values for plants are likely due to evaporation that took place in storage and/or insufficient sample processing on the water extraction line. May Full Belly Farm asparagus samples were an exception, reflecting lighter isotope values ($\delta^{18}\text{O}$ values -6.44, -6.06, and -5.32 per mil). These plant tissue samples plot closest to a 20cm soil water sample from this crop ($\delta^{18}\text{O}$ -5.92 per mil). Accordingly, if there was more confidence regarding sample integrity, and a greater number of samples for this location, one may infer that this asparagus plant accessed water at 20 cm depth.

In general, the intersection of the evaporative lines and the GMWL are very low (Table 1). Two explanations for these low δ values are 1) low temperature and/or 2) precipitation very late in the rainout (Rayleigh Distillation). Explanation 1 is highly unlikely, given the very warm California May and June temperatures. Explanation 2 is plausible, particularly if there was recently a heavy rainout. While there was not significant rain leading up to May sample collection, there was 0.52 inches of rain during June sample collection. Still, 0.52 inches does not constitute a heavy rainout (< 0.8 inches is a light precipitation event). Even so, perhaps the June precipitation demonstrates a rain event that displayed the end result of Rayleigh distillation, which was captured in the soil samples. The fact that the June intersection δ values are overall

lower than the May values may further support the idea that the end of a rainout has been captured in the June soil samples.

While most crops appeared to display one trend, May 2017 Riverdog almonds and June 2017 Full Belly almonds appeared to have two evaporative signals (Figs. 5 and 9). Explanations for this could be 1) two separate rain events, 2) one rain event and one irrigation event, 3) two irrigation events. It is difficult to determine which one of these explanations are valid, given the lack of precipitation isotope and irrigation isotope data. Precipitation isotope data is based on a single $\delta^{18}\text{O}$ value reported as a 5-year average from Vachon et al. (2010). These $\delta^{18}\text{O}$ values were plotted on the GMWL to speculate a precipitation isotope values. However, precipitation isotopes values can vary greatly, so any type of interpretation based on precipitation is not valid. Furthermore, it is difficult to assess the irrigation water content of the samples, since the irrigation source (groundwater versus stream water) and schedules are unknown. Groundwater and stream water from Cache Creek are both used for irrigation, highlighting the importance of knowing the irrigation [source] schedule. With sufficient irrigation data, it may possible to identify two separate irrigation events for the May Riverdog almonds and June Full Belly almonds.

Secondary evaporation, or the amount effect, may also be an explanation for the two different slopes. Dansgaard (1964) describes the amount effect as evaporation that occurs before rain hits the ground, when humidity is particularly low. Subsequently, a lower slope is projected for rainfall data. This phenomenon is best seen in arid climates during rainfall events that total less than 20 mm (Clark & Fritz, 1997). Guinda, California, in May and June 2017 meet the criteria of having less than 20 mm rainfall events. Humidity in May ranged from 11%-100%,

and in June 14%-100% (Weather Underground, 2018). The minimum humidity values for May and June may be sufficient for secondary evaporation to occur.

Relative humidity can also be used to interpret the soil water slopes. Gonfiantini (1986) approximated that slopes of 6.8, 5.2, 4.5, 4.2, and 3.9 indicate relative humidity at 95%, 75%, 50%, 25% and 0%, respectively. Based on Gonfiantini's approximations, May Full Belly Farm almonds ($s=3.07$), May Riverdog almonds (slope 1) ($s=2.72$), May Riverdog chard ($s=3.69$), June Full Belly almonds (slope 1) ($s=3.27$), and June Riverdog asparagus would indicate 0% relative humidity. However, relative humidity was never reported less than 11% for May 2017 and 14% for June 2017 (Weather Underground, 2018). Similarly, May Full Belly asparagus ($s=5.50$), May Riverdog almonds (slope 2) ($s=6.76$), May Riverdog asparagus ($s=5.51$), June Full Belly almonds ($s=6.04$), June Full Belly asparagus ($s=5.93$), and June Riverdog almonds ($s=6.10$), would indicate greater than 75% relative humidity. Relative humidity was reported greater than 75% several days in both May and June 2017.

In hindsight, it would have been better to have more frequent sampling and a greater sample size to work with in general. Most beneficial, more empirical data (e.g. precipitation and irrigation isotope values) would improve this study. A closer site location for this study would have made it easier to address sample collection issues. Additionally, water extractions in the laboratory work may not be optimal for analysis due to poor precision reported from the water isotope data.

Water extractions via cryogenic vacuum distillation has been a common method for recovering soil water for decades. However, Orłowski et al. (2016) acknowledge that the overarching challenge with this extraction method is the inability to recapture the predetermined isotopic composition of soil water (reference sample). It appears that only Koeniger et al. (2011)

and West et al. (2006) have been able to recover both $\delta^2\text{H}$ or $\delta^{18}\text{O}$ successfully in oven-dried soils with an added known water isotope signature. This study was consistent with most studies, unable to demonstrate replicate $\delta^2\text{H}$ or $\delta^{18}\text{O}$ from reference samples, with ± 5.6 per mil for $\delta^{18}\text{O}$ and ± 13.89 per mil for $\delta^2\text{H}$. A positive development, data collected from two samples on the same extraction line used for this study showed standard deviations of replicate reference analyses of <0.3 per mil for $\delta^{18}\text{O}$ in April 2018. A formal procedure should be employed to the specifics of the method unique (e.g., extraction time, soil type, water volume added, etc.) if there is continued replication with this high level of precision.

Important to note, [fractionation] variations in soil water isotopic recovery have been reported based on soil type (Orlowski, 2016). Fractionation in water recovery appears most significant in soils with a large fraction of small pore spaces, such as soils with high clay content (Barnes and Turner, 1998). This fractionation based on soil texture highlights the importance of using the same soil type for the reference soil samples and soil samples collected in the field. However, the reference soil used for this study was obtained just outside of Lapham Hall at UWM [and different in texture, composition, etc. than soil samples from Full Belly Farm and Riverdog Farm]. Going forward, collecting additional soil samples from the field work site(s) to use for the reference samples is recommended (therefore using soil type as a control).

Finally, it may be possible to improve observation of soil water partitioning into mobile and less mobile pools by coupling in situ and ex situ water isotope measurements, as described by Oerter et al. (2017). This is discussed in more detail under Future Work.

Water Fraction

No notable trends are observed in the water fraction data, except perhaps for almonds. When considering just almonds (FB), the greatest range in water fraction occurred within the 0-

10 cm profile (0.04 to 0.15 in May and 0.02 to 0.31 in June). However, the June range is highly suspicious. The June 0.02 minimum may be due to evaporation [in storage], while the 0.31 value looks more like a typo in record-keeping. A 0.31 water fraction value is nearing field capacity. Based on observation in the field, this soil sample was not at field capacity. However, this value could be reasonable if this soil was collected during irrigation. Still, if one were to consider these reported Full Belly almonds May and June 0-10 cm water fraction ranges, it could be suggested that this greater range in water fraction at the top of the soil profile can be attributed to the type of irrigation system. The almonds were irrigated via medium elevation spray application, meaning the water directly hit the soil surface and percolated downwards (opposed to the buried drip irrigation lines used for asparagus, where the irrigation water never directly contacts the surface). The almond water fraction range closest to the surface (0-10 cm) may range accordingly due to the varying levels of vegetative cover, (shade or grass), provided by individual [samples] almond tree locations. The almonds orchards had grass cover, while all other crops samples were tilled soil lacking grass. Perhaps the arability of the soil impacted the reported water fraction values for this study. However, as repeatedly noted, the sample storage leaves the water fraction values highly questionable.

Soil Textures

A limited number of samples were run in the Malvern to determine soil texture. However, they appeared to confirm the silty loam texture consistent with Yolo soil series description. A coarser soil ($\approx 25\%$ coarse fragments) was observed in the field at the Riverdog Farm asparagus crop location, but data from this study shows no noteworthy impact on soil water isotope values or water fractions relative to the silty loam texture. As discussed earlier, soil texture may impact the extent of fractionation during water extractions. Given that there are

many variables in this type of study, (e.g. crop type, age of plant, irrigation schedule, etc.), perhaps it makes sense to keep the soil type/texture constant in the future.

Data Collection

This project originally set out to use isotope data to construct ternary diagrams, plotting plant water based on end-members groundwater, irrigation water, and precipitation. However, no explicit groundwater samples were collected, so there was no ability to construct ternary diagrams. To further complicate matters, irrigation water is sometimes groundwater and sometimes stream water (schedule unknown). Also, isotopic values for precipitation are not empirical, and are merely suggested based on the monthly average (over a 5-year period) precipitation value obtained from a publication with northern California oxygen values pulled from the USNIP database (Vachon, 2010). Precipitation hydrogen values were not provided in the paper, so $\delta^2\text{H}$ values were speculated by their correspondence to $\delta^{18}\text{O}$ on the GMWL. Using the isotopic information available in this project, precipitation and irrigation values are too similar to discriminate in most cases. Finally, while stream water isotopic data was obtained, it seems nonessential since the plants are not in close proximity to the stream. In addition, stream isotopic values typically vary widely over the course of a year.

The study location also provided challenges for data collection. It was difficult to frequently collect samples since the study location was in California. These difficulties were highlighted in the first two field work visits. During the initial September 2016 field work visit, too small amount of plant tissue samples was collected to obtain water extractions. During the February 2017 field work visit, local flooding impeded our ability to collect soil and crop root samples, and the increment borer used to obtain almond tree xylem samples broke. Challenges associated with the ability to frequently sample could have been abated if the study site was in

closer proximity to the University of Wisconsin-Milwaukee, as fieldwork would have been more easily rescheduled.

Finally, soil samples were only collected at 0-30 cm depth. Wang, et al. (2010) used water isotopes to show that corn mainly accesses water at 50 cm during its flowering stage, and isotopic data for greater depths would have made for a more robust study for plant water acquisition depth in the soil profile.

Sample Integrity

Sample storage for this project introduced concerns regarding sample integrity. For example, May 2017 samples were stored in coolers filled with bagged ice for transport from California to Wisconsin. The bagged ice melted in the coolers, so bagged samples were immersed in water. While sample bags were sealed, there is room for concern that an additional water source (melted ice) may have contaminated samples. Adding to concerns, soil and plant tissue samples were stored at room temperature. Consequently, soil and plant tissue samples may have been subject to evaporation, thus altering the sample water isotope signatures. It is highly likely that samples underwent substantial evaporation during storage, as soil water fraction results for May and June 2017 are suspiciously similar. Based on observations during sample collection, June 2017 soils contained more water than May 2017 samples. This is substantiated by rain history during these sample times. While there was no precipitation the week leading up to May field work, there was 0.52 inches of rain reported for the first day of June 2017 field work. Despite the differences in observation and reported precipitation, the stored samples yielded similar water fraction results for both May and June.

Sample Processing

Sample processing is also a concern for this project. Most notably, it appears that considerable fractionation occurred during the cryogenic vacuum distillation procedure. Based on observation, uncollected water vapor could be seen in the line during sample processing. Replicate samples appeared to confirm fractionating during sample processing (Table 1). Recommendations for sampling processing improvement can be found in Future Work.

Hypotheses

The four hypothesis this study originally set out to test are addressed below.

- 1) *Plants access distinct reservoirs of water within soil based upon age-dependent growth needs.* This was not addressed. A closer location for field work will enable improved access (less time and expense) to test plants during different growth stages.
- 2) *Plant water acquisition is influenced by the unique hydrology of soils that are governed by soil texture and landscape position.* Data generated in this study does not sufficiently address this hypothesis. Plant type needs to be held constant with different soil textures and/or landscape positions to effectively address this idea. Plant water acquisition may be influenced by root morphologies or age-dependent growth needs.
- 3) *The loci of plant water uptake cannot be predicted from measurement of soil moisture status in soil surface horizons.* Perhaps this hypothesis is best addressed in this study. If soil moisture status refers to water fraction, it was determined that no conclusion could be made to connect water fraction and plant water acquisition (refer to Discussion: Water Fraction section).
- 4) *Plant root morphology has a direct impact on the loci of plant water uptake.* This hypothesis was unable to be tested mostly due to a limited number of samples. Again, a

closer location would improve the ability for increased sample collection. This is discussed in detail in the Future Work section.

FUTURE WORK

Sample Collection Methods

Plant Selection: Root Architecture, Phenologies, Accessibility

If considering plant root architecture, research types of plant root architecture prior to sampling. Plant root architectures in crops have been previously established and categorized (Rogers, 2015).

Initial discussion for this project touched on plant water uptake in relation to age-dependent growth needs. While interesting to consider phenologies in the context of ES and precision irrigation applications, sample collection methods were not sufficient to address any potential phenology and plant water acquisition correlation(s). Going forward, it will be important to have information regarding crop and orchard schedules. Some crops (perennials) are easier to sample because they maintain roots in the ground year-round (e.g. asparagus), while other crops (annuals) are more difficult to plan for sample collection because their roots are present for a limited time (e.g. corn). There is additional concern for sampling crop plants in their fragile early growth stage, so not to incur damage to/destroy the plant. Established orchards are an ideal choice for sampling, because they are 1) available to sample year-round and 2) there is limited concern for tree destruction, and 3) successful xylem water extractions have been repeatedly demonstrated in other studies (Brooks, et al., 2010, Goldsmith, et al., 2011, Zang, et al., 2015). Perennial crops, like asparagus, are also a good choice.

To capture water from various growth stages, it is important to have the ability to sample plants/crops throughout a growing season. It is strongly recommended that future studies take place in a more local capacity (e.g. if based in Wisconsin, conduct this type of research in Wisconsin) to sufficiently capture water from various growth stages. Added benefits for keeping

similar studies nearby are 1) low travel cost, 2) less travel time (easier access), and 3) local relevancy/importance. An alternative solution to obtain samples from distant farm locations could be having someone at the farm sample regularly and ship samples to UWM overnight, but this is likely cost-prohibitive.

Plant Samples

Plant tissue sample volumes should be sufficient to yield enough water for isotopic analysis, including replicates. The necessary amount of plant tissue to be collected should be determined prior to fieldwork. A surplus of [backup] plant tissue samples should be collected in case samples are compromised/destroyed during sample storage or processing.

For tree xylem samples, it is recommended to bring at least two increment borers for field work. Increment borers are easily subject to breaking, so it is important to have a backup readily available. Additionally, individuals using the increment borer should be strong enough to use the tool and obtain cores. This is noted specifically for sappy trees; almond trees proved quite difficult to fully insert the increment borer.

Water Samples

Proper planning for water sample collection is essential if the goal of study is to use a mass balance approach to trace water inputs (precipitation, irrigation water), fluxes, and pools. Sufficient collection of rainwater is necessary to obtain empirical precipitation isotope signatures. Precipitation should be collected per the IAEA/GNIP Precipitation Sampling Guide instructions (IAEA, 2018). Several precipitation collection methods are detailed for event-based and monthly collection of rainwater. Event-based precipitation collection is optimal, as isotopic signatures can vary greatly for each rain event. It is also important to identify the source of irrigation water (groundwater, stream water, etc.).

Soil Samples

Soil sample collection depths for this study were collected from 0-30 cm. This limited depth presents only a narrow view of plant water acquisition. Going forward, it is recommended that sample collection depths extend deeper within the soil profile (~80 cm) to observe more meaningful trends.

Sample Storage

Sample storage methods should be improved for 1) transport from the sampling site to the laboratory and 2) storage at the laboratory. Soil and plant tissue samples should double-bagged in well-sealed, high quality plastic bags. This is necessary to avoid sample cross-contamination and evaporation. During sample transport, samples should be placed in coolers filled with frozen freezer-packs and not bagged ice. Bagged ice carries the risk of melting and contaminating the samples, thus altering sample water isotope compositions. Placing freezer-packs in sealed plastic bags serves as an additional safeguard to avoid sample contamination. Samples should be promptly frozen once they arrive at the laboratory. Going forward, it will be important to make sure there is sufficient freezer space to store all samples.

Pedons

USDA soil classification should be determined via pedon assessments. For thorough soil classification, pedon assessment should be conducted when soil is not saturated. Obtaining adequate soil classification information is not possible if rain occurs during field work. Again, easy access to site location is important in this instance. If the field work site is close, one can more easily reschedule a time to obtain pedon information. Additionally, it is essential to budget for enough time to dig pedons—these can take a longer to complete than originally anticipated.

Matric Potential

In-situ measurements are necessary if wanting to incorporate matric potential into the study. Tensiometer installations are suggested going forward.

Sample Processing Methods

Apparatus Design

It is recommended that future cryogenic vacuum distillation apparatus designs omit the use of a heat gun as the heat source. Applied heat is unevenly distributed when using the heat gun, and invites fractionation when all water vapor is not removed from the soil or plant tissue sample. There is more confidence in avoiding fractionation when using a hot plate as the heat source (as described by Ehleringer et al., 2010), where heat application is more easily controlled and constant. Going forward, a temperature of 90-100°C via hot plate is suggested.

Furthermore, standardizing the extraction time may prove useful. A suggested extraction time to begin with is one hour. This time can be adjusted as seems fit.

Another issue to address is the limited number of samples that can be simultaneously processed. The current extraction line can process two samples at a time. Similar studies [with publishable results] use extraction lines that have the capability of processing 18 or 24 samples at a time (Orlowski, 2016). Expanding the line to simultaneously process more samples could yield more data in a more time-sensitive manner.

Reference Samples

Given the challenges presented with recapturing reference sample water isotopes from soil via vacuum cryogenic distillation (Orlowski, et al., 2016), frequently running reference samples is essential. It is recommended that reference samples be run every four samples to monitor the reliability of generated isotope data. Additionally, it is important to use the same soil type for the reference samples as collected in the field (as noted in the Discussion section).

Cleaning Glassware

Glass vial walls routinely retained soil residue after emptying soil from processed sample vials. A soft brush (e.g. pipe cleaner) is recommended to use to clean the glassware. Other methods for cleaning glassware may be too abrasive and compromise the structural integrity of the sample vials.

Isotopic Analysis Methods

Irrigation Considerations

Irrigation schedule, amount, and source (e.g. groundwater versus stream water) should be recorded for the duration of the study. This information is important to factor in for mass balance consideration.

Bayesian Stable Isotope Mixing Model

Soil depth of plant water acquisition, as well as percent composition of soil water sources (groundwater, irrigation water, and rainwater), should be evaluated using a Bayesian stable isotope mixing model, as did Yang, et al., (2015) for a similar study. Yang, et al., (2015) used MixSir, a Bayesian stable isotope mixing model program, to evaluate irrigation infiltration (depth) against crop water uptake depth. The added value of MixSir is that it accounts for the uncertainty of numerous [water] sources and isotope signatures, which is highly applicable to plant water uptake research. Upon using this program, the proportional contributions of crop/orchard water sources can be plotted on a soil water ternary diagram with end-members groundwater, irrigation water, rainwater (as originally intended for this project).

In-situ Coupled with Ex-situ Monitoring

Oerter et al. (2017) used a combination of in-situ and ex-situ water isotope monitoring in attempt to observe ecohydrological separation in an irrigated setting. The study was carried out

in a small, irrigated urban ornamental garden on the University of Utah campus. In-situ monitoring consisted of water vapor probes installed at various depths in the soil subsurface, temperature sensors, and a membrane inlet-based laser spectroscopy (Fig. 24).

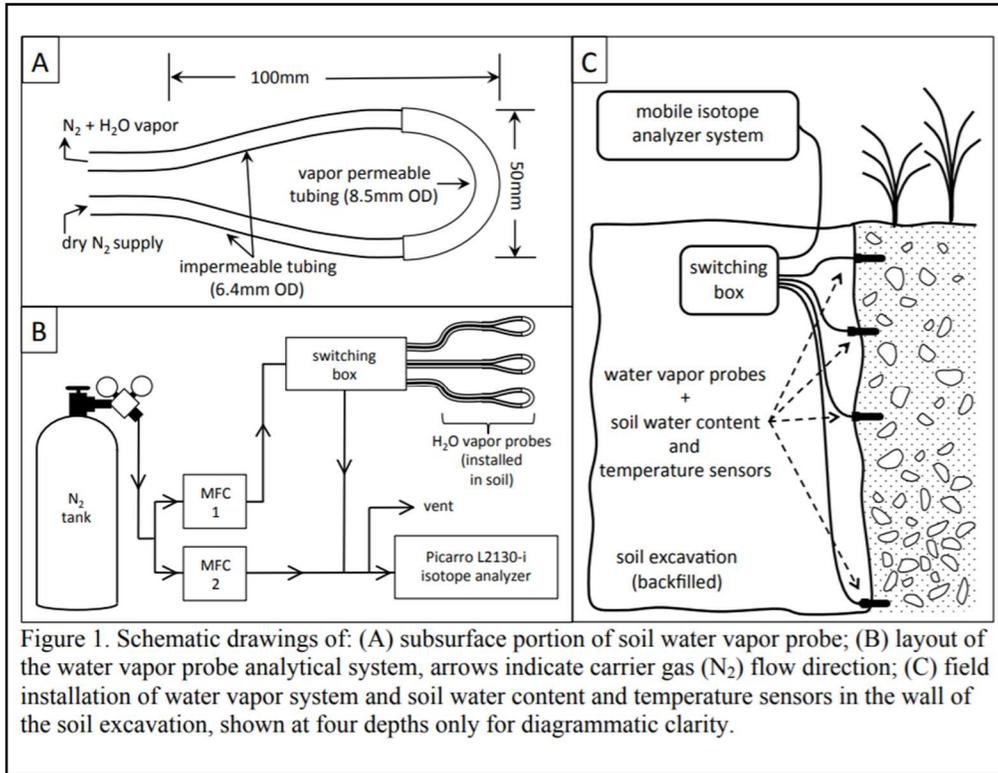


Figure 24. Schematic diagram of sampling and monitoring methods used in an ecohydrological separation in an irrigated setting study by Oerter et al. (2017).

Additionally, an auger was used to collect soil samples. Soil samples and plant tissue (stems) were subject to cryogenic vacuum distillation. The in-situ isotope ratio infrared spectroscopy (IRIS) measurements represented mobile water, while the soil samples that underwent vacuum distillation represented bulk soil water.

Advantages of this study design include close proximity (on-campus) and low overhead (if IRIS is available) to conduct field work, and one person can easily conduct the work (no field assistant necessary). Also, the study duration was nine months. This timeframe suggests this type of work is doable on a [2-year] master's thesis timeline. However, conducting a similar

study to Oerter et al. (2017) on the UWM campus precludes examination of certain crop types, e.g. corn.

CONCLUSION

The original project set out to determine the depth at which irrigated plants acquire water. However, analysis limitations did not allow for such assessment. Using the available data, this project attempted to reconstruct the precipitation isotope signature for the time of sampling. The precipitation isotope signature was inferred as the intersection between the GMWL and a linear regression run through the water isotope values extracted from soil samples at a given plant location. Mostly due to sample storage and processing, these results are questionable.

This was an ambitious and interesting project, serving as a good start for method development for future similar projects. Future projects should refer to the work of Yang, et al. (2015) and Asbjornsen, et al. (2008) as a framework for conducting this type of research. Yang, et al., (2015) used water isotopes to evaluate the depth of irrigation water infiltration and crop plant water acquisition, concluding that irrigation water depths exceeded plant water uptake depths. Asbjornsen, et al., (2008) considered various root morphologies to evaluate perennial and annual plant water uptake in an agricultural Midwest setting. Furthermore, this research should be conducted at an easily accessible site to enable easier and better data collection. Ultimately, this project became an exercise in method development for plant water acquisition research.

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APPENDICES

Appendix A:

May 2017 Soil Depth/Plant Tissue, Sample ID, Location

Full Belly Farm Almonds

1. Plant Tissue, *FBM-AL1-00*
0-10 cm, *FBM-AL1-01*
10-20 cm, *FBM-AL1-02*
20-30 cm, *FBM-AL1-03*
N 38° 48' 29.8", W 122° 10' 53.7", Altitude: 105m

2. Plant Tissue, *FBM-AL2-00*
0-10 cm, *FBM-AL2-01*
10-20 cm, *FBM-AL2-02*
20-30 cm, *FBM-AL2-03*
N 38° 48' 29.2", W 122° 10' 53.7", Altitude: 107m

3. Plant Tissue, *FBM-AL3-00*
0-10 cm, *FBM-AL3-01*
10-20 cm, *FBM-AL3-02*
20-30 cm, *FBM-AL3-03*
N 38° 48' 29.6", W 122° 10' 58.8", Altitude: 108m

4. Plant Tissue, *FBM-AL4-00*
0-10 cm, *FBM-AL4-01*
10-20 cm, *FBM-AL4-02*
20-30 cm, *FBM-AL4-03*
N 38° 48' 33.0", W 122° 10' 53.5", Altitude: 102m

5. Plant Tissue, *FBM-AL5-00*
0-10 cm, *FBM-AL5-01*
10-20 cm, *FBM-AL5-02*
20-30 cm, *FBM-AL5-03*
N 38° 48' 32.9", W 122° 10' 56.7", Altitude: 105m

6. Plant Tissue, *FBM-AL6-00*
0-10 cm, *FBM-AL6-01*
10-20 cm, *FBM-AL6-02*
20-30 cm, *FBM-AL6-03*
N 38° 48' 33.2", W 122° 11' 01.5", Altitude: 104m

Full Belly Farm Asparagus,

1. Plant Tissue, *FBM-AS1-00*,
0-10 cm, *FBM-AS1-01*
10-20 cm, *FBM-AS1-02*
20-30 cm, *FBM-AS1-03*
N 38° 51' 57.5", W 122° 13' 04.1", Altitude: 113m

2. Plant Tissue, *FBM-AS2-00*
0-10 cm, *FBM-AS2-01*
10-20 cm, *FBM-AS2-02*
20-30 cm, *FBM-AS2-03*
NA

3. Plant Tissue, *FBM-AS3-00*
0-10 cm, *FBM-AS3-01*
10-20 cm, *FBM-AS3-02*
20-30 cm, *FBM-AS3-03*
NA

Riverdog Farm Almonds

1. Plant Tissue, *RDM-AL1-00*
0-10 cm, *RDM-AL1-01*
10-20 cm, *RDM-AL1-02*
20-30 cm, *RDM-AL1-03*
N 38° 46' 41.1", W 122° 10' 08.6", Altitude: NA

2. Plant Tissue, *RDM-AL2-00*
0-10 cm, *RDM-AL2-01*
10-20 cm, *RDM-AL2-02*
20-30 cm, *RDM-AL2-03*
N 38° 46' 37.4", W 122° 10' 07.2", Altitude: 78m

3. Plant Tissue, *RDM-AL3-00*
0-10 cm, *RDM-AL3-01*
10-20 cm, *RDM-AL3-02*
20-30 cm, *RDM-AL3-03*
N 38° 46' 39.2", W 122° 10' 06.5", Altitude: 95m

4. Plant Tissue, *RDM-AL4-00*
0-10 cm, *RDM-AL4-01*
10-20 cm, *RDM-AL4-02*
20-30 cm, *RDM-AL4-03*
N 38° 46' 44.1", W 122° 10' 08.0", Altitude: 92m

5. Plant Tissue, *RDM-AL5-00*
 0-10 cm, *RDM-AL5-01*
 10-20 cm, *RDM-AL5-02*
 20-30 cm, *RDM-AL5-03*
 N 38° 46' 45.2", W 122° 10' 09.8", Altitude: 97m
6. Plant Tissue, *RDM-AL6-00*
 0-10 cm, *RDM-AL6-01*
 10-20 cm, *RDM-AL6-02*
 20-30 cm, *RDM-AL6-03*
 N 38° 46' 47.4", W 122° 10' 08.6", Altitude: 92m

Riverdog Farm Asparagus

1. Plant Tissue, *RDM-AS1-00*
 0-10 cm, *RDM-AS1-01*
 10-20 cm, *RDM-AS1-02*
 20-30 cm, *RDM-AS1-03*
 N 38° 49' 32.0", W 122° 12' 21.6", Altitude: 127m
2. Plant Tissue, *RDM-AS2-00*
 0-10 cm, *RDM-AS2-01*
 10-20 cm, *RDM-AS2-02*
 20-30 cm, *RDM-AS2-03*
 N 38° 49' 31.8", W 122° 12' 19.4", Altitude: 121m
3. Plant Tissue, *RDM-AS3-00*
 0-10 cm, *RDM-AS3-01*
 10-20 cm, *RDM-AS3-02*
 20-30 cm, *RDM-AS3-03*
 N 38° 49' 30.2", W 122° 12' 20.1", Altitude: 122m

Riverdog Farm Chard

1. Plant Tissue, *RDM-CHI-00*
 0-10 cm, *RDM-CHI-01*
 10-20 cm, *RDM-CHI-02*
 20-30 cm, *RDM-CHI-03*
 N 38° 49' 55.3", W 122° 12' 08.7", Altitude: 118m
2. Plant Tissue, *RDM-CH2-00*
 0-10 cm, *RDM-CH2-01*
 10-20 cm, *RDM-CH2-02*
 20-30 cm, *RDM-CH2-03*
 N 38° 49' 53.1", W 122° 12' 07.5", Altitude: 114m

3. Plant Tissue, *RDM-CH3-00*
0-10 cm, *RDM-CH3-01*
10-20 cm, *RDM-CH3-02*
20-30 cm, *RDM-CH3-03*
N 38° 49' 51.8", W 122° 12' 06.5", Altitude: 113m

APPENDIX B:

June 2017 Soil Depth/Plant Tissue, Sample ID, Location

June 2017 Full Belly Farm Almonds

1. Plant Tissue, *FBJ-AL1-00*
0-10 cm, *FBJ-AL1-01*
10-20 cm, *FBJ-AL1-02*
20-30 cm, *FBJ-AL1-03*
N 38° 48' 30.2", W 122° 11' 02.0", Altitude: 108m

2. Plant Tissue, *FBJ-AL2-00*
0-10 cm, *FBJ-AL2-01*
10-20 cm, *FBJ-AL2-02*
20-30 cm, *FBJ-AL2-03*
N 38° 48' 31.6", W 122° 10' 57.5", Altitude: 109m

3. Plant Tissue, *FBJ-AL3-00*
0-10 cm, *FBJ-AL3-01*
10-20 cm, *FBJ-AL3-02*
20-30 cm, *FBJ-AL3-03*
N 38° 48' 32.5", W 122° 10' 56.3", Altitude: 108m

4. Plant Tissue, *FBJ-AL4-00*
0-10 cm, *FBJ-AL4-01*
10-20 cm, *FBJ-AL4-02*
20-30 cm, *FBJ-AL4-03*
N 38° 48' 34.7", W 122° 10' 56.1", Altitude: 107m

5. Plant Tissue, *FBJ-AL5-00*
0-10 cm, *FBJ-AL5-01*
10-20 cm, *FBJ-AL5-02*
20-30 cm, *FBJ-AL5-03*
N 38° 48' 35.5", W 122° 10' 59.6", Altitude: 105m

6. Plant Tissue, *FBJ-AL6-00*
0-10 cm, *FBJ-AL6-01*
10-20 cm, *FBJ-AL6-02*
20-30 cm, *FBJ-AL6-03*
N 38° 48' 36.6", W 122° 11' 05.4", Altitude: 102m

June 2017 Full Belly Farm Asparagus

1. Plant Tissue, *FBJ-AS1-00*
0-10 cm, *FBJ-AS1-01*
10-20 cm, *FBJ-AS1-02*
20-30 cm, *FBJ-AS1-03*
N 38° 51' 57.0", W 122° 13' 04.0", Altitude: 114m

2. Plant Tissue, *FBJ-AS2-00*
0-10 cm, *FBJ-AS2-01*
10-20 cm, *FBJ-AS2-02*
20-30 cm, *FBJ-AS2-03*
N 38° 51' 54.9", W 122° 13' 00.2", Altitude: 112m

3. Plant Tissue, *FBJ-AS3-00*
0-10 cm, *FBJ-AS3-01*
10-20 cm, *FBJ-AS3-02*
20-30 cm, *FBJ-AS3-03*
N 38° 51' 56.0", W 122° 12' 59.7", Altitude: 119m

June 2017 Riverdog Farm Almonds

1. Plant Tissue, *FBJ-AL1-00*
0-10 cm, *FBJ-AL1-01*
10-20 cm, *FBJ-AL1-02*
20-30 cm, *FBJ-AL1-03*
N 38° 46' 38.5", W 122° 10' 07.0", Altitude: 105m

2. Plant Tissue, *FBJ-AL2-00*
0-10 cm, *FBJ-AL2-01*
10-20 cm, *FBJ-AL2-02*
20-30 cm, *FBJ-AL2-03*
N 38° 46' 42.0", W 122° 10' 06.9", Altitude: 103m

3. Plant Tissue, *FBJ-AL3-00*
0-10 cm, *FBJ-AL3-01*
10-20 cm, *FBJ-AL3-02*
20-30 cm, *FBJ-AL3-03*
N 38° 46' 40.9", W 122° 10' 08.7", Altitude: 96m

4. Plant Tissue, *FBJ-AL4-00*
0-10 cm, *FBJ-AL4-01*
10-20 cm, *FBJ-AL4-02*
20-30 cm, *FBJ-AL4-03*
N 38° 46' 40.4", W 122° 10' 07.6", Altitude: 88m

5. Plant Tissue, *FBJ-AL5-00*
0-10 cm, *FBJ-AL5-01*
10-20 cm, *FBJ-AL5-02*
20-30 cm, *FBJ-AL5-03*
N 38° 46' 44.9", W 122° 10' 08.8", Altitude: 86m

6. Plant Tissue, *FBJ-AL6-00*
0-10 cm, *FBJ-AL6-01*
10-20 cm, *FBJ-AL6-02*
20-30 cm, *FBJ-AL6-03*
N 38° 46' 48.5", W 122° 10' 10.3", Altitude: 94m

June 2017 Riverdog Farm Asparagus

1. Plant Tissue, *RDJ-AS1-00*
0-10 cm, *RDJ-AS1-01*
10-20 cm, *RDJ-AS1-02*
20-30 cm, *RDJ-AS1-03*
N 38° 49' 28.6", W 122° 12' 18.3", Altitude: 123m

2. Plant Tissue, *RDJ-AS2-00*
0-10 cm, *RDJ-AS2-01*
10-20 cm, *RDJ-AS2-02*
20-30 cm, *RDJ-AS2-03*
N 38° 49' 28.9", W 122° 12' 16.1", Altitude: 125m

3. Plant Tissue, *RDJ-AS3-00*
0-10 cm, *RDJ-AS3-01*
10-20 cm, *RDJ-AS3-02*
20-30 cm, *RDJ-AS3-03*
N 38° 49' 27.6", W 122° 12' 16.1", Altitude: 125m

Appendix C:
May 2017 Isotope Data

May-17	Avg Precip		Irrigation		Soil 10 cm		Soil 20 cm		Soil 30 cm		Plant Tissue	
Full Belly Almonds	δ18O	δ2H	δ18O	δ2H								
Site 1	-5.70	-35.56	-8.12	-54.49	-6.87	-60.10	-7.43	-56.56	2.57	-33.01	6.66	5.53
Site 2	-5.70	-35.56	-8.12	-54.49	-5.51	-48.91	-9.63	-71.22	-3.34	-46.60	2.34	-34.45
Site 3	-5.70	-35.56	-8.12	-54.49	-4.21	-51.60	-8.62	-62.64	0.82	-34.19	-7.18	-59.79
Site 4	-5.70	-35.56	-8.12	-54.49	0.87	-30.95	-4.34	-46.95	-6.03	-51.04	-7.94	-62.15
Site 5	-5.70	-35.56	-8.12	-54.49	-4.18	-42.40	-6.53	-54.51	-7.56	-57.72	NA	NA
Site 6	-5.70	-35.56	-8.12	-54.49	-0.05	-33.27	NA	NA	-4.70	-50.02	NA	NA
Full Belly Asparagus												
Site 1	-5.70	-35.56	-5.82	-42.30	-1.86	-31.81	-1.02	-26.53	-3.69	-38.60	-6.44	-55.03
Site 2	-5.70	-35.56	-5.82	-42.30	0.41	-29.12	-3.76	-43.52	-5.92	-54.65	-5.52	-53.53
Site 3	-5.70	-35.56	-5.82	-42.30	-7.07	-69.54	-3.68	-42.12	-3.35	-49.39	-6.06	-47.52
Riverdog Almonds												
Site 1	-5.70	-35.56	-5.99	-44.42	-4.51	-46.54	-4.53	-46.45	-7.76	-71.66	74.54	64.69
Site 2	-5.70	-35.56	-5.99	-44.42	-0.24	-43.14	-7.21	-65.78	3.19	-40.20	-3.86	-48.88
Site 3	-5.70	-35.56	-5.99	-44.42	4.17	-27.38	-8.35	-77.25	-6.39	-57.77	-5.95	-54.92
Site 4	-5.70	-35.56	-5.99	-44.42	-2.53	-49.83	NA	NA	-6.51	-61.52	NA	NA
Site 5	-5.70	-35.56	-5.99	-44.42	-6.66	-42.40	-6.09	-54.51	-7.38	-57.72	32.24	-62.15
Site 6	-5.70	-35.56	-5.99	-44.42	-5.28	-54.69	-0.17	-41.43	NA	NA	NA	NA
Riverdog Asparagus												
Site 1	-5.70	-35.56	-5.99	-44.42	-3.53	-54.62	-3.80	-43.27	-10.28	-80.34	-7.64	-73.59
Site 2	-5.70	-35.56	-5.99	-44.42	-7.69	-79.55	NA	NA	-7.06	-52.29	-3.86	-51.73
Site 3	-5.70	-35.56	-5.99	-44.42	-6.13	-64.14	-13.76	-106.67	-7.82	-60.78	-5.83	-46.25
Riverdog Chard												
Site 1	-5.70	-35.56	-5.99	-44.42	-4.67	-45.96	-5.22	-46.81	0.12	-30.47	NA	NA
Site 2	-5.70	-35.56	-5.99	-44.42	-3.32	-52.68	-7.74	-66.65	-6.86	-60.70	26.15	-1.47
Site 3	-5.70	-35.56	-5.99	-44.42	3.26	-23.05	NA	NA	-5.25	-48.07	13.19	-17.52

Appendix D:
June 2017 Isotope Data

June	Avg Precip		Irrigation		Soil 10		Soil 20		Soil 30		Plant Tissue	
	$\delta^{18}\text{O}$	$\delta^2\text{H}$										
Full Belly Almond												
Site 1	-7.57	-50.53	-7.27	-51.11	NA	NA	4.49	-38.66	NA	NA	-9.43	-71.86
Site 2	-7.57	-50.53	-7.27	-51.11	-13.13	-96.29	-8.31	-64.41	-5.49	-53.13	-3.88	-27.02
Site 3	-7.57	-50.53	-7.27	-51.11	-7.71	-67.75	-8.05	-63.10	-11.15	-86.56	-4.06	-51.54
Site 4	-7.57	-50.53	-7.27	-51.11	-11.53	-94.20	-5.66	-55.39	-7.83	-60.56	-2.23	-44.77
Site 5	-7.57	-50.53	-7.27	-51.11	-6.27	-57.34	-11.75	-92.96	-8.13	-66.32	-3.19	-55.32
Site 6	-7.57	-50.53	-7.27	-51.11	-0.94	-60.91	-7.81	-80.98	-8.17	-71.03	-0.08	-50.24
Full Belly Asparagus												
Site 1	-7.57	-50.53	-4.83	-38.00	12.96	1.43	-4.26	-51.05	-5.65	-59.32	2.45	-43.66
Site 2	-7.57	-50.53	-4.83	-38.00	-5.54	-63.63	-5.67	-61.34	-6.08	-64.63	-5.59	-56.19
Site 3	-7.57	-50.53	-4.83	-38.00	-4.12	-52.09	-2.71	-44.95	-4.93	-53.25	-1.34	-29.44
Riverdog Almonds												
Site 1	-7.57	-50.53	-4.65	-40.25	-3.52	-47.28	-7.89	-63.38	-10.02	-83.89	21.68	-5.77
Site 2	-7.57	-50.53	-4.65	-40.25	-7.77	-66.23	-5.54	-50.26	-9.08	-77.77	-4.71	-50.05
Site 3	-7.57	-50.53	-4.65	-40.25	-7.43	-66.27	-8.38	-72.30	-9.93	-83.25	0.60	-34.02
Site 4	-7.57	-50.53	-4.65	-40.25	-7.06	-74.67	-8.87	-80.08	-11.71	-96.10	10.04	-22.60
Site 5	-7.57	-50.53	-4.65	-40.25	-10.23	-85.82	-10.01	-82.06	-9.80	-81.23	2.97	-39.19
Site 6	-7.57	-50.53	-4.65	-40.25	-0.98	-27.33	-12.79	-96.63	-4.63	-48.76	9.40	-19.12
Riverdog Asparagus												
Site 1	-7.57	-50.53	-4.65	-40.25	-8.00	-77.59	-3.64	-60.23	-8.00	-70.92	-6.35	-67.14
Site 2	-7.57	-50.53	-4.65	-40.25	-4.78	-65.33	-3.67	-70.12	-5.52	-68.28	-0.70	-34.88
Site 3	-7.57	-50.53	-4.65	-40.25	-8.31	-86.25	-8.95	-80.85	-7.66	-80.59	-2.58	-38.16

APPENDIX E:

May 2017 Soil Water Fractions

May 2017 Soil Water Fractions	
Site	Water Fraction
FB Site 1 almonds 0-10cm	0.14
FB Site 1 almonds 10-20cm	0.12
FB Site 1 almonds 20-30cm	0.13
FB Site 2 almonds 0-10 cm	0.14
FB Site 2 almonds 10-20cm	0.12
FB Site 2 almonds 20-30cm	0.11
FB Site 3 almonds 0-10cm	0.15
FB Site 3 almonds 10-20cm	0.14
FB Site 3 almonds 20-30cm	0.14
FB Site 4 almonds 0-10 cm	0.04
FB Site 4 almonds 10-20cm	0.05
FB Site 4 almonds 20-30cm	0.04
FB Site 5 almonds 0-10cm	0.12
FB Site 5 almonds 10-20cm	0.10
FB Site 5 almonds 20-30cm	0.10
FB Site 6 almonds 0-10 cm	0.07
FB Site 6 almonds 10-20cm	0.06
FB Site 6 almonds 20-30cm	0.06
FB Site 1 asparagus 0-10cm	0.16
FB Site 1 asparagus 10-20cm	0.15
FB Site 1 asparagus 20-30cm	0.18
FB Site 2 asparagus 0-10 cm	0.15
FB Site 2 asparagus 10-20cm	0.17
FB Site 2 asparagus 20-30cm	0.16
FB Site 3 asparagus 0-10cm	0.14
FB Site 3 asparagus 10-20cm	0.15
FB Site 3 asparagus 20-30cm	0.13
RD Site 1 almonds 0-10cm	0.16
RD Site 1 almonds 10-20cm	0.10
RD Site 1 almonds 20-30cm	0.10
RD Site 2 almonds 0-10 cm	0.10
RD Site 2 almonds 10-20cm	0.11
RD Site 2 almonds 20-30cm	0.13
RD Site 3 almonds 0-10cm	0.11
RD Site 3 almonds 10-20cm	0.10
RD Site 3 almonds 20-30cm	0.11
RD Site 4 almonds 0-10 cm	0.13
RD Site 4 almonds 10-20cm	0.08
RD Site 4 almonds 20-30cm	0.08
RD Site 5 almonds 0-10cm	0.20
RD Site 5 almonds 10-20cm	0.14
RD Site 5 almonds 20-30cm	0.11
RD Site 6 almonds 0-10 cm	0.14
RD Site 6 almonds 10-20cm	0.13
RD Site 6 almonds 20-30cm	NA
RD Site 1 asparagus 0-10cm	0.06
RD Site 1 asparagus 10-20cm	0.09
RD Site 1 asparagus 20-30cm	0.09
RD Site 2 asparagus 0-10 cm	0.08
RD Site 2 asparagus 10-20cm	0.09
RD Site 2 asparagus 20-30cm	0.19
RD Site 3 asparagus 0-10cm	0.09
RD Site 3 asparagus 10-20cm	0.11
RD Site 3 asparagus 20-30cm	0.11

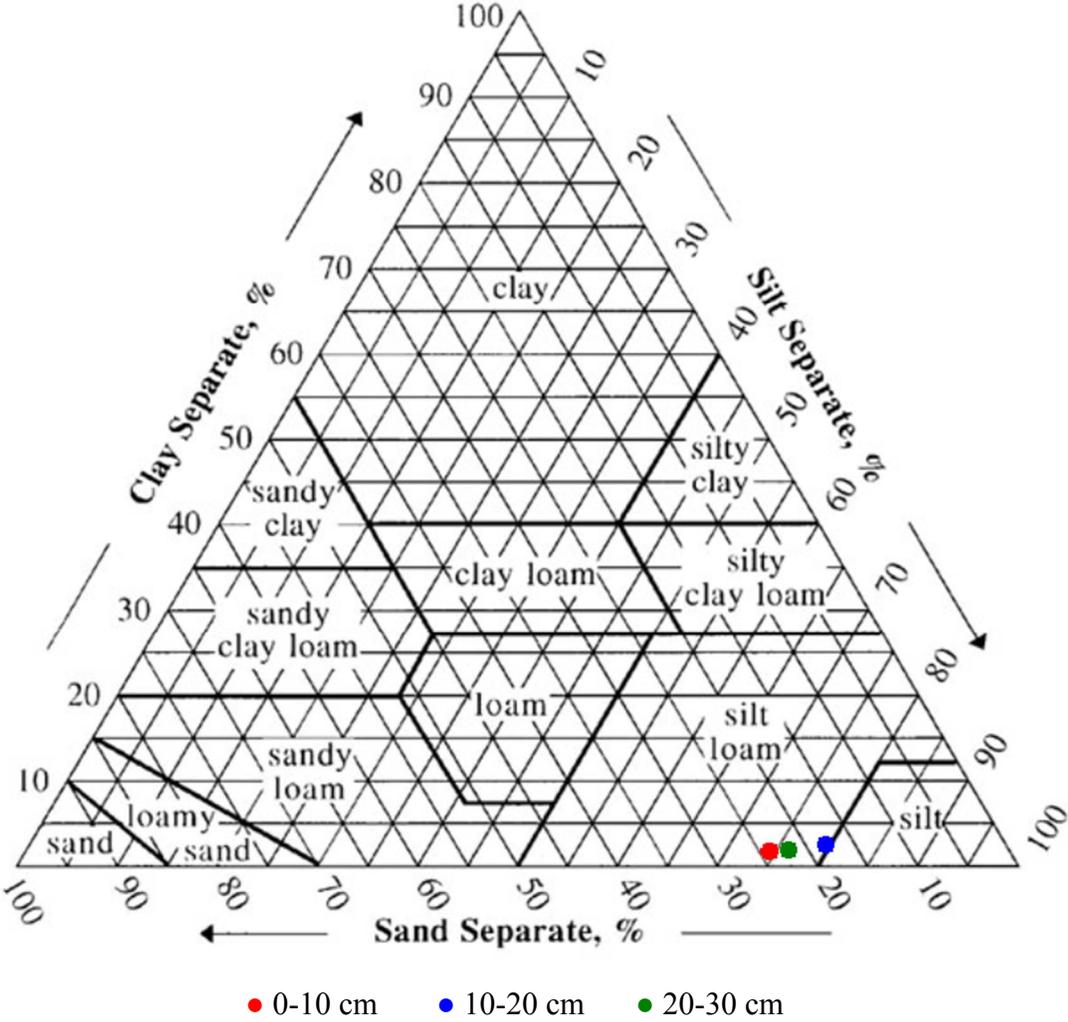
**Appendix F:
June 2017 Soil Water Fractions**

June 2017 Soil Water Fractions	
Site	Water Fraction
FB Site 1 almonds 0-10cm	0.20
FB Site 1 almonds 10-20cm	0.20
FB Site 1 almonds 20-30cm	0.19
FB Site 2 almonds 0-10 cm	0.02
FB Site 2 almonds 10-20cm	0.17
FB Site 2 almonds 20-30cm	0.12
FB Site 3 almonds 0-10cm	0.13
FB Site 3 almonds 10-20cm	0.09
FB Site 3 almonds 20-30cm	0.07
FB Site 4 almonds 0-10 cm	0.31
FB Site 4 almonds 10-20cm	0.11
FB Site 4 almonds 20-30cm	0.11
FB Site 5 almonds 0-10cm	0.10
FB Site 5 almonds 10-20cm	0.08
FB Site 5 almonds 20-30cm	0.08
FB Site 6 almonds 0-10 cm	0.05
FB Site 6 almonds 10-20cm	0.15
FB Site 6 almonds 20-30cm	0.06
FB Site 1 asparagus 0-10cm	0.12
FB Site 1 asparagus 10-20cm	0.12
FB Site 1 asparagus 20-30cm	0.13
FB Site 2 asparagus 0-10 cm	0.14
FB Site 2 asparagus 10-20cm	0.64
FB Site 2 asparagus 20-30cm	0.11
FB Site 3 asparagus 0-10cm	0.15
FB Site 3 asparagus 10-20cm	0.13
FB Site 3 asparagus 20-30cm	0.16
RD Site 1 almonds 0-10cm	0.13
RD Site 1 almonds 10-20cm	0.09
RD Site 1 almonds 20-30cm	0.10
RD Site 2 almonds 0-10 cm	0.15
RD Site 2 almonds 10-20cm	0.16
RD Site 2 almonds 20-30cm	0.19
RD Site 3 almonds 0-10cm	0.17
RD Site 3 almonds 10-20cm	0.13
RD Site 3 almonds 20-30cm	0.15
RD Site 4 almonds 0-10 cm	0.12
RD Site 4 almonds 10-20cm	0.10
RD Site 4 almonds 20-30cm	0.15
RD Site 5 almonds 0-10cm	0.17
RD Site 5 almonds 10-20cm	0.14
RD Site 5 almonds 20-30cm	0.12
RD Site 6 almonds 0-10 cm	0.18
RD Site 6 almonds 10-20cm	0.14
RD Site 6 almonds 20-30cm	0.16
RD Site 1 asparagus 0-10cm	0.14
RD Site 1 asparagus 10-20cm	0.10
RD Site 1 asparagus 20-30cm	0.13
RD Site 2 asparagus 0-10 cm	0.09
RD Site 2 asparagus 10-20cm	0.08
RD Site 2 asparagus 20-30cm	0.12
RD Site 3 asparagus 0-10cm	0.12
RD Site 3 asparagus 10-20cm	0.15

RD Site 3 asparagus 20-30cm	0.14
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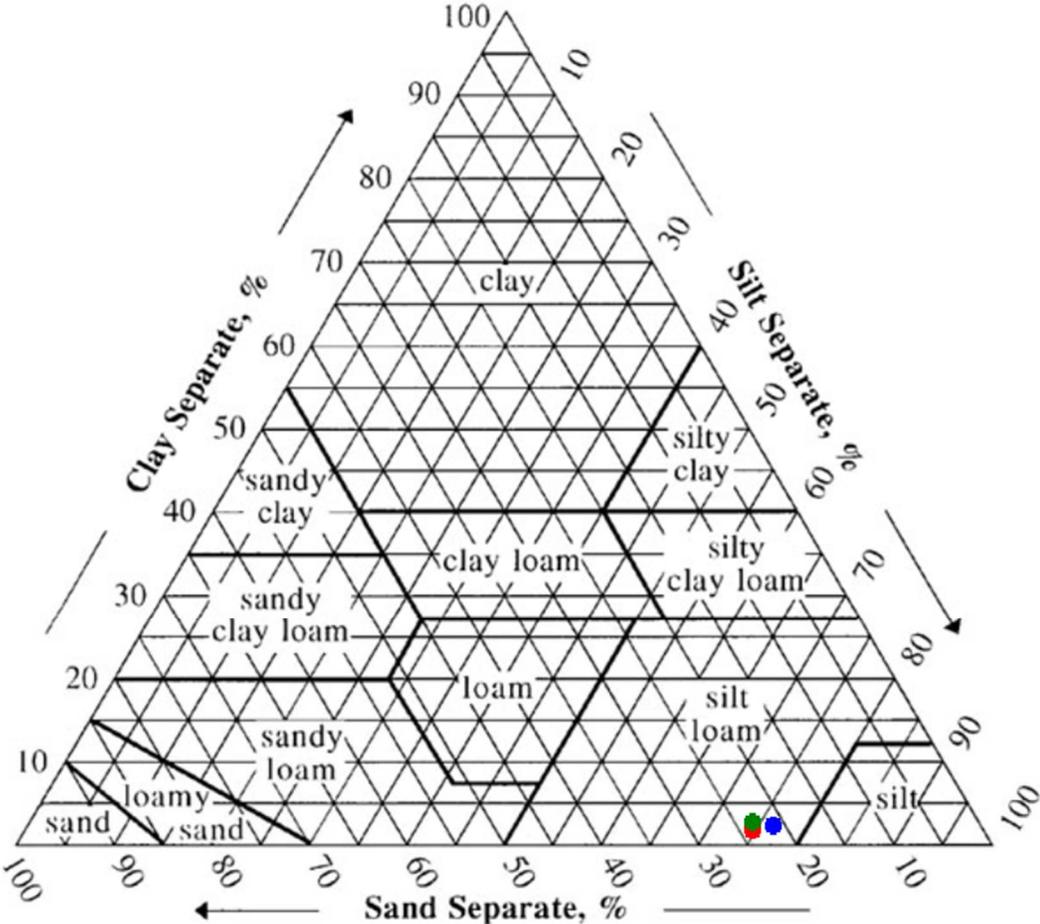
Appendix G:

May Full Belly Almonds Site 1 Soil Texture Triangle



Appendix H:

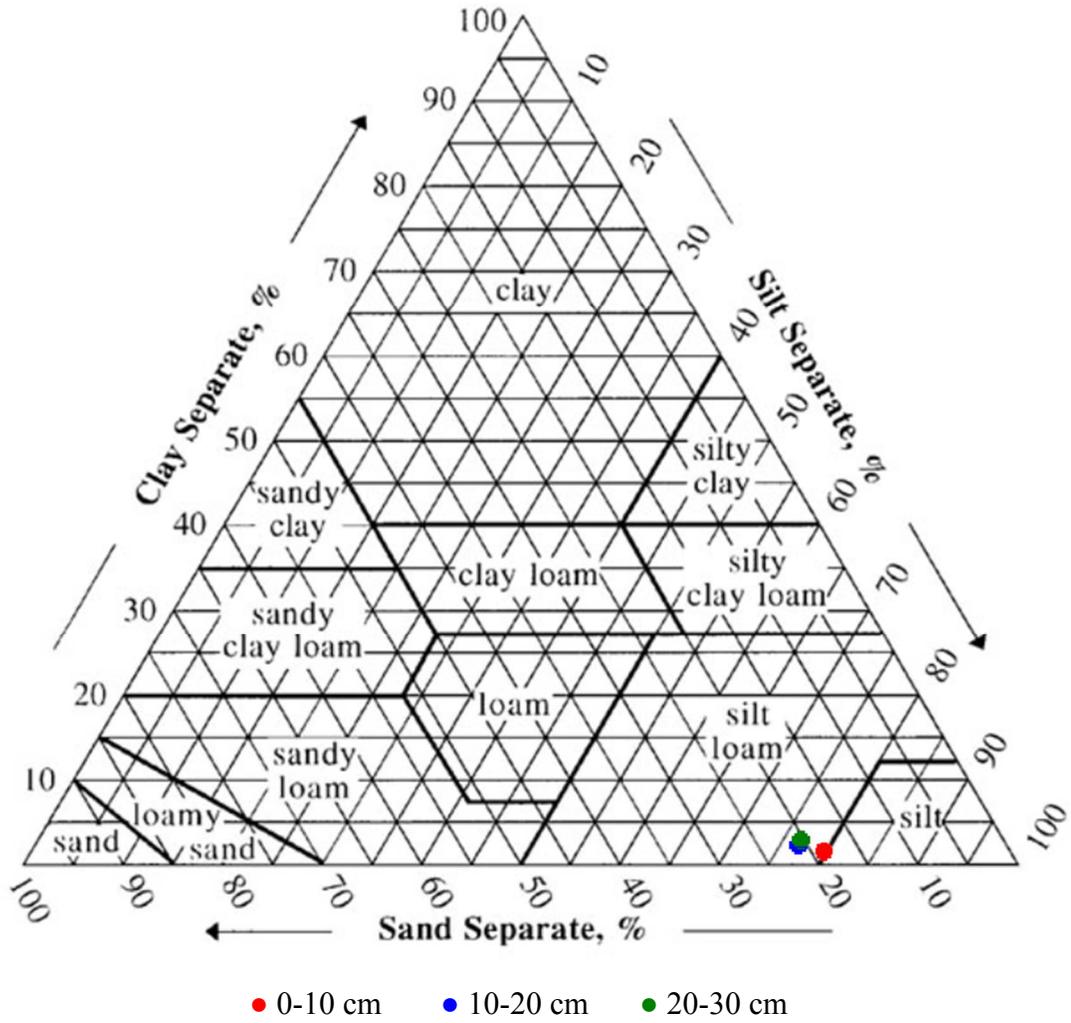
May Full Belly Almonds Site 2 Soil Texture Triangle



● 0-10 cm ● 10-20 cm ● 20-30 cm

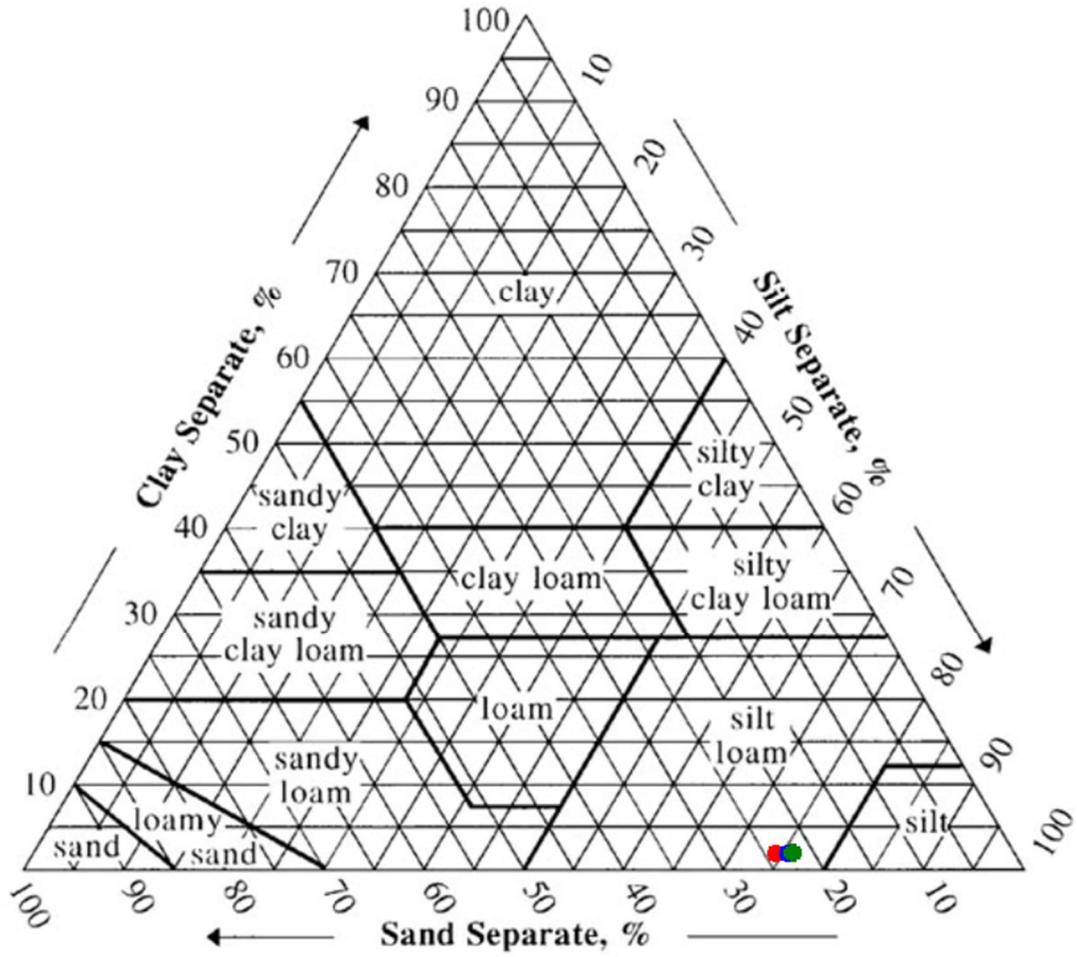
Appendix I:

May Full Belly Almonds Site 3 Soil Texture Triangle



Appendix J:

May Full Belly Asparagus Site 1 Soil Texture Triangle



● 0-10 cm ● 10-20 cm ● 20-30 cm

Appendix K:

May Full Belly Asparagus Site 3 Soil Texture Triangle

