ABSTRACT

HOLLAND, STEPHEN. Below-Canopy Water and Energy Transfer in a North Carolina Vineyard. (Under the direction of Joshua Heitman).

Producing European grape varieties for wine making is a burgeoning, but challenging industry in the southeastern U.S. High precipitation and soil with poor internal drainage lead to high humidity that, in turn, creates ideal conditions for fungal diseases. Without adaptations to management practices to reduce canopy humidity, fungal diseases will continue to limit the local wine grape industry. Altering inter-row management may offer a solution. We hypothesized that inter-row crops, typically fescue in southeastern vineyards, serve as a pump extracting water from the soil more efficiently than evaporation from bare surface conditions. This increases below canopy humidity because of limited mixing between the near-surface microclimate and the atmosphere above the canopy. The following objectives seek to test this hypothesis; 1) develop methodology to continuously measure water fluxes from the vineyard inter-row, 2) estimate and compare surface water vapor flux under i) bare soil conditions and ii) fescue cover crop conditions in the inter-row, and 3) determine effects of surface water vapor flux on canopy humidity. Measurements of below canopy water vapor flux were collected based on surface energy balance with a novel micro-Bowen ratio (MBR) system in a commercial vineyard. ET rates were well correlated between MBR systems and micro-lysimeters ($R^2 = 0.87$, slope = 1.13) and between the MBR systems and eddy covariance measurements ($R^2 = 0.80$, slope = 0.80). MBR results indicate that the vapor flux is greater in the fescue inter-row compared to the bare soil inter-row (e.g. 32% greater in May). As a result of greater inter-row evapotranspiration (ET), the soil water

content was lower in the fescue inter-row. The soil water content was not, however, depleted sufficiently to beneficially compete with the grapevines for soil water. This was further supported with grapevine water stress measurements, which indicated no stress for grapevines with fescue inter-rows. Direct measurements of relative humidity (RH) and a simple, one-dimensional model were used to determine the effects of the surface vapor flux on the canopy humidity. The measured and modeled RH were significantly correlated and both showed an increase in RH above the fescue inter-row compared to bare soil (2% and 5%, respectively, during the growing season), due to greater ET. Model results were assumed to be a better representation of actual effects of ground cover because of constraints imposed by plot size on measurements. The increased RH above the fescue inter-row suggests that fescue may impose a greater risk to grapevine health. Altering management practices to decrease the amount of water entering the canopy atmosphere, such as changing the width of the grass inter-row or using grass with lower ET, may lead to a more productive vineyard.

Below-Canopy Water and Energy Transfer in a North Carolina Vineyard

by
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BIOGRAPHY

Stephen Holland was born in Dallas, Texas on October 7, 1987. He later moved to

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outside and later grew an appreciation for nature. He received his Bachelor of Science in

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ACKNOWLEDGMENTS

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Chapter 1. Introduction

Today, most wine is made from the Old World species of grape, *Vitis vinifera*. Grape domestication began in the Tigris-Euphrates Valley in modern-day southern Iraq (Powell, 1995). The earliest evidence of winemaking dates back to the late 4th millennium B.C. in the Zagros Mountains in modern-day Iraq and Iran (Badler, 1995). There is evidence of more widespread grapevine cultivation and wine production as early as the 3rd millennium B.C. in Mesopotamia and Egypt (Hedrick, 1919; Winkler et al., 1974; James, 1995; Powell, 1995).

Early civilizations indulged in the consumption of wine, particularly the elite, as it was thought to be a symbol for all that was good and pure (Gorny, 1995). As the consumption of wine spread throughout local populations, many uses emerged. Wine was used in trade, as a symbol of social and economic status, and in ritual practices (Algaze, 1995; Badler, 1995; Stronach, 1995). In ancient Egypt, wine was used for medicinal purposes to restore one's appetite, bring down swelling in the limbs, and reduce fever (Lesko, 1995).

From its place of origin, domesticated grapes spread to Anatolia (modern-day Turkey) and Egypt. Later, it is thought that the Phoenicians carried the grape and wine to Greece, Italy, and France while navigating the Mediterranean Sea (Hedrick, 1919; Winkler et al., 1974). Eventually the wine grape made its way to northern Africa, much of Europe from Spain north to Germany and England, and east to Asia via Persia and India (Winkler et al., 1974; Robinson, 1986). In more recent times the wine grape has spread across much of the world, particularly in areas with temperate climates, as a result of European colonization (Winkler et al., 1974).

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When European colonists came to North America they found a large variety of grapes growing abundantly, but the wine it produced was not desirable, so using native grapes to make wine was not pursued until much later. Instead, *Vitis vinifera* grapes were brought to the eastern U.S. by the English in the 17th century followed shortly by the introduction of the grape to California by the Spaniards (Winkler et al., 1974). However, early growers had trouble establishing long-term growth, likely due to problems with climate, nematodes, phylloxera, Pierce's disease, and fungal diseases (Winkler et al., 1974; Weaver, 1976). After years of trial and error, a big step towards establishing *Vitis vinifera* grapes in the U.S. was made when it was discovered that native American grapes are resistant to phylloxera. Thus, grafting *Vitis vinifera* vines onto native American rootstocks such as muscadine (*Vitis rotundifolia*) became common practice (Granett et al., 2001). California's mild climate allowed the Old World species of grape to flourish, but problems still existed in the Eastern U.S. A hardier grape was sought after by viticulturists, which eventually led them to using French-American hybrids. These "French hybrids" kick-started the wine industry in the eastern U.S., specifically around Lake Erie, New York, Ohio, and Missouri (Thomas, 1996). John Adlum is credited as being the "Father of American Viticulture" whose early efforts of using hybrids led to the first commercial wine produced on the East Coast (Pinney, 1989).

In North Carolina, establishing a wine industry using Old World grape varieties took longer than other areas in the eastern U.S., although, the native muscadine (*Vitis rotundifolia*) and fox grapes (*Vitis labrusca*) grew abundantly and were a food staple for the native population. Early attempts at establishing vineyards using *Vitis vinifera* grapes by John Lawson, Gabriel Johnston, and Arthur Dabbs were well-documented, but these attempts did

not turn winemaking into a formidable industry in colonial North Carolina (Helsley, 2010). Eventually Scuppernong wine made from native muscadine grapes became very popular and led to the establishment of many commercial vineyards in North Carolina. In 1840, North Carolina led the rest of the U.S. in wine production due to the popularity of wine made from native grapes (Pinney, 1989; Helsley, 2010). Unfortunately, attempts at growing Old World grapes continued to be difficult. The abundance of local diseases, warm summer nights, irregular rainfall, and late frosts led many people to believe European or Old World grapes could not successfully be grown in this part of the U.S. (Helsley, 2010). This, in addition to legislative efforts to curtail alcohol production and consumption such as Prohibition, delayed any further efforts at establishing European grapes.

It was not until the last quarter century anyone had success at growing European grapes in North Carolina. Biltmore and Westbend vineyards led the way in successfully growing European grapes (Helsley, 2010). In the first decade of the 21st Century, the number of vineyards and wineries has grown at a substantial pace. In 2009, there were 89 wineries and approximately 400 commercial growers with a combined acreage of 1,800 acres ranking North Carolina as ninth in the nation in wine production. The wineries and vineyards in 2009 had an economic impact of $1.28 billion and supported over 7,500 jobs. Vineyards and wineries have not only supported the North Carolina economy through wine production and sales, but have also had an impact on tourism, community support, vineyard development, and wine industry research and education (Rimerman, 2011).

The recent success of North Carolina's wine industry can be credited to a few successful management practices such as grafting European grape shoots to native

rootstocks, orienting vine rows in a north/south direction, selecting sites with well to excessively drained soils, and the application of fungicides (Granett et al., 2001; Wolf, 2008; Giese, 2010). These management practices have proven to be somewhat successful, but these practices limit much of the land available for establishing vineyards. There are also still problems with production of hybrid European variety grapes due to excessive vine vigor, frost-prone areas, pests, and diseases. For instance, much of North Carolina is susceptible to Pierce's disease since much of the state does not get cold enough during the winter to limit the occurrence of Pierce's disease (Wolf, 2008). Another major limitation to the production of hybrid European variety grapes, which will be the focus of this paper, is high humidity which leads to many fungal diseases that thrive in warm-temperature climates (Carroll and Wilcox, 2003; Willocquet and Clerjeau, 1998; Thomas et al., 1988; van den Berg and Lentz, 1968), such as powdery mildew and black rot (Lipps, 2010; Wolf, 2008).

Problem Statement

In order to address the problem of commonly occurring fungal diseases that limit hybrid European grape production, it is desirable to find other solutions that will alleviate some of the excess moisture both below the canopy and within the soil. A substantial volume of research has been conducted on vineyards in the west coast and the north-Atlantic region, but there is a lack of research on systems commensurate with conditions in the southeastern U.S. In order for grape growers in the southeastern U.S. to understand the influence that inter-row crops and trellis systems have on available soil water and below-canopy humidity, research needs to focus on these factors in the southeastern vineyard system. We hypothesize that fescue in the vineyard inter-row (i.e., current management practice) serves as a pump

extracting water from the soil, which increases the canopy humidity by transmitting water to the below-canopy atmosphere more effectively than direct evaporation from bare soil in the vineyard inter-row.

<u>Research Objectives and Thesis Organization</u>

Measurements of below-canopy water vapor flux were based on the surface energy balance with a novel micro-Bowen ratio (MBR) system. The objectives of the study were to 1) determine the validity of water and energy fluxes from MBR systems by comparing to other methods (i.e. microlysimeters and eddy covariance), 2) compare surface water vapor and latent heat flux from bare soil and fescue cover crop conditions in the vineyard inter-row, and 3) determine effects of surface water vapor flux on canopy humidity.

To achieve objective 1, the MBR systems were installed at a commercial vineyard in North Carolina in order to continuously measure the water and energy fluxes in the vineyard inter-row. At three different study periods, a microlysimeter experiment was conducted in order to compare the water vapor fluxes from both methods. An additional microlysimeter and MBR system comparison was performed at a bare field site in Clayton, NC. An eddy covariance system was also used to compare the water vapor flux from the vineyard when there was no grapevine transpiration. Both the microlysimeter and eddy covariance experiments were used to test the validity of the MBR systems (Chapter 2). The MBR systems were then used to compare the surface water vapor flux from two treatments in the vineyard inter-row (i.e., bare soil and fescue). Additional measurements were made to observe the water dynamics of the vineyard such as soil water content. The relative humidity was directly measured above both treatments in the vineyard inter-row, however, due to

limited plot sizes a relative humidity model was used to estimate the effects of the vapor flux

on the canopy humidity (Chapter 3). A general summary and conclusions from the previous

chapters as well as recommended future studies are provided in Chapter 4.

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Chapter 2. Micro-Bowen Ratio (MBR) Systems for Measuring Evapotranspiration (ET) in a Vineyard Inter-Row.

<u>**Introduction**</u>

Many systems are made up of different components that contribute to whole-system evapotranspiration (ET) (e.g., agro-forestry systems, vineyards, orchards, row crops). Vineyards can be considered to consist of three components: vines, inter-row, and soil/plants underneath the vine row. All three components influence the micrometeorological conditions of the vineyard system. The grapevines, when fully mature, create canopies that disrupt wind patterns and create an obstacle for water and energy transport to the atmosphere (Heilman et al. 1994; Hicks 1973; Weiss and Allen 1976a; Weiss and Allen 1976b). The effect of the grapevine canopy on the vineyard energy balance is influenced by the training or trellising system (Smart, 1985; Heilman et al. 1996; Williams et al., 2003). The inter-row may be a source or sink of energy, particularly in the form of sensible heat. Heilman et al. (1994) and Hicks (1973) found that sensible heat flux from the inter-row contributed to the latent heat flux of the vineyard by providing energy for vine ET. Depending on the water regime and management, the inter-row may also contribute more directly to the system-level latent heat flux via inter-row ET (Yunusa et al., 1997; Centinari et al., 2012; Fandino et al., 2012). Underneath the vine row, the bare soil also serves as a source or sink of energy. During the dormant season when the grapevines have been pruned, the bare soil contributes relatively more latent and sensible heat to the vineyard energy balance because there is no grapevine canopy.

Measuring ET is important for understanding water dynamics in many environments. ET can be measured at different scales ranging from a catchment (Zhang et al., 2001) or larger, down to individual plants (Dugas et al., 1991; Braun and Schmid, 1999). As such, there are many methods for determining ET. Examples at the plot and field scale include remote sensing (Jackson et al., 1977; Seguin and Itier, 1983; Stone and Horton; 1974), lysimetry (Lascano and van Bavel, 1986), eddy covariance (Wilson et al., 2011), Penman-Monteith or Priestley-Taylor models (Sumner and Jacobs, 2005), and the Bowen ratio method (Bowen, 1926; Bland et al., 1996). The selected method for measuring ET often depends on the scale of interest (spatial and temporal) and availability of equipment and instrumentation.

The Bowen ratio method has been studied extensively and has been proven to accurately measure ET for many different environments ranging from an irrigated alfalfa field (Todd et al., 2000) to an urban setting (Kalanda et al., 1980). Advantages include providing continuous measurements of the energy balance and ET, and once established the system is inexpensive to operate and maintain. While traditional Bowen ratio methods have proven effective for measuring whole-system ET (Sauer et al., 2002; Sinclair et al., 1975; Spittlehouse and Black, 1980), it is also desirable to know ET for components below the system level.

Separating each component of a vineyard system is important in order to determine how each component contributes to the vineyard energy and water balance under different management scenarios (Heilman et al., 1996; Fandino et al., 2012). Studies have used Bowen ratio methods for separating individual component energy fluxes, but these studies usually

involved application of additional methods like sap flow gauges (Heilman et al., 1994; Zeggaf et al., 2008) where transpiration of a canopy or soil evaporation are found by the difference between either the system ET and soil evaporation or system ET and canopy ET, respectively. Challenges of such approaches include reconciling method bias amongst differing methods and scaling sap flow and chamber data from individual plants to the field scale (Heilman et al., 1994; Zeggaf et al., 2008). Traditional Bowen ratio systems integrate the entire vineyard system, which doesn't allow the separation of each component's energy balance (Zhang et al., 2007). Micro-Bowen ratio (MBR) systems are a relatively new idea that may be used to separate ET components within a system (Ashktorab et al., 1989; Zeggaf et al., 2008). An MBR system is a down-scaled version of Bowen ratio systems, used to measure a small footprint within a whole system. In the case of the vineyard, this footprint could be on the order of only a few meters across the vine inter-row. Because this inter-row zone has important implications for the whole vineyard system, devising a technique for continuous measurement of inter-row ET can be valuable (Yunusa et al., 1997; Lopes et al., 2004; Centinari et al., 2009). The goal of this work is to test the application of an MBR system for measurement of ET in a vineyard inter-row. We considered vineyard inter-rows with both grassed and bare soil conditions in this test, as well as an additional test at a bare surface vineyard site. We first demonstrate MBR energy balances measured for inter-row conditions, and then compare ET determined from the MBR to estimates obtained from micro-lysimeters, and from a system-integrating eddy covariance system during a period without grape transpiration at the vineyard.

Materials and Methods

Background

The Bowen ratio (Bowen, 1926) is the ratio of the sensible heat flux to the latent heat flux. It is used to determine the following surface energy balance:

$$R_N = G + H + LE \tag{1}$$

where R_N is the net radiation, G is the soil heat flux, H is the sensible heat flux, and LE is the latent heat flux. All terms use the units W m^{-2}. For G, H, and LE, densities away from the surface are positive. The opposite sign convention was used for R_N.

The Bowen ratio (β) can be estimated by measuring the differences in water vapor concentration and air temperature at two heights (Arya, 2001):

$$\beta = H/LE = [P_a C_p (\Delta T)] \,/\, [\lambda \varepsilon (\Delta e)] \tag{2}$$

where P_a is the atmospheric pressure (kPa), C_p is the specific heat capacity of air (1004.67 J kg^{-1} K^{-1}), ΔT is the air temperature difference between two heights (K), λ is the latent heat of vaporization for water (2.45 MJ kg^{-1}), ε is the ratio of the molecular weights of air and water (0.622), and Δe is the vapor pressure difference between two heights (kPa). The eddy diffusivities for heat (K_h) and water vapor (K_w) are not included in the calculation because their ratio (K_h/K_w) is assumed to be equal to one. LE is calculated from β, R_N, and G:

$$LE = (R_N - G) \,/\, (1+\beta) \tag{3}$$

In order to satisfy the assumptions of the Bowen ratio method for measurement (Fritschen and Fritschen, 2005), it is desirable to have an adequate fetch-to-height ratio. The fetch is the area of influence that is being measured by a particular instrument. In general, as the height of a measurement increases, the fetch size increases. It is important to have the

instrument's fetch size within the footprint of the desired flux (i.e. sensible heat and latent heat). According to Heilman et al. (1989), a fetch-to-height ratio of 20:1 is adequate for the Bowen ratio method. There are physical limits in a vineyard system that may prevent achieving a fetch-to-height ratio of 20:1 across the inter-row (typical widths < 3 m). Fetch may be of less concern across the inter-row, however, because cross-row wind speed is lower than down-row wind speed near the surface at similar above canopy wind speeds (Heilman et al., 1994).

Micro-Bowen Ratio (MBR) Systems

The Bowen ratio was estimated by using micro-Bowen ratio (MBR) systems (Ashktorab et al., 1989; Zeggaf et al., 2008). For this study, the MBR systems (Fig. 2.1) employed a LI-840A CO_2/H_2O gas analyzer (LI-COR, Lincoln, NE) that measures the concentration of water vapor (ppt) and CO_2 (ppm) in air. Each MBR system contains two air intakes with a filter assembly (PP Systems, Amesbury, MA) to filter out any debris or liquid water. The air intakes were placed at 1 and 6 cm above the grass/soil surface. A micro diaphragm gas sampling pump (KNF Neuberger, Inc., Trenton, NJ) was used to suck air throughout the MBR systems. A Kyotto relay (Kytech Electronics, LTD, Pingzhen City, Taiwan) was programmed to turn on and off the solenoid (Numatics, Novi, MI) every five minutes to alternate which air intake (top or bottom) the measurements were taken from inside the gas analyzer. Due to the gas analyzer measurement constraints, a Kyotto relay was programmed to turn the pump off when the measured relative humidity at 30 cm increased above 92% and would turn back on when the relative humidity dropped back to 88%. Two flow meters (Cole-Parmer Instrument Co., Vernon Hills, IL) were used to control the amount

of air sucked into each MBR system. The flow meters were set at 0.8-1.0 L per min. based on recommendations from the LI-COR 840A instruction manual.

The air traveled from the air intakes through Synflex1300 tubing (Eaton Hydraulics, Eden Prairie, MN) to a thermistor enclosure (Carlon, Memphis, TN). The synflex1300 tubing and thermistor enclosure were wrapped in silver metalized polyester (Mylar®) tape (CS Hyde Company, Inc., Lake Villa, IL) to reflect sunlight so the air temperature could be accurately measured. In the thermistor enclosure, the air traveled from the synflex1300 tubing to Tygon® tubing (Saint-Gobain Performance Plastics, Akron, OH) via a tube fitting (Swagelok, Solon, OH). A thermistor was built to measure the air temperature from each air intake. Each thermistor contained a nylon barb tee (Thogus, Avon Lake, Ohio) and a thermistor (BetaTHERM USA, LLC, Shrewsbury, MA), which were covered with epoxy (J-B Weld, Sulphur Springs, TX) as an electrical insulator and adhesive.

The air would then travel from the thermistor enclosure to the main enclosure (Vynckier Enclosure Systems Inc., Houston, TX) via Tygon® tubing and synflex1300 tubing. A water trap was installed in the tubing, which was built using a borosilicate glass scintillation vial (Fisher Scientific, Pittsburg, PA) and a nylon barb elbow held together with epoxy. From the water trap, the air travelled to the solenoid and then to the gas analyzer through a flow meter. From the gas analyzer, the air travelled out the main enclosure to the outflow via the pump.

A CR10X data logger (Campbell Scientific, Logan, UT) was installed inside the main enclosure to record all measurements every five minutes. Relative humidity and air temperature were measured with a HMP60 relative humidity/temperature probe (Vaisala,

Woburn, MA) placed inside a gill radiation shield (RM Young, Traverse City, MI) at a height of 30 cm located on the side of the main enclosure. Additional supporting measurements (R_N, G) are described specific to each of two field campaigns in the following sections.

The Bowen Ratio Energy Balance (BREB) was determined each 30 minutes and then recomputed using a moving average (n = 3) for each hour to smooth short-term fluctuations. Data from the MBR systems were rejected for the following conditions; $-1.05 > \beta > -0.95$. The reason for using this criteria is because the denominator approaches zero in Eq. (3), resulting in LE and H values of abnormally large magnitude. This condition usually occurs around sunset or sunrise and during precipitation when the direction of the temperature gradient is opposite of the vapor flux gradient (Perez et al., 1999). Data were also rejected during precipitation because ET was assumed to be near zero.

Field Campaigns

Vineyard

The BREB was estimated with MBR systems and supplementary data at a commercial vineyard, elevation 366 m (Fig. 2.2), located near Dobson, NC. The predominate soil type is the Fairview series (fine, kaolinitic, mesic, Typic Kanhapludult) with a sandy clay loam surface texture. The mean annual precipitation is 112 cm and the mean annual air temperature is 13$^\mathrm{o}$C (USDA-NRCS Web Soil Survey). The site is located on gently rolling hills with a slope of 2-15%. The site has single-curtain, bilateral cordon-trained Chardonnay (*Vitis vinifera*) grapevines planted in 2001. The vine rows are oriented north-south with a row spacing of 2.7 m. The width of the grassed inter-row is 1.5-1.8 m, which contains weedy fescue (*Festuca arundinacea*), and the width of the bare soil below the vine row is 0.9-1.2 m.

Grapevine canopy width varied between 0.3-0.8 m and canopy height from the ground varied between 0.9-1.9 m, and the height of the canopy from the cordon varied between 0.3-1.4 m. Canopy dimensions varied within the growing season.

Two treatments (bare soil and fescue) were maintained in the inter-row (Fig. 2.3). On March 1, 2011 six plots (three plots per treatment) were laid out at the study site each measuring 6.1 m down the inter-row with a 1.5 m buffer zone on either end for a total length of 7.6 m. Each plot was as wide as the distance between the vine rows (2.7 m). A non-selective, contact herbicide, RELY® (Bayer CropScience, Leverkusen, Germany), was sprayed to eliminate vegetation in the bare soil plots.

On April 7, 2011 five MBR systems were installed at the study site. Data were continuously collected through April 2012. All but two of the plots contained an MBR system (i.e., two MBR systems for each treatment) with the fifth MBR system installed directly underneath the vine row. The study site, except for the bare soil inter-row plots, was maintained in a way to best replicate the surrounding management practices. Site maintenance included mowing the grass, pruning the grapevines, spraying the grapevines, and spraying any vegetation present in the bare soil plots and in the vine rows.

Supplemental data used to complete the BREB include net radiation, soil water content, soil temperature, soil heat flux, and atmospheric pressure. A net radiometer and a soil heat flux plate were installed in each treatment to measure net radiation and soil heat flux, respectively. The soil heat flux plates (REBS, Seattle, WA) were installed at a depth of 6 cm. A CS-616 soil water content reflectometer (Campbell Scientific) was installed horizontally at a depth of 3 cm in the middle of each plot. Soil temperature was measured by

two thermocouples that were installed at a depth of 2 and 4 cm in each plot that contained a soil heat flux plate. Soil water content and soil temperature were used to correct for energy storage change above the heat flux plates (Sauer and Horton, 2005). The thermocouples were built using thermocouple wire (Omega, Stamford, CT) and OmegaBond 101 epoxy (Omega). Net radiation was measured using NR Lite2 net radiometers (Kipp and Zonen, Bohemia, NY) placed about 23.5 cm above the surface and in the middle of the inter-row. Due to a limited number of channels on each CR10X data logger, an additional CR1000 data logger (Campbell Scientific) was placed in the field to record soil temperature and soil water content data.

The BREB under the vine row was estimated with a similar method as was used in the inter-row, except the soil water content and soil temperature were measured at slightly different depths. A CS-615 soil water content reflectometer (Campbell Scientific) was installed horizontally at a depth of 6 cm and the soil temperature was measured at depths of 1.5 and 4.5 cm beneath the vine row with two thermocouples. These data were recorded on a CR23X data logger (Campbell Scientific).

A barometer (Vaisala, model PTB101b) was installed in one of the MBR systems to measure atmospheric pressure (mbar) every 5 minutes. However, due to logging errors, the LI-7500 open path CO_2/H_2O gas analyzer (LI-COR) that was part of the above canopy eddy covariance system (discussed below) provided atmospheric pressure (kPa) for part of the study. A tipping bucket rain gauge (Texas Electronics, Dallas, TX) provided precipitation measurements (mm).

The MBR systems were compared to the lysimeter method for both treatments in the inter-row for three different time periods. The micro-lysimeters (MLs) were built using a design similar to Heitman et al. (2010) and Singer et al. (2010). SDR 21 PVC pipe with an inside diameter of 8 cm was cut into 10 cm long sections. Each 10 cm x 8 cm section was beveled with a lathe on one end to provide a cutting edge when the lysimeters were hammered into the ground. On March 1, 2011 five MLs were installed in three nests per plot (45 total per treatment). The MLs were installed vertically into the ground until the top of each ML was flush with the surface.

On June 14, 2011 at approximately 12:00 pm a ML from two nests in each plot was extracted. Immediately after each ML was extracted a rag was used to clean off any soil remaining on the outside of the PVC pipe. In order to disrupt hydraulic contact between the soil in the ML and the soil directly underneath the ML, a thin plastic bag was used to cover the bottom opening of the PVC pipe, which was held in place by a rubber band and tape. Each ML was weighed with a balance that had a precision of 0.01 g and then reinstalled in the same position it held prior to the extraction.

After six hours, the same MLs were extracted at 6:00 pm, wiped off with a rag to rid it of any soil collected on the side, weighed, and reinstalled. The same process was repeated at 6:00 am on June 15, 2011, except an additional ML from the same nests were extracted at that time, wiped off, wrapped with a plastic bag, weighed, and reinstalled. Six hours later, at about 12:00 pm the same two MLs from each nest in use were extracted, wiped off, weighed, and reinstalled. At each time step, the extraction, weighing, and reinstallation were performed one plot at a time. This same procedure was carried out again on July 28-29 and

August 15-16, 2011. However, an extra time period was measured on July 29 and August 16. Data from the MBRs systems were compared to the MLs by integrating fluxes from the MBR systems for corresponding time intervals. However, due to power outage and inconsistent measurements from one of the gas analyzers, only one MBR system was used for each treatment for comparing to the MLs. Each ML estimate represents the mean of at least six measurements per interval.

The MBR systems were also compared to an eddy covariance (EC) system installed at 3 m above the canopy. The EC system consisted of a CSAT3 three dimensional sonic anemometer (Campbell Scientific) and a LI-7500 open path CO_2/H_2O Gas Analyzer. The EC system, placed at 3 m height, was intended to measure the energy fluxes at the system-level for the vineyard, which included only grassed-inter-rows. Comparison between the MBR and EC methods were only made when there was no grapevine transpiration (November-February). The pooled daily ET from the MBR systems in the fescue inter-row and in the vine row were spatially weighted and compared to the vineyard ET estimated by the EC system. The spatial weighting was initially set at 0.67 and 0.33 for inter-row and below-vine, respectively, based on approximate measured dimensions. We also attempted to optimize the comparison by adjusting the spatial weighting via minimizing the sum of square error for this comparison.

Bare field site

The MBR systems were temporarily placed at a second study site located at the North Carolina State University Central Crops Research Station in Clayton, NC for a short-duration test. The site is in the upper coastal plain on relatively flat terrain (2-6 % slope). The

elevation is approximately 107 m and the dominant soil types are the Norfolk series (fine-loamy, kaolinitic, thermic Typic Kandiudult) and Varina series (fine, kaolinitic, thermic Plinthic Paleudult) both with a loamy sand surface texture (USDA-NRCS Web Soil Survey). A 6.1 m x 4.6 m bare plot was maintained at the site and was surrounded by a tilled field. Between March 19 and March 20, 2012 two MBR systems were placed in the bare plot with the air intakes placed 1 and 6 cm above the surface. Two solar panels and four batteries were installed to provide power to the MBR systems. On April 16, 2012 a third MBR system replaced one of the two installed MBR systems in the bare plot.

The BREB was estimated at this site from March 19 through April 30, 2012. A weather station was installed in the bare plot in the spring of 2011 that provided net radiation (NR Lite2), relative humidity, and temperature measurements (HMP60). A nearby weather station provided precipitation and wind speed measurements. A soil heat flux plate (REBS, Seattle, WA) was installed at a depth of 4 cm. A CS-616 soil water content reflectometer was placed at 0-4 cm in order to correct for energy storage change above the soil heat flux plate. Thermocouples were used to provide soil temperature measurements at depths of 1.8 and 3.6 cm. The same procedure used at the vineyard site was used to correct for the energy storage above the heat flux plate at the bare field site.

A second comparison between a MBR system and the MLs was performed. The same MLs described above were used at Clayton. Due to an error with one of the thermistors, only one MBR system was used for comparing the two methods at Clayton. Thirty-two MLs were installed in three nests in the bare plot. Four MLs were extracted, weighed, and reinstalled at 10:00 am, 2:00 pm, and 6:00 pm on March 23, 2012. A series of ML experiments were run

on March 26-30. The same time steps from March 23 were used during this second trial. However, on March 26 and 27, MLs were extracted at 6:00 am to measure ET between 6:00 am and 10:00 am. The ET rate during this time period was found to be near zero, so this time interval was excluded for the rest of the ML experiment. Each ML estimate represents the mean of at least four measurements per interval.

Results and Discussion

Field Observations (BREB)

Representative clear sky BREBs computed for fescue and bare soil conditions in the inter-row at the vineyard site are shown in Fig. 2.4. Daily trends show the energy fluxes near zero during the night. Beginning around sunrise, when incoming radiation gradually becomes greater than outgoing radiation, the energy fluxes become positive. Throughout the day, the energy fluxes follow a similar trend to the net radiation in that they increase and usually peak around solar noon and then decrease as the sun begins to set.

Seasonal changes in the energy fluxes are also observed in Fig. 2.4. The net radiation is greatest during the spring and summer (Fig. 2.4A-2.4D) and then decreases during the fall and winter (Fig. 2.4E & 2.4F). The duration of positive net radiation becomes shorter as the grapevine canopy begins to develop (Fig. 2.4C & 2.4D) and the length of daylight decreases (Fig. 2.4E & 2.4F). Table 2.1 shows the amount of net radiation partitioned to latent heat and sensible heat between 8:00 am and 6:00 pm EST (Eastern Standard Time) for both treatments on representative days. The amount of net radiation partitioned to the latent heat flux decreases during the winter due to grass in the inter-row entering winter dormancy and less

atmospheric evaporative demand. Only the sensible heat flux increases during the winter when less energy is partitioned to the latent and soil heat fluxes (Fig. 2.4E & 2.4F).

The soil heat flux differed considerably between the treatments for the study period. For the bare soil, the daily soil heat flux ranged from about -0.6 to 3.3 MJ m^{-2} and the daily average was 1.42 MJ m^{-2}. For the fescue, the daily soil heat flux ranged from about -0.3 to 1.8 MJ m^{-2} and the daily average was 0.59 MJ m^{-2}. This difference is due to the bare soil surface lacking ground cover. Less ground cover causes a greater daily soil heat flux because the soil is left exposed to the atmosphere and there is greater thermal conductivity due to greater soil water content in the bare soil. Also, because less energy is partitioned to the latent heat flux and the net radiation is slightly higher for the bare soil, there is more energy available for the soil heat flux.

Both the daily and seasonal trends in the energy fluxes appear reasonable (Fig. 2.4) with a few small anomalies. Because the BREB is based on measured water vapor and air temperature gradients, any subtle changes in these measurements will be reflected in the computed energy balance. This may result in irregular spikes as observed for the bare soil condition (Fig. 2.4), particularly during the night when strong winds and overcast skies create near-neutral conditions (Arya, 2001). For example, a strong gust of wind may cause the air temperature and water vapor gradients to be less pronounced causing less certainty in the computed direction (i.e. positive or negative) and magnitude of the latent heat and sensible heat even with adequate fetch.

Other studies' estimates of the inter-row ET in similar settings as this study may help further explain the present results. Centinari et al. (2009) measured ET of the fescue in the

inter-row of a vineyard located in Geneva, New York using MLs. A comparison between ET measured for both vineyards of similar training systems (i.e., single curtain) for six representative days is shown in Table 2.2. The range in ET for the New York vineyard is 1.3 to 2.5 mm d^{-1} compared to 2.7 to 3.6 mm d^{-1} at the North Carolina vineyard. Heilman et al. (1994) measured daily evaporation above a bare-soil inter-row in a west Texas vineyard over an eight day period beginning on May 31 (DOY 152). The range in evaporation was 1.3 to 2.7 mm d^{-1}, which was estimated between 6:00 am and 8:00 pm LST (Local Standard Time) for each day. This range is similar, but less than what was estimated for daily evaporation at the North Carolina vineyard during the same time of year over the bare soil inter-row; 1.9 to 3.4 mm d^{-1}. It is reasonable for the North Carolina vineyard to have greater ET than the New York vineyard because the temperature is warmer in North Carolina and there is adequate soil moisture resulting in greater ET. The difference between ET at the Texas and North Carolina vineyards is likely due to the condition of the bare soil (e.g., soil texture, moisture) in the inter-row. Thus, the results of the above studies are similar to the ET rates measured in our study, and suggests that the MBR systems provide reasonable estimates of ET.

Comparisons of MBR systems to other methods

Lysimetry

The relationship between the ET rates from MLs and MBR systems for the inter-row at the vineyard site is shown in Fig. 2.5. Correlation was slightly stronger for the grass (R^2 = 0.99, Fig. 2.5A) than for the bare soil (R^2 = 0.89, Fig. 2.5B) inter-row. The ET rates, as determined by the MBR systems, tended to overestimate the ML ET rates, as ET rates increased (fescue slope: 1.17, bare soil slope: 1.60). The greater overestimation of the MBR

ET rate in the bare soil plots may be due to limited plot sizes. This will cause some influence from the fescue inter-row ET in the surrounding vineyard to increase the MBR ET rate in the bare soil plots. Also, there is likely greater surface roughness in the bare soil compared to the evenly-mowed fescue. The MBR systems are sensitive to surface roughness because as surface roughness increases, turbulence may cause the temperature gradients to become less pronounced, which results in greater estimated ET (Eq. 2).

The relationship between the methods at the bare field site is shown in Fig. 2.6. The correlation is not as good ($R^2 = 0.66$) as that at the vineyard site. One reason why the correlation is weaker at the bare soil site compared to the vineyard site may be due to wind speed. Strong wind gusts may create some error in the measured air temperature and water vapor gradients. The average wind speed during the measured time intervals at the bare field site was 2.9 m s^{-1} at a height of 2 m. The average wind speed at the vineyard corrected for 2 m (Allen et al., 1998) was much less; 1.0 m s^{-1}. However, the slope, 0.98, found in the relationship between both methods at the bare soil site suggests that the MBR ET rates are less biased and do not indicate overestimation, unlike the MBR systems at the vineyard site. Observations at the bare soil site further support the interpretation that the bare soil ET rates measured in the inter-row of the vineyard are elevated by ET from the grassed inter-rows in the surrounding vineyard. Pooled ET rates for both methods in the vineyard and bare field sites are compared in Fig. 2.7. The ET rates show strong correlation ($R^2 = 0.87$) when pooled together across several surface conditions with limited bias (slope = 1.13). We also excluded nighttime ET rates (i.e., 6:00 pm – 6:00 am) and found that there is less bias (slope = 0.96), but the correlation is weakened ($R^2 = 0.74$) (data not shown).

Other studies have compared MBR approaches with lysimeter methods for different systems. Ashktorab et al. (1989) compared ET from a similar MBR system with a 6.1 m diameter, 90 cm deep weighing lysimeter over a bare loam soil in California. In their analysis they found a correlation with $R^2 = 0.83$ and slope = 0.82, implying that the MBR system underestimated ET. Zeggaf et al. (2008) used a traditional Bowen ratio system to measure ET above a maize canopy and a similar MBR system to measure ET underneath the canopy. A 1.5 m diameter, 1.5 m deep weighing lysimeter was used to measure the ET rate from the maize field. Below-canopy ET was assumed to be the difference between ET from the maize field and that from the maize itself, which was measured with sap flow gauges. Their correlation had $R^2 = 0.72$ with a slope = 0.89 above the maize field and $R^2 = 0.36$ with a slope = 0.78 above the bare soil surface. The weaker correlation over a bare soil inter-row found in the Zeggaf et al. (2008) study may be due to not directly measuring bare soil evaporation. Any error associated with the weighing lysimeter method and sap flow gauge method would have been more pronounced in the evaporation rates of the bare soil because it was assumed to be a difference of the two methods. Although the agricultural systems in the above studies are different, the estimated correlations along with the correlation found in this study ($R^2 = 0.87$, slope = 1.13) suggests there is good potential for using the MBR method.

Eddy Covariance (EC)

The correlation ($R^2 = 0.80$, slope = 0.80) for the ET rates from the EC system and MBR systems are shown for clear days during the vines' dormant season (November-February) in Fig. 2.8A. The average ET rate from the EC system was lower than the average ET rate from the MBR systems by 8%. The estimated correlation ($R^2 = 0.80$, slope = 0.75)

between the ET rates from the EC system and MBR systems using spatially weighted row widths as determined by the least sum of square error are shown in Fig. 2.8B. Optimizing the comparison between the MBR system and EC system does not appear to make an improvement in the correlation. This changed the width of the grassed inter-row from 1.84 to 1.70 m and the width of the bare strip width under the vine row from 0.90 to 1.04 m. Though the resulting widths are realistic and representative of the range of measured conditions within the vineyard, the correlation changed only slightly. Differences in measured ET may be due to the EC system representing a much larger area than the MBR systems so that any areas where the microclimate may vary considerably will have less influence on the EC system method. In other words, the MBR systems may be in a relatively dry part of the vineyard compared to the area that the EC system sees. Errors may also be associated with the different principles and measurements used to measure the vineyard latent heat flux.

Dugas et al. (1991) compared EC systems with Bowen ratio systems over an irrigated spring wheat crop in Arizona. On average, the latent heat flux from the EC systems underestimated the latent heat flux from the Bowen ratio systems by 28% compared to 8% at the North Carolina site. Fritschen et al. (1992) compared the latent heat flux from EC systems with Bowen ratio systems over a freshly burned field and over a grass field. In the burned field, an average correlation ($R^2 = 0.49$) and an average slope (0.58) were estimated. However, there was a large range in data (R^2: 0.002 to 0.89, slope: -0.57 to 1.13) over the sixteen-day period. In the grass field, where only one day's data was reported, a stronger correlation ($R^2 = 0.76$) and an improved slope of the regression relationship (1.11) were observed. As was the case for the lysimetry studies, the estimated correlations for the above

EC and Bowen ratio studies along with the correlation found in this study ($R^2 = 0.80$, slope = 0.80) also suggests the potential for using the MBR method in a range of systems.

<u>Summary and Conclusion</u>

The energy fluxes estimated by the MBR systems show reasonable trends over both short (daily) and long (seasonal) time periods. The measured ET rates are similar to the vapor fluxes measured by other researchers in similar conditions in the inter-row of a vineyard. ET rates were well correlated between both the MBR systems and MLs ($R^2 = 0.87$, slope = 1.13) and between the MBR systems and the EC system ($R^2 = 0.80$, slope = 0.80). Comparison of the correlation between the different methods in this study to other correlations found between similar methods, supports the validity of the MBR systems. In conclusion, the MBR systems provided a reasonable approach for estimating vineyard inter-row energy fluxes and evapotranspiration. Because MBR systems are able to measure a small footprint, it can be used to continuously measure the energy fluxes for components within a whole-system. The MBR systems may be used to separate the energy fluxes of individual components in systems other than a vineyard, although, further investigation is needed to support this conclusion. Understanding how each component contributes to whole-system energy flux is useful for many applications from agricultural management practices to creating water budgets in a natural environment.

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Chapter 3: Implications of an Inter-Row Fescue Cover Crop on the Below-Canopy

Water Budget in a North Carolina Vineyard

<u>**Introduction**</u>

Management of ground surface conditions (e.g., cover crops, weeds, mulch, and bare soil) below a crop canopy can have important implications for the canopy micro-climate (Stigter, 1984; Sauer and Norman, 1995). Vineyards, in particular, provide a unique environment where the grapevines interfere with water and energy transport from the surface to the atmosphere (Heilman et al., 1994; Hicks, 1973; Weiss and Allen, 1976a, 1976b), which, when coupled with evapotranspiration (ET) processes occurring below the grape canopy, influences the canopy microclimate. Many studies have examined the influence of the grapevine canopy architecture on the canopy microclimate (Shaulis et al., 1966; Shaulis and May, 1971; Smart, 1985; Smart, 1988; Morsil et al., 1992; Heilman et al., 1996). There is, however, a lack of research that examines how different inter-row conditions (i.e., ground covers) affect below-canopy humidity.

Canopy humidity is of particular concern in southeastern U.S. vineyards due to the presence of many fungal diseases that thrive in warm, humid climates (Carroll and Wilcox, 2003; Willocquet and Clerjeau, 1998; Thomas et al., 1988; van den Berg and Lentz, 1968). In the U.S., common fungal diseases include powdery mildew and bunch rot (Lipps, 2010; Wolf, 2008). Fungal diseases can reduce carbon assimilation (Nail and Howell, 2004; Moriondo, 2005), which then adversely affects crop growth and yield. Management practices have adapted to reduce fungal diseases by means of training, pruning, and the application of

fungicides (Lipps, 2010; Wolf, 2008; English et al., 1990; English et al., 1989). Considering effects of ground surface management may also be important to limiting incidence of disease.

In addition to fungal diseases, vine vigor is also a common problem in vineyards. Vine vigor can lead to undesirable grape composition, which leads to poor quality wine (Dry and Loveys, 1998). Common practice is to have fescue or other grasses established within the inter-row of a vineyard. It is presumed that fescue may benefit the grapevines by competing for soil water, which might also decrease vine vigor (Celette et al., 2008; Celette et al., 2005; Guerra and Steenwerth, 2012; Ripoche et al., 2011). However, along with the potential for increased water use, there is an increased ET water vapor stream into the canopy, which also may contribute to high canopy humidity.

With the potential importance of below-canopy management on canopy humidity and water availability for vineyard systems, the goal of this study was to determine the influence of fescue cover crops on below-canopy water budgets. Using novel instrumentation developed to measure ET in the inter-row (Chapter 2), we compared water vapor fluxes (i.e., ET) for fescue and bare surface conditions. While the bare surface condition may not provide a viable alternative management scenario due to practical considerations, it provides a means to determine the consequence of having active ET in the inter-row (fescue) vs. only evaporation. We hypothesize that fescue is more efficient at extracting water from the soil when compared to bare soil evaporation, possibly limiting water availability for the grapes, but also increasing below-canopy humidity.

Materials and Methods

Vineyard

The vineyard system examined in the experiments is explained in detail in Chapter 2. In general it was a commercial vineyard site located near Dobson, NC (Fig. 2.2). The site has single-curtain, bilateral cordon-trained Chardonnay (*Vitis vinifera*) planted in vine rows oriented north-south with a row spacing of 2.7 m. The width of the grassed inter-row is 1.5-1.8 m, which contains weedy fescue (*Festuca arundinacea*), and the width of the bare soil below the vine row is 0.9-1.2 m. Grapevine canopy width varied between 0.3-0.8 m and canopy height from the ground varied between 0.9-1.9 m, and the height of the canopy from the cordon varied between 0.3-1.4 m. Canopy dimensions varied within the grape growing season (i.e. March – October). The tire tracks from field equipment were located approximately 0.7 m from the center of the vine row. The predominate soil type is the Fairview series (fine, kaolinitic, mesic, Typic Kanhapludult) with a sandy clay loam surface texture.

Bowen ratio energy balance

The Bowen ratio energy balance (BREB) of the inter-row was estimated with micro-Bowen ratio (MBR) systems (Fig. 2.1) and supplementary data, from April 2011 – April 2012. Two treatments (bare soil and fescue) were maintained in the vineyard inter-row (Fig. 2.3). Three plots per treatment were established at the study site, each measuring a total of 7.6 m down the inter-row; plots were as wide as the distance between the vine rows (2.7 m). Four MBR systems were installed at the vineyard (two MBR systems per treatment). The study site, except for the bare soil inter-row plots, was maintained in a way to best replicate

the surrounding management practices. The fescue in the inter-row of the surrounding vineyard was mowed about every 10-14 days. The height of the fescue ranged from about 6-15 cm. Supplemental data used to complete the BREB include net radiation, soil water content, soil temperature, soil heat flux, and atmospheric pressure. For further detail, refer to Ch.2 Materials and Methods.

Soil water & grapevine stress

Soil water depletion was estimated by measuring the soil volumetric water content with a CS-616 soil water content reflectometer (Campbell Scientific, Logan, UT). The soil water content sensors were placed vertically at a depth of 10-38 cm in the middle of each plot and averaged for each treatment. Gravimetric samples collected during the observation period were used to develop a calibration relationship between sensor estimates and actual soil water content. Soil water content values from the sensors were subsequently corrected according to this calibration relationship.

Grapevine stress was estimated with a Model 600 pressure chamber instrument (PMS Instrument Company, Albany, OR) on grapevines that were surrounded by grassed inter-rows (i.e., conventional management practice). Following a method similar to Chone et al. (2001), the pressure chamber was used to estimate grapevine stress by measuring the leaf water potential. The leaf water potential was measured on at least fifteen mature leaves for seven different days throughout the 2011 grape growing season. The leaves were bagged one hour prior to measurements to prevent leaf transpiration so the leaf water potential would equal the stem water potential (Begg and Turner, 1970). Grapevine stress was assumed to occur if the measured pressure dropped below -10 bars (Bogart, n.d.).

Soil physical properties

Soil samples were collected in order to measure the water retention, bulk density, and particle size distribution. Soil cores centered at a depth of 3.8, 11.4, and 42 cm were excavated in the center of the inter-row, tire track, and vine row. Results from all samples were averaged for the water retention data regardless of depth and position. The soil cores centered at 3.8 and 11.4 cm were excavated using an Uhland core sampler with cores that have an inside diameter of 7.62 cm and a height of 7.62 cm. The soil cores centered at 42 cm were excavated with an AMS soil sampler (AMS, Inc., American Falls, ID) with cores that have an inside diameter of 6.10 cm and a height of 7.62 cm. After excavation, the soil cores were placed in a bag, wrapped and taped to prevent water loss, and labeled for later use.

Low pressure water retention measurements were performed on the intact cores using a method similar to Klute and Page (1982). In the lab, the soil cores were weighed and then placed in Buchner funnels containing a 1 bar ceramic plate. The soil cores and ceramic plates were saturated and a graduated cylinder was placed at the bottom of the funnel in order to collect the water that was drained once pressure had been applied to the cores via a central pressurized air reservoir. Water retention measurements were performed for the following pressures: 10, 33.33, and 50 kPa. Pressure was applied for at least twenty-four hours or until no more water was lost from the cores. The volume of water drained at each pressure was recorded before applying the next pressure. The volumetric water content at the 33.33 kPa pressure was used as an estimate for the field capacity (FC; McIntyre, 1974; Addiscott and Whitmore, 1991).

After applying the above pressures, the soil was removed from the cores and dried in the oven. Once the soil was oven-dried, the soil was weighed to determine the bulk density (Troeh and Thompson, 2005). The soil samples were then placed in a grinder and passed through a 2 mm sieve before particle size analysis and water retention measurements in the high pressure system were conducted. The particle size was measured using the hydrometer method (Day, 1965).

Water retention measurements in the high pressure system were determined using a procedure similar to Klute and Dirksen (1986). The soil samples were placed in rubber rings on three pre-saturated ceramic plates, each to be used for a specific pressure in the high pressure system. Samples were saturated on each plate and placed in the chambers. After closing the chamber, the following pressures were applied to the samples in separate runs: 100, 500, and 1500 kPa. After four days, when hydraulic equilibrium was assumed to have been reached, the samples were removed from plates and weighed. The samples were placed in an oven and weighed again after oven-drying. Volumetric water content at each pressure was calculated using the bulk density measurements. The volumetric water content at the 1500 kPa pressure was used as an estimate of the permanent wilting point (PWP; Soil Science Society America, 1997). The plant available water was estimated by the difference between FC and PWP (Soil Science Society America, 1997).

Below-canopy humidity

The below-canopy humidity was directly measured with a HMP60 relative humidity/temperature probe (Vaisala, Woburn, MA) placed inside a gill radiation shield (RM Young, Traverse City, MI) 30 cm above the surface in each treatment in the inter-row (as

described in Chapter 2). At 30 cm the microclimate is assumed to be representative of the below-canopy climatic conditions. A HMP60 relative humidity/temperature probe was also placed at a height of 1.25 m above the surface of the inter-row. At 1.25 m the microclimate is assumed to be representative of the climatic conditions within the inter-row at the canopy height. A HMP45 relative humidity/temperature probe (Vaisala) was placed 3 m above the surface for above canopy climatic conditions.

Relative humidity model

At the measurement height of 30 cm and higher, the measured relative humidity is likely influenced by the surrounding vineyard, because the fetch extends beyond the vineyard inter-row. This was of concern for the bare surface plots, which differed from surrounding vineyard management. Thus, as an alternative to the measurements at 30 cm height, we also considered a simple, 1-D model encompassing the ground surface to the top of the canopy (Fig. 3.1). Unlike the measured relative humidity at 30 cm, the model includes inputs that were measured closer to the surface (i.e. surface vapor flux from the MBR systems) that do not require as much fetch, together with measured inputs above the canopy, not influenced by the inter-row treatments. The model was used to further estimate any affects the surface conditions have on the below-canopy relative humidity. The model begins with a simple balance of mass fluxes from the ground surface to above the canopy:

$$J_{cf} = g(C_f - C_a) = J_f \tag{1}$$

$$J_{cs} = g(C_s - C_a) = J_s \tag{2}$$

where J_{cf} and J_{cs} are the vapor fluxes from the canopy for the fescue and bare soil inter-row, respectively (mmol m^{-2} s^{-1}), g is the aerodynamic conductance above the canopy (mol m^{-2} s^{-}

[1]), C_f and C_s are the concentrations of water vapor within the canopy for the fescue and bare soil inter-row, respectively (mmol mol^{-1}), C_a is the concentration of water vapor above the canopy (mmol mol^{-1}, and J_f and J_s are the vapor fluxes from the surface for the fescue and bare soil inter-row, respectively (mmol m^{-2} s^{-1}). If we solve Eq. 1 and 2 for C_a, which we assume is independent of surface conditions, and set both equations equal to each other we have

$$C_f - C_s = (J_f - J_s)/g \tag{3}$$

If we then divide both sides of the equation by C_{sat}, which is the saturated concentration of water vapor above the canopy (mmol mol^{-1}), we have

$$((J_f - J_s)/g)/C_{sat} = \Delta RH \tag{4}$$

where ΔRH is the difference in relative humidity between the fescue and bare soil inter-row. The aerodynamic conductance was determined using the procedures as described by Campbell and Norman (1998) and McInnes and Heilman (2005). We assumed the vapor flux from the inter-row surface conditions can be measured by the MBR systems (as described in Chapter 2). The concentration of water vapor above the canopy was determined from measurements at 3 m height.

In addition to assuming the vapor flux is one-dimensional, several other assumptions must also be satisfied in order to apply Eq. 4 to the vineyard system. We assume that the flux from the canopy ($J_{c(f,s)}$) is controlled by the concentration gradient across the upper canopy. Increases in the canopy humidity ($C_{(f,s)}$) can enhance the vapor flux out of the canopy, but this effect is limited by g. We also assume that g is the same for both treatments (Eq. 3). We used SAS software version 9.2 (Cary, NC) to determine whether the correlation between the

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measured difference in relative humidity between the two treatments at 30 cm and the
modeled difference in relative humidity between the two treatments was significant (95%
confidence level).

Results and Discussion

Vineyard conditions

From April 2011 – April 2012, the average temperature for the greater Dobson area
was 15 $^{\circ}$C, which was warmer than the historical average temperature, 13 $^{\circ}$C (NC State
Climate Office). The total precipitation for the study period was 157 cm, compared to the
historical average annual precipitation, 119 cm (NC State Climate Office). During the grape
growing season (March - October), the total precipitation and average temperature were 111
cm and 19 $^{\circ}$C, respectively, compared to the historical averages of 83 cm and 17 $^{\circ}$C,
respectively (NC State Climate Office). The above average rainfall makes humidity in the
vineyard more of a concern, particularly during the grape growing season, because there was
likely more soil water available for ET. Warmer temperatures increase the atmospheric
evaporative demand, which further increases ET.

Evapotranspiration and soil water

The energy fluxes estimated by the BREB for representative days throughout the
study period are shown in Table 3.1. The fraction of available energy (i.e., $R_N - G$)
partitioned to the latent heat flux (i.e., ET) for the fescue inter-row ranged from 31-99%. As
was the case for other days not shown, the fraction of available energy partitioned to the
latent heat flux in the fescue inter-row varied but was mostly a function of the time of year.
During the grape growing season (i.e. March – October) the fraction of available energy

partitioned to the latent heat flux averaged 92%, which indicates grass was transpiring at near the maximum possible rate. During the dormant season for the grapes (November – February) the latent heat flux accounted for 63% of the available energy. The latent heat flux during the dormant season is a smaller proportion of the available energy likely because grass was entering winter dormancy and also because of less atmospheric evaporative demand associated with lower temperatures.

Comparing the latent heat flux of the fescue to that of the bare soil provides an indication of the consequence of active transpiration in the inter-row (i.e., ET for fescue vs. evaporation only for bare soil). The fraction of available energy partitioned to the latent heat flux for the bare soil inter-row ranged from 15-92% (Table 3.1). This partitioning, as was the case for the fescue inter-row, also varied throughout the year. The fraction of available energy partitioned to the latent heat flux during the grape growing season averaged 73%. During the grape dormant season, latent heat flux of the bare soil averaged 44% of available energy, likely due to less atmospheric evaporative demand. The differences in the daily ET between fescue and bare soil range from 0.22 - 1.89 mm with an average daily difference of 0.88 mm. The average differences in daily ET during the grape growing season and during the dormant season were 1.06 and 0.51 mm, respectively.

Another way to consider the difference in ET between the two treatments is by comparing the difference over a longer time scale (e.g., a month). Evapotranspiration (i.e., cumulative latent heat flux) for May 2011 for each treatment is shown in Fig. 3.2. Cumulative ET for the bare soil inter-row was 78 mm, which is 32% less than cumulative ET for the fescue inter-row, 115 mm. The difference between ET for the treatments becomes

more pronounced when observing the cumulative ET over longer time periods. This same

trend occurs over the entire grape growing season (data not shown). May ET for both

treatments was much less than the measured precipitation, 163 mm. However, because the

fescue ET constitutes a larger portion of this precipitation, the consequence for having fescue

in the inter-row is more water entering the below-canopy atmosphere.

More water entering the canopy atmosphere should be reflected by lower soil water

content. Inter-row soil water content was consistently lower for fescue when compared to

bare soil (Fig. 3.3). Fescue also depletes soil water at a greater rate than bare soil following

rainfall events as observed, for example, between days 148-158. This is consistent with the

greater ET observed in the fescue inter-row. The same trend was observed throughout the

grape growing season during dry-down periods (i.e., between rainfall events).

From water retention measurements, the soil water content at FC is 0.38 cm^3 cm^{-3} and

the soil water content at PWP is 0.27 cm^3 cm^{-3}, resulting in 0.11 cm^3 cm^{-3} plant available

water. These results are typical for a sandy clay loam (USDA-NRCS, 1998). It has been

reported that fescue in the inter-row benefits the grapevines by competing for soil water,

which could reduce vine vigor (Celette et al. 2008; Celette et al. 2005; Guerra and

Steenwerth 2012; Ripoche et al. 2011). However, in the present study the soil water content

seldom reaches the PWP for fescue (Fig. 3.3). Instead, the soil water content for both

treatments mostly remains within the range of readily available water, with slightly lower soil

water content in the fescue inter-row. Because the soil water remains readily available, there

does not seem to be much of an advantage to having fescue in the inter-row in terms of

limiting vine growth and vigor. The grapevine stress measurements collected for the standard

management system (i.e. fescue inter-row) also indicate that the soil water content was not low enough to cause any stress under typical management conditions in the surrounding vineyard (Table 3.2).

It should be noted that beginning around DOY 285 (Fig. 3.3) the rate of depletion of soil water for fescue is similar to the rate of depletion of soil water for bare soil due to similar daily ET during the dormant season (discussed above). This is likely due to less favorable conditions for transpiration (i.e. cooler temperatures) resulting in less atmospheric evaporative demand along with some of the grass entering winter dormancy (discussed above). Less transpiration will cause the soil water to be depleted at a lower rate in the winter compared to the depletion rate during spring and summer.

The BREB and soil water content measurements both show that fescue is more efficient at pumping water from the soil to the atmosphere, but with limited benefit in terms of reducing water availability. That fescue is more effective at pumping water from the soil to the atmosphere is further supported by considering the fraction of available energy partitioned to latent heat as a function of soil water content (Fig. 3.4). The fraction of available energy partitioned to the latent heat flux does not vary significantly with soil water content for fescue. With bare soil, however, the fraction of available energy partitioned to evaporation shows a stronger positive relationship with soil water content. In other words, fescue transpires water into the below-canopy atmosphere regardless of soil moisture conditions, whereas evaporation is reduced for bare soil as soil water content begins to decrease below field capacity. This is of concern because increased water transmitted into the canopy from below may elevate canopy humidity without the benefit of reducing vine vigor.

Below-canopy humidity measurements

The measured relative humidity for the bare soil and fescue inter-row conditions at a height of 30 cm for four representative days during the grape growing season is shown in Fig. 3.5. For both treatments, the relative humidity is highest during the night, decreases from morning to midday, and then increases again in late afternoon. The relative humidity ranges from around 37 to 97% and the temperature ranges from 14 to 34 ^{o}C. The relative humidity and temperature at times, particularly in the morning and evening, are ideal for fungal diseases to occur in both treatments. This was the case throughout the study period. The relative humidity was, on average, 2% higher in the fescue inter-row throughout the grape growing season. The greatest difference in the relative humidity occurred in June (~2.2%) and the smallest difference occurred in September (~1.0%). The difference in relative humidity between the two treatments was similar throughout the day (Fig. 3.5). The relative humidity was greater in the fescue inter-row because there was a greater incoming surface vapor flux (as discussed in the previous section).

Although differences in relative humidity between treatments may seem small, the difference may be significant enough to increase the likelihood of fungal disease occurrence, especially during the day when temperatures are warmer. For instance, optimal conditions for bunch rot occurs around 94% relative humidity (Snow, 1949; Van der berg and Lentz, 1968; Thomas et al., 1988). The number of times the relative humidity at 30 cm exceeded 93% during the grape growing season using 30 min. time intervals for fescue was 2,200, whereas for bare soil it was 1,418. Despite a small difference in relative humidity at 30 cm, the relative humidity in the fescue inter-row exceeds the 93% relative humidity threshold much

more frequently (43%) than the relative humidity in the bare soil inter-row. The relative

humidity at 30 cm is not only indicative of the risk for grapevine diseases in the canopy, but

also may be a good indicator of the presence of fungal diseases on the vineyard floor since

some fungi such as *Eutypa, Botrytis,* and *Botryosphaeriaceae* that cause grapevine diseases

can be present in dead tissue left on the vineyard floor (Marois et al., 1992; Wolf, 2008;

Urbez-Torres, 2010).

Modeling below-canopy humidity

A modeling approach (Eq. 4) was also used for analysis because the measured

relative humidity at 30 cm in the bare soil treatment is likely influenced by the surrounding

vineyard (i.e., fetch for the 30 cm measurement height extends beyond the bare soil plot

treatments). The surface vapor flux (measured by the MBR systems) used as a model input

was measured closer to the surface and the measured inputs above the canopy were not

influenced by the inter-row treatments. The comparison between the modeled difference in

relative humidity and the measured difference in relative humidity at 30 cm between the two

treatments during the grape growing season for relatively clear sky days is shown in Fig. 3.6.

The modeled approach estimates the fescue inter-row vapor flux increases the relative

humidity by an average of 5% compared to an estimated increase of 2% from direct

measurements. The range in the modeled difference in relative humidity between fescue and

bare soil is -1 to 13% and the range for the measured difference is 0 to 7%. Both approaches

show that the fescue inter-row vapor flux increases the below-canopy relative humidity.

The slope of the regression relationship (1.55) shows that the modeled difference in

relative humidity overestimates the measured difference in relative humidity. The correlation

is not strong (R^2 = 0.51), but the estimated p-value is less than 0.0001, indicating a significant correlation. The overestimation of the modeled approach compared to the measured approach is not surprising. It is expected that the modeled approach will overestimate the measured approach because of the influence of limited plot size on the 30 cm height measurements in the present experiments. If relative humidity measurements were made in larger bare soil plots, we suspect that the difference in the measured relative humidity values would become more similar to the modeled difference in relative humidity. If we assume the modeled approach is more representative of the difference between the relative humidity for the bare soil and fescue inter-rows and look at another relative humidity threshold, the difference in relative humidity seems to be a concern. If we use, for example, a relative humidity threshold greater than 74% for the occurrence of *Aspergillus* (Snow, 1949) we observe this threshold is met by the fescue inter-row for sixteen of the thirty-nine days shown in Fig. 3.6, compared to eleven of the thirty-nine days in the bare soil inter-row. Thus, although the difference in relative humidity on average is small, there are times when the difference in relative humidity is large enough that certain thresholds are met by only the fescue inter-row conditions, which may imply the need for altering management practices.

The problem with an overabundance of moisture has been addressed by means of the application of fungicides, removal of leaves and dead tissue, and site selection (English et al., 1990; English et al., 1989; Marois et al., 1992; Wolf, 2008; Giese, 2010; Lipps, 2010). However, in order to improve grapevine production, further adaptation may be needed. Management practices such as changing the system geometry (e.g., width of grassed inter-row), using grass that transpires less than fescue, or using mulch in the inter-row that limits

the amount of water entering the canopy microclimate may help to alleviate issues with commonly occurring fungal diseases. Creating less ideal conditions for fungal diseases will improve wine quality and quantity (i.e., from increased grape yields), cut management costs (e.g., hand labor), and possibly reduce the amount of fungicide applied.

Summary and Conclusion

The MBR system ET measurements show that the vapor flux is greater for the fescue inter-row compared to the bare soil inter-row. The cumulative monthly difference in ET for fescue and bare soil in May was 37 mm (32%). This led to more rapid soil water depletion and lower water contents in the fescue inter-row. The soil water content did not, however, reach the permanent wilting point for most of the study period, which, along with lack of measureable grapevine stress, suggests that the fescue may not compete for soil water with the grapevines to the extent that vine vigor is decreased.

Measured and modeled differences in the relative humidity between fescue and bare soil treatments indicate that the higher fescue inter-row vapor flux does increase the relative humidity compared to the bare soil inter-row. The measured difference in relative humidity would be expected to increase if the bare soil plots were larger, and would thus more closely resemble the modeled approach, which indicated relative humidity differences on the order of 5%. Both the vapor flux and relative humidity data suggest that fescue in the inter-row may have adverse affects on the below-canopy humidity, which may lead to a greater risk of grapevine fungal diseases. Reconsidering vineyard management practices in the inter-row may lead to less occurrences of grapevine fungal diseases and improve production for European grape varieties in North Carolina and other warm, humid regions.

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Chapter 4: Summary and Conclusions

We studied the water dynamics of a North Carolina vineyard in order to address problems associated with high canopy humidity. Grapevines, when mature, disrupt wind patterns and create an obstacle for water and energy transfer to the atmosphere from the ground surface. Therefore, we focused on understanding the contribution of evapotranspiration (ET) from the ground surface to canopy humidity. Our goal was to understand the consequence of having fescue in the inter-row (i.e., conventional management practice) on the water dynamics of the vineyard by comparing fescue ET to bare soil evaporation in the inter-row.

A micro-Bowen ratio (MBR) system was implemented as a method to measure ET of the inter-row within the context of the whole vineyard system. This method was first tested against other methods used to measure ET, which were micro-lysimeters and an eddy covariance system. We found that the MBR systems were in good agreement with these other two methods and, thus, provided a reasonable approach for estimating vineyard inter-row energy fluxes and ET. Because the MBR system requires a smaller footprint than other standard methods (eddy covariance), and is less destructive and labor intensive than other small-scale methods (micro-lysimeters), we were able to continuously measure ET of the vineyard inter-row.

Small inter-row field plots were established within a commercial vineyard to compare two treatments: conventional inter-row management with grass and bare soil. We observed greater ET in the fescue inter-row compared to the bare soil inter-row. The increased ET was correlated with a greater decrease in soil water content. However, soil water content was not

depleted to a level that provided any beneficial competition for soil water between the fescue and grapevines.

The elevated ET in the fescue inter-row increased the humidity in the vineyard, which was estimated by direct measurements and a model. The modeled approach overestimated the difference in the relative humidity between the two inter-row surface conditions compared to the measured approach. This is likely due to the limited size of the bare soil plots. The measured relative humidity was likely being influenced by the surrounding vineyard, which contained fescue in the inter-row. If the relative humidity measurements were taken in larger bare plots the measured difference in the relative humidity between the two treatments would probably be greater, which would be more representative of the modeled results.

The measured and modeled difference in the relative humidity averaged 2 and 5%, respectively, and ranged from near 0 to 13 %. The relative humidity in the fescue inter-row met the fungal disease thresholds for bunch rot and *Aspergillus* more often than the bare soil. Both the measured and modeled approach suggest that fescue in the inter-row may lead to a higher risk of fungal diseases due to increased humidity.

Future Work

Further adaptation in vineyard management will lead to a more productive agricultural system. Some potential management practices that could lead to a more productive vineyard by addressing the issue with high humidity include using grass in the inter-row that transpires less than fescue, changing the system geometry such as altering the grassed inter-row width, or using different ground cover in the inter-row such as mulch. If

less transpiration occurs in the inter-row, then we can assume that less water will enter the canopy atmosphere, which may decrease canopy humidity and lower the risk of fungal diseases.

We suggest that future studies consider how inter-row conditions will influence the below-canopy humidity by comparing the humidity over treatments with adequate plot sizes. However, this may be a problem because establishing bare soil in the inter-row of a large area may lead to significant erosion. Also, a lot of resources would be needed to establish and maintain different grass species in the inter-row. One example for testing how different inter-row management practices influence the below-canopy humidity would be establishing a field trial that measures the below-canopy humidity over plots with different grassed inter-row widths. The plots would be relatively inexpensive and simple to maintain. It would be desirable to measure the relative humidity over each plot at various heights, keeping in mind fetch requirements, and directly comparing the relative humidity for each treatment. Measuring soil water content and grapevine stress in each plot would also be useful to get a complete picture of the vineyard water dynamics. It is recommended that treatments go across vine rows, especially if grapevine stress is measured by treatment. This same study could also incorporate different ground cover such as maintaining mulch in some of the plots. Studies looking at humidity should be conducted in similar conditions (e.g., climate) that are commensurate to conditions in North Carolina or other areas with high humidity and warm temperatures.

In general, in terms of the methodology we tested herein, we found the MBR systems to be valuable for separating the energy fluxes for the inter-row components within a

vineyard. To further validate the MBR system method, MBR systems should be tested in other systems that are composed of different components (e.g., orchards). MBR systems may be used to separate the energy fluxes of different components in different systems in order to have a better understanding of how much each component contributes to the whole-system energy flux. Since the MBR systems use a gas analyzer that also measures carbon dioxide concentrations and, thus, a carbon dioxide gradient, it may be used for measuring carbon dioxide flux. Testing the carbon dioxide flux from the MBR systems with other methods of measuring carbon dioxide fluxes may prove beneficial since MBR systems create little disturbance, require a small footprint, and are not labor intensive.

Table 2.1. Amount of net radiation partitioned to latent and sensible heat for the inter-row of a vineyard system.

DOY	LE/R_N		H/R_N	
	Fescue	Bare Soil	Fescue	Bare Soil
107	0.85	0.56	0.04	0.28
193	0.89	0.77	0.03	0.07
43*	0.31	0.14	0.67	0.84

*Day of year (DOY) from 2012

Table 2.2. Evapotranspiration rates for fescue inter-row of a vineyard in North Carolina and New York. New York data after Centinari et al., 2009.

DOY	Evapotranspiration	
	mm d^{-1}	
	New York*	*North Carolina*
198	2.5	3.3
221	2.4	3.6
234	2.0	2.7
243	1.6	2.8
251	1.8	3.0
253	1.3	2.7

*Approximate values; exact values were not reported

Table 3.1. Estimated energy fluxes for fescue inter-row and bare soil inter-row at the vineyard on selected dates.

DOY	R_n - G		H		LE	
	MJ m^{-2}					
	Fescue	Bare Soil	Fescue	Bare Soil	Fescue	Bare Soil
107	12.07	12.81	0.52	4.27	11.55	8.54
130	11.12	9.07	0.11	2.64	11.01	6.44
172	11.13	8.16	0.39	2.04	10.75	6.14
193	10.69	10.53	0.31	0.88	10.37	9.65
215	9.21	7.21	0.34	1.80	8.86	5.41
271	7.31	7.27	0.25	1.24	7.06	6.03
277	6.78	5.30	0.51	1.87	6.26	3.43
322	4.67	4.63	0.16	3.59	4.51	1.04
336	3.80	3.95	0.52	1.27	3.27	2.69
6 (2012)	5.04	3.34	3.20	2.77	1.84	0.57
43 (2012)	8.16	7.96	5.60	6.80	2.57	1.17
66 (2012)	8.31	7.95	3.43	3.60	4.87	4.35

*DOY = day of year, R_n = net radiation, G = soil heat flux, H = sensible heat flux, LE = latent heat flux
**Values between 8:00 am and 6:00 pm EST

Table 3.2. Leaf water potential under typical (i.e., grassed inter-row) management conditions in the vineyard. Each value consists of at least 15 measurements.

DOY (2011)	Leaf Water Potential
	-bar
140	4.8 (0.5)*
166	4.5 (0.6)
181	4.3 (0.7)
199	2.9 (0.5)
209	3.9 (1.0)
227	3.9 (0.5)
244	5.3 (0.7)

*DOY = day of year.
**Values in parenthesis are the standard deviation.
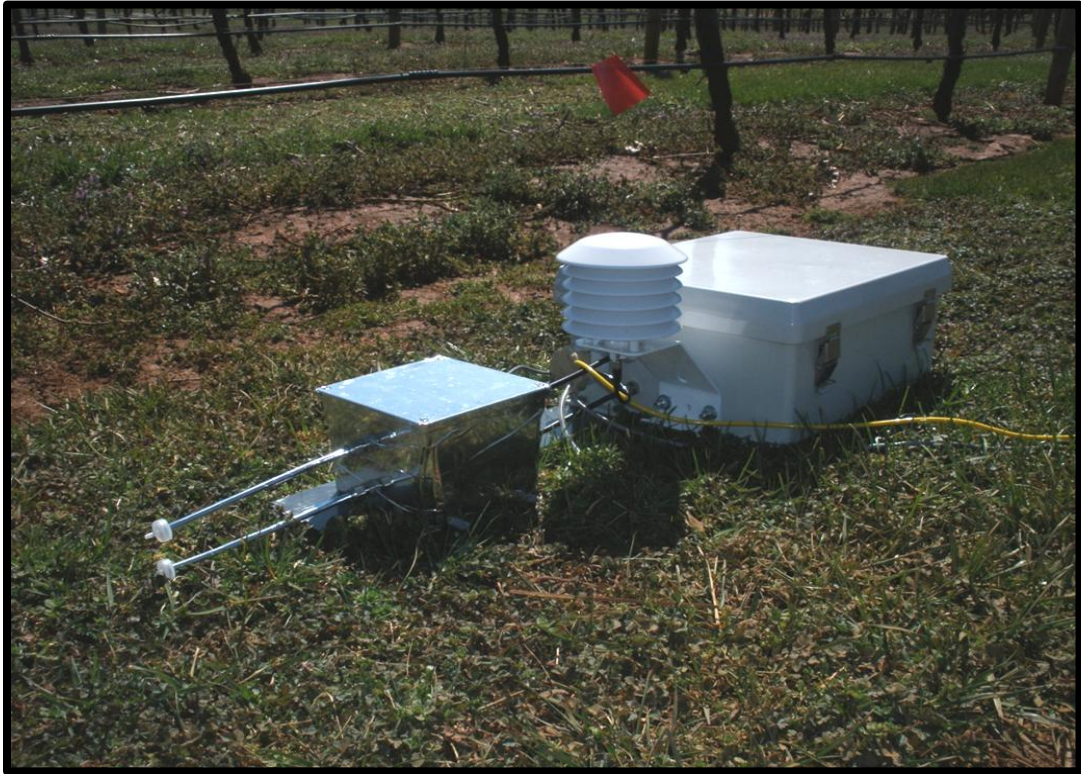
Figure 2.1. Micro-Bowen ratio system at vineyard site.

Figure 2.2. Vineyard site.
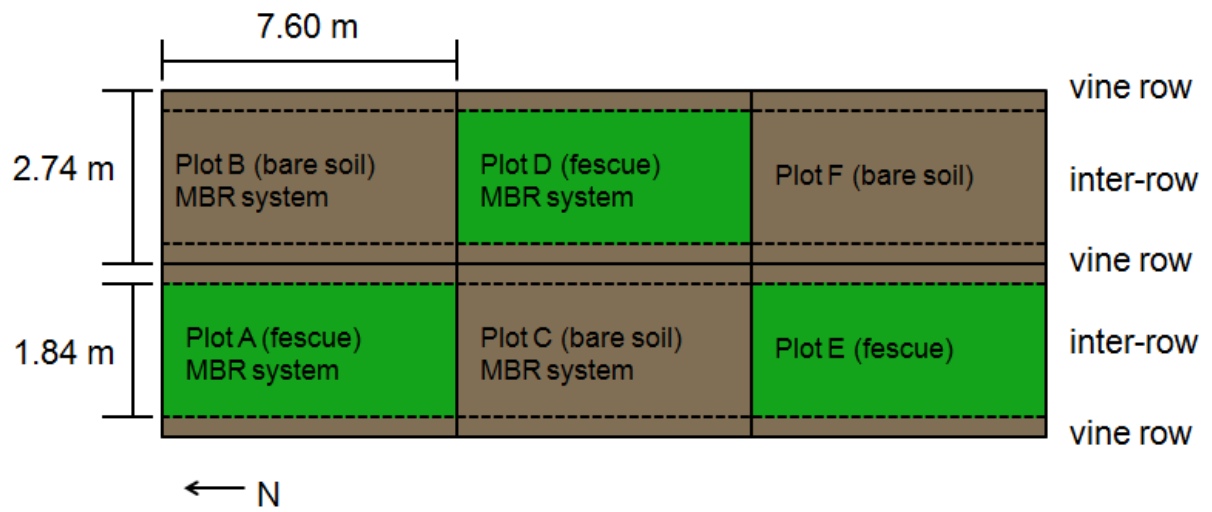
Figure 2.3. Treatment layout at vineyard site.
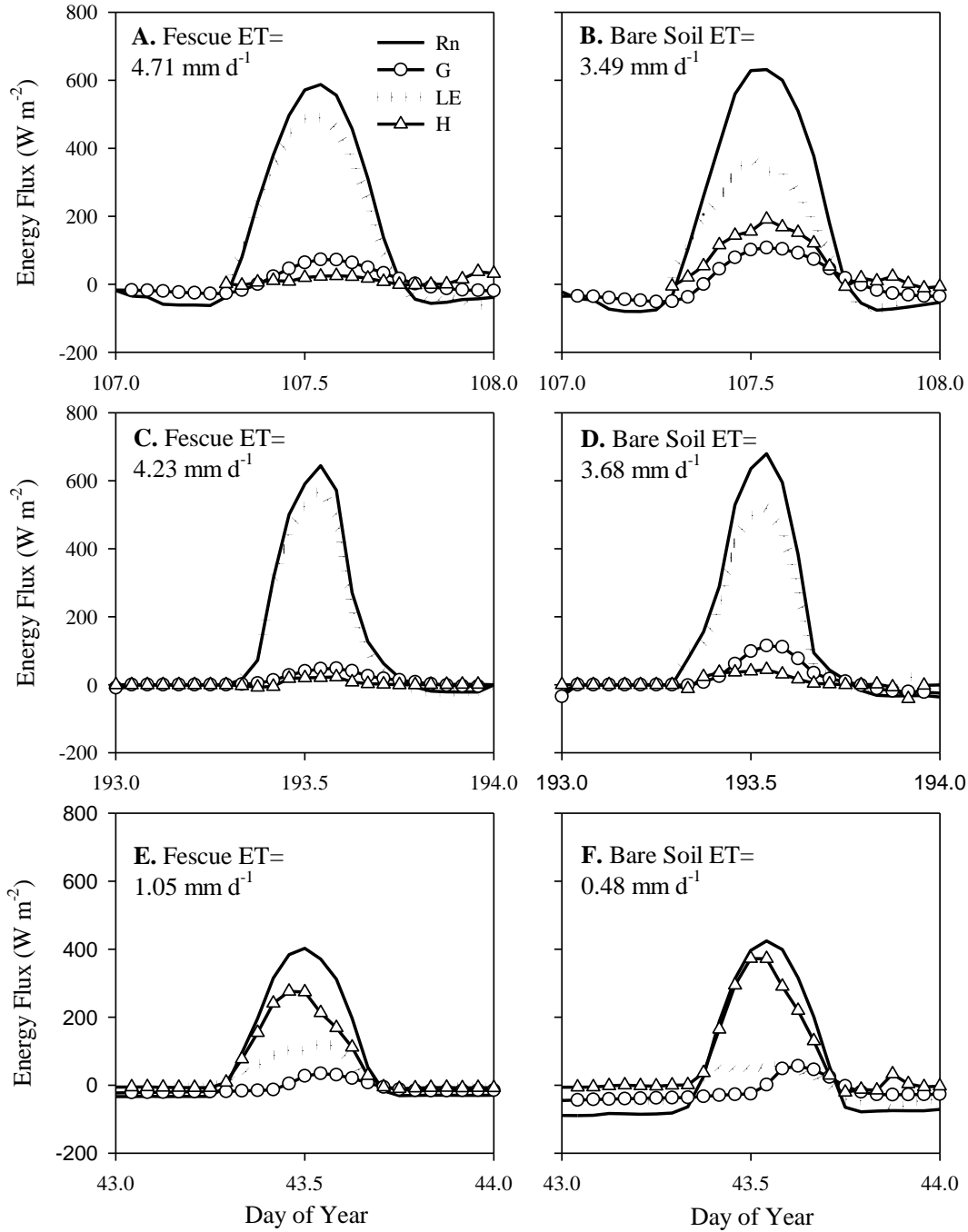
Figure 2.4. Example Bowen ratio energy balance for fescue (left column) and bare soil (right column) inter-row conditions at the vineyard (2011-2012). Panels A-D are from 2011 and panels E and F are from 2012. RN (net radiation), G (soil heat flux), LE (latent heat flux), H (sensible heat flux).
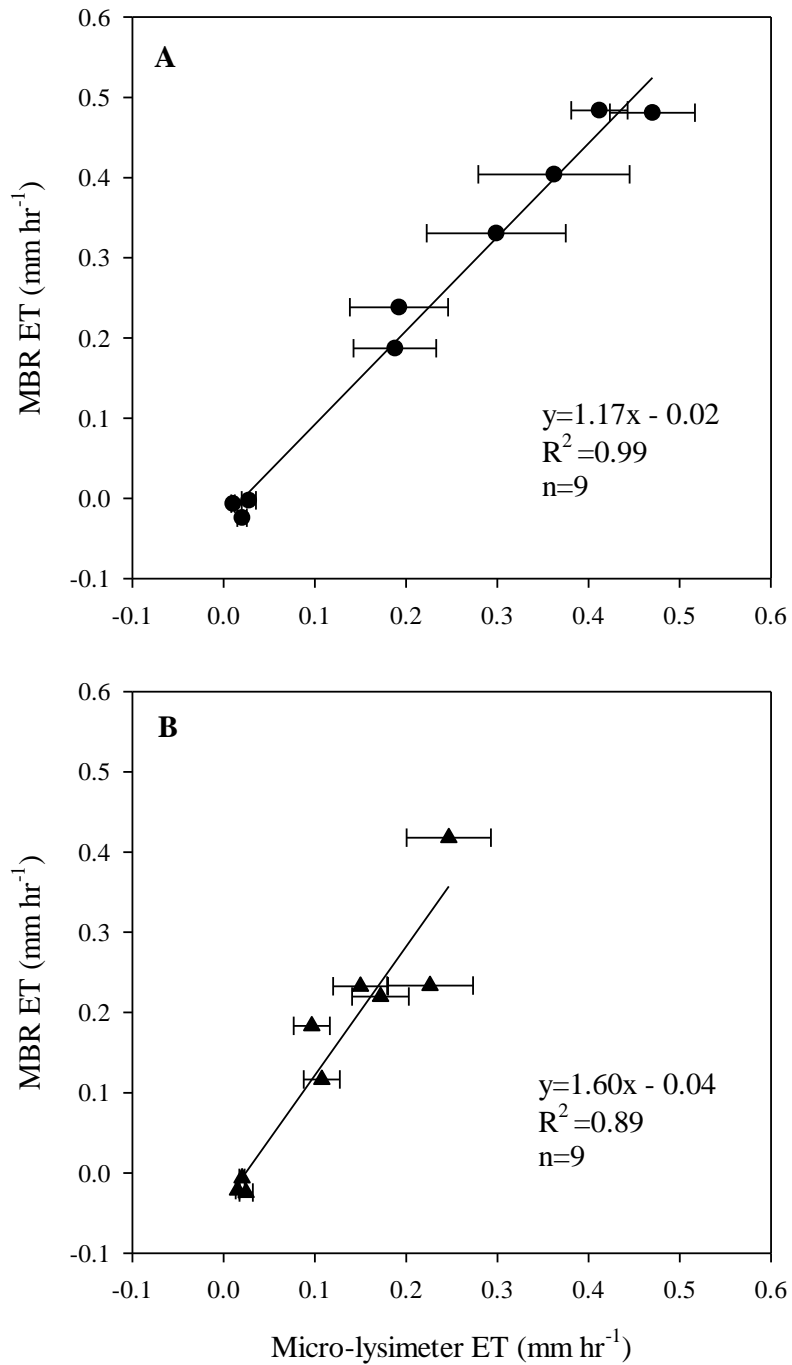
Figure 2.5. Micro-lysimeter vs. micro-Bowen ratio (MBR) system evapotranspiration (ET) for fescue (A) and bare soil (B) inter-row conditions.
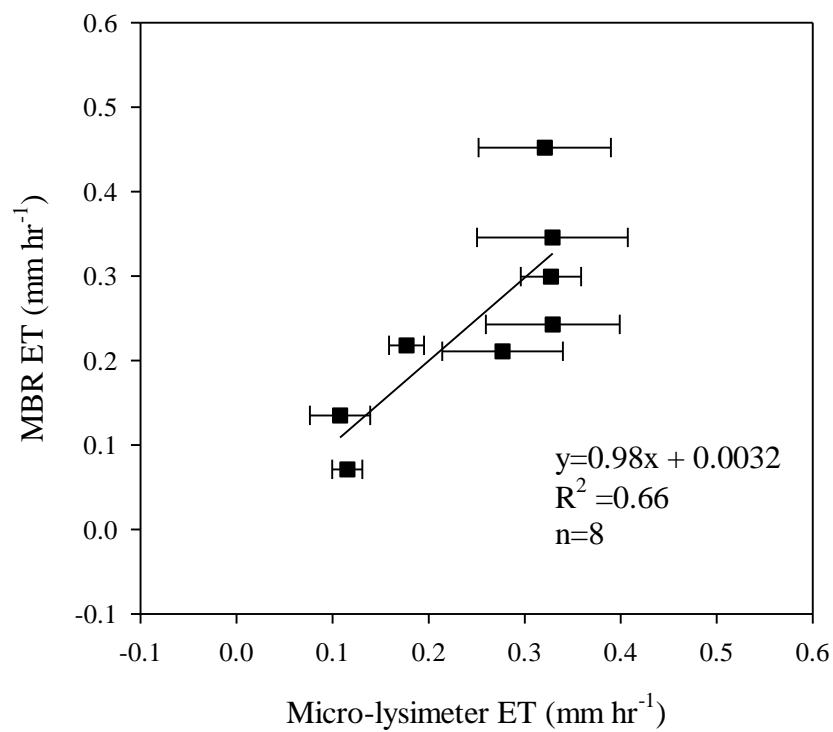
Figure 2.6. Micro-lysimeter vs. micro-Bowen ratio (MBR) system evapotranspiration (ET) for bare soil condition at bare field site.
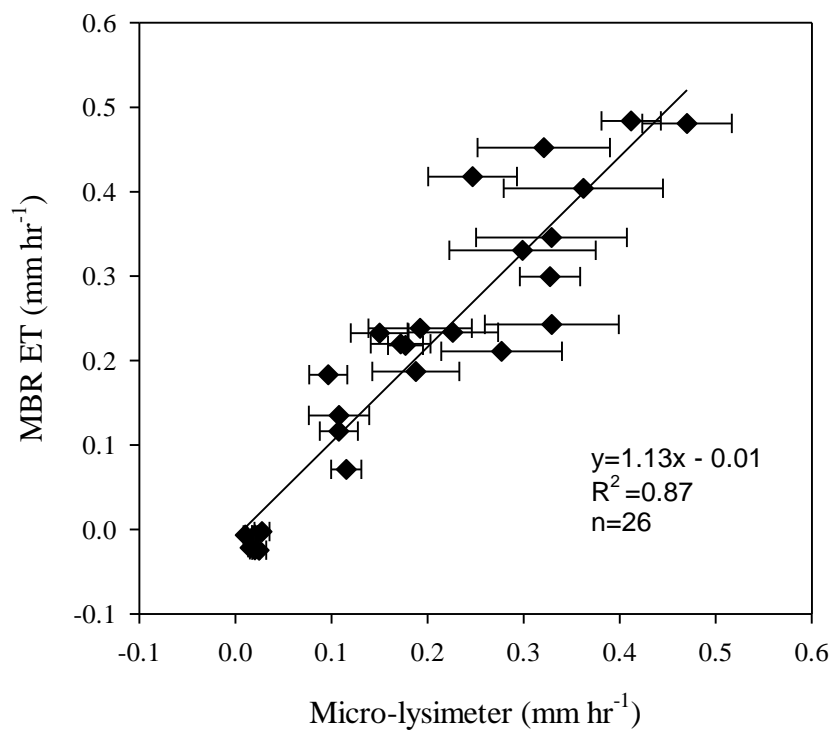
Figure 2.7. Pooled micro-lysimeter vs. micro-Bowen ratio (MBR) systems evapotranspiration (ET) for vineyard and bare field sites.
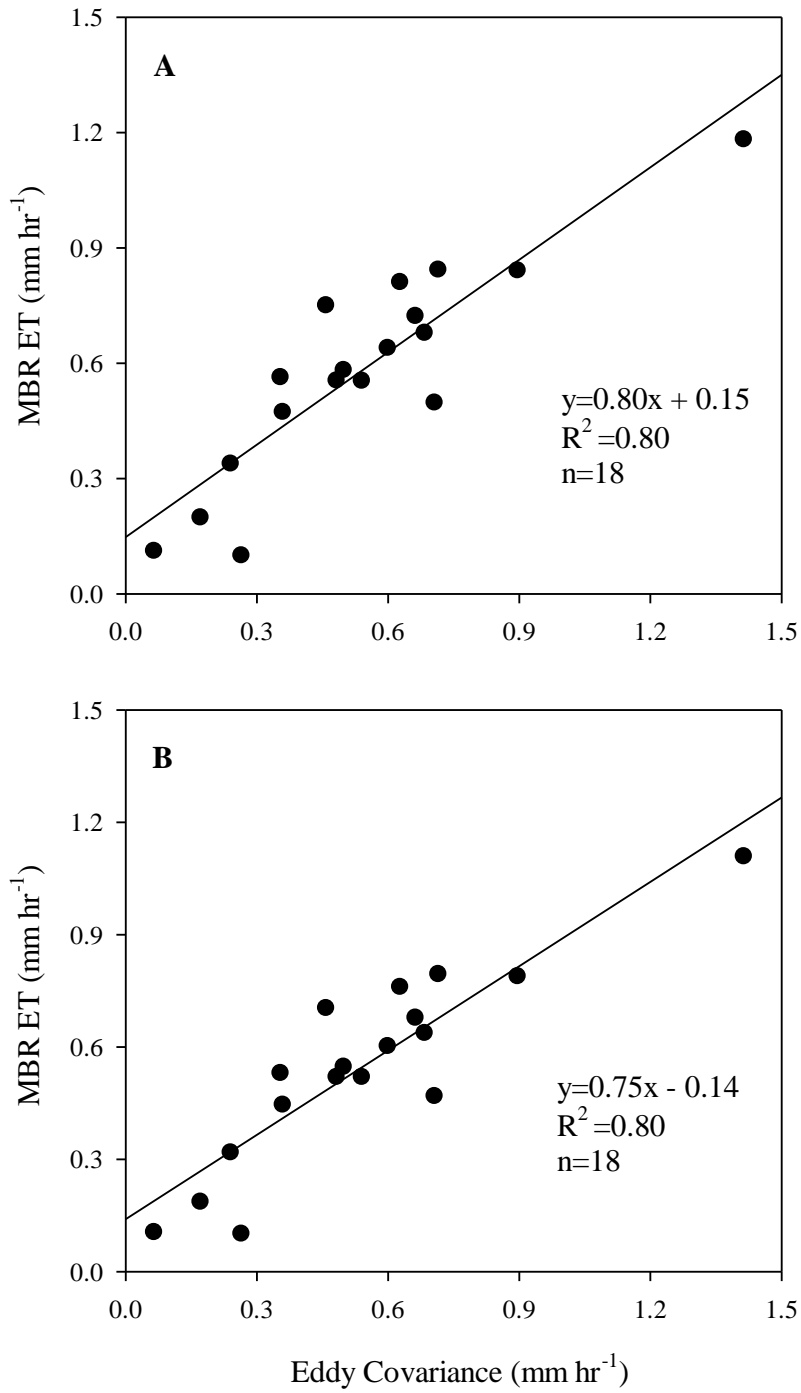
Figure 2.8. Eddy covariance vs. micro-Bowen ratio (MBR) systems evapotranspiration (ET) using measured row widths (A) and optimized row widths (B).

Conc. of water vapor in air (C_a)

Vapor flux from canopy ($J_{cf'cs}$)

Conc. of water vapor w/in canopy ($C_{f's}$)

Vapor flux ($J_{f's}$)
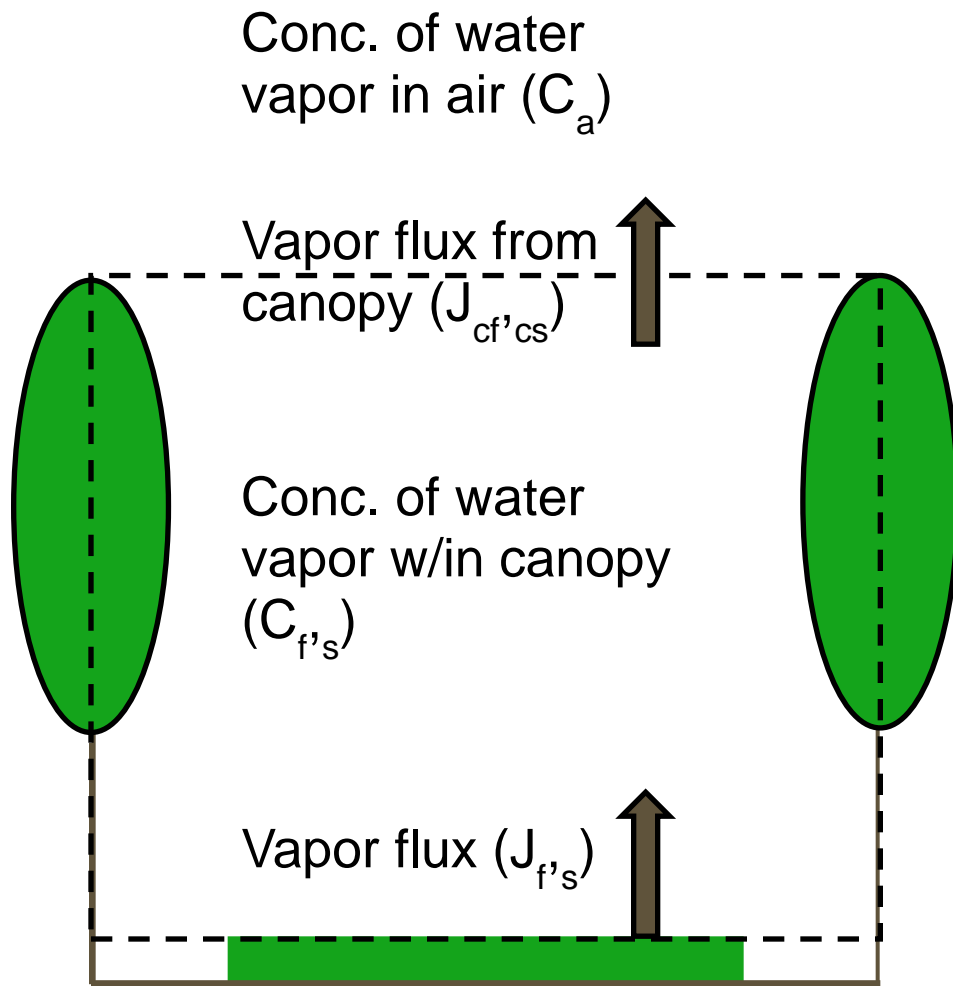
Figure 3.1. Relative humidity model for vineyard.
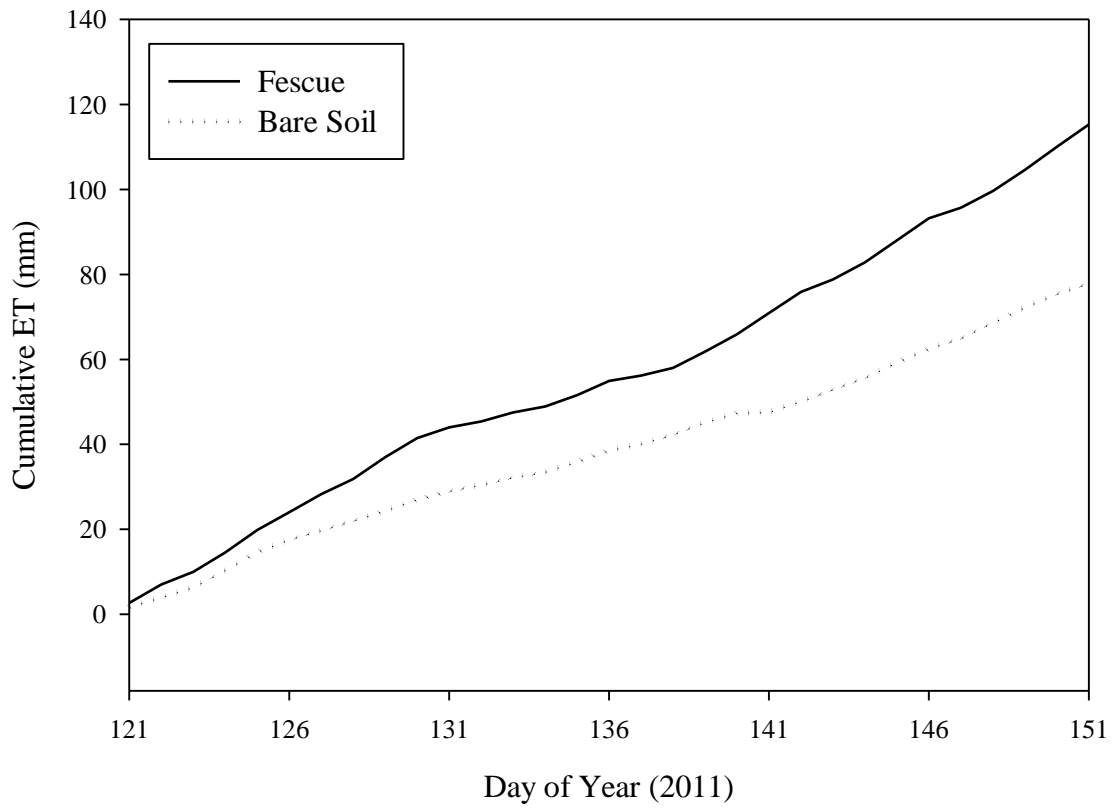
Figure 3.2. May cumulative evapotranspiration (ET) for bare soil and fescue inter-row.
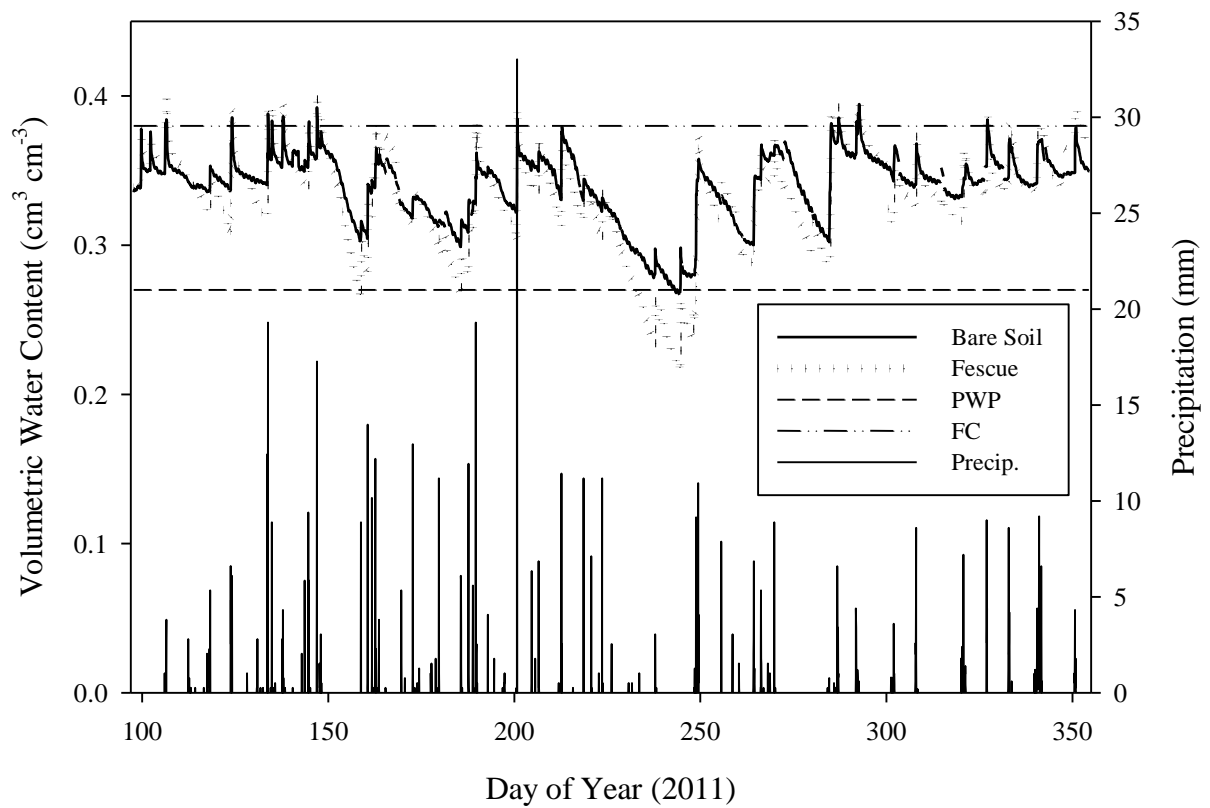
Figure 3.3. Soil volumetric water content by treatment, field capacity (FC), permanent wilting point (PWP), and precipitation. Soil volumetric water content was averaged for three soil water content sensors for each treatment at 10-38 cm depth.
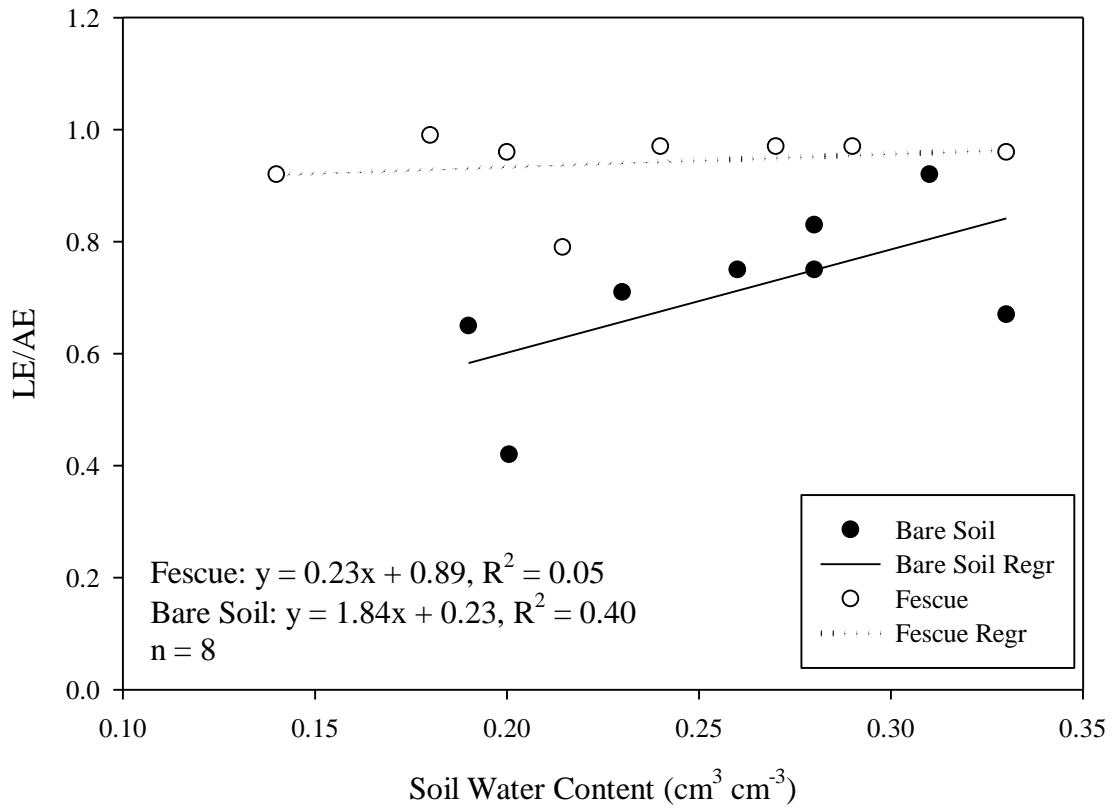
Figure 3.4. Fraction of available energy (AE) partitioned to latent heat flux (LE) as a function of soil water content for fescue and bare soil inter-row conditions during the grape growing season (March − October) in the vineyard.
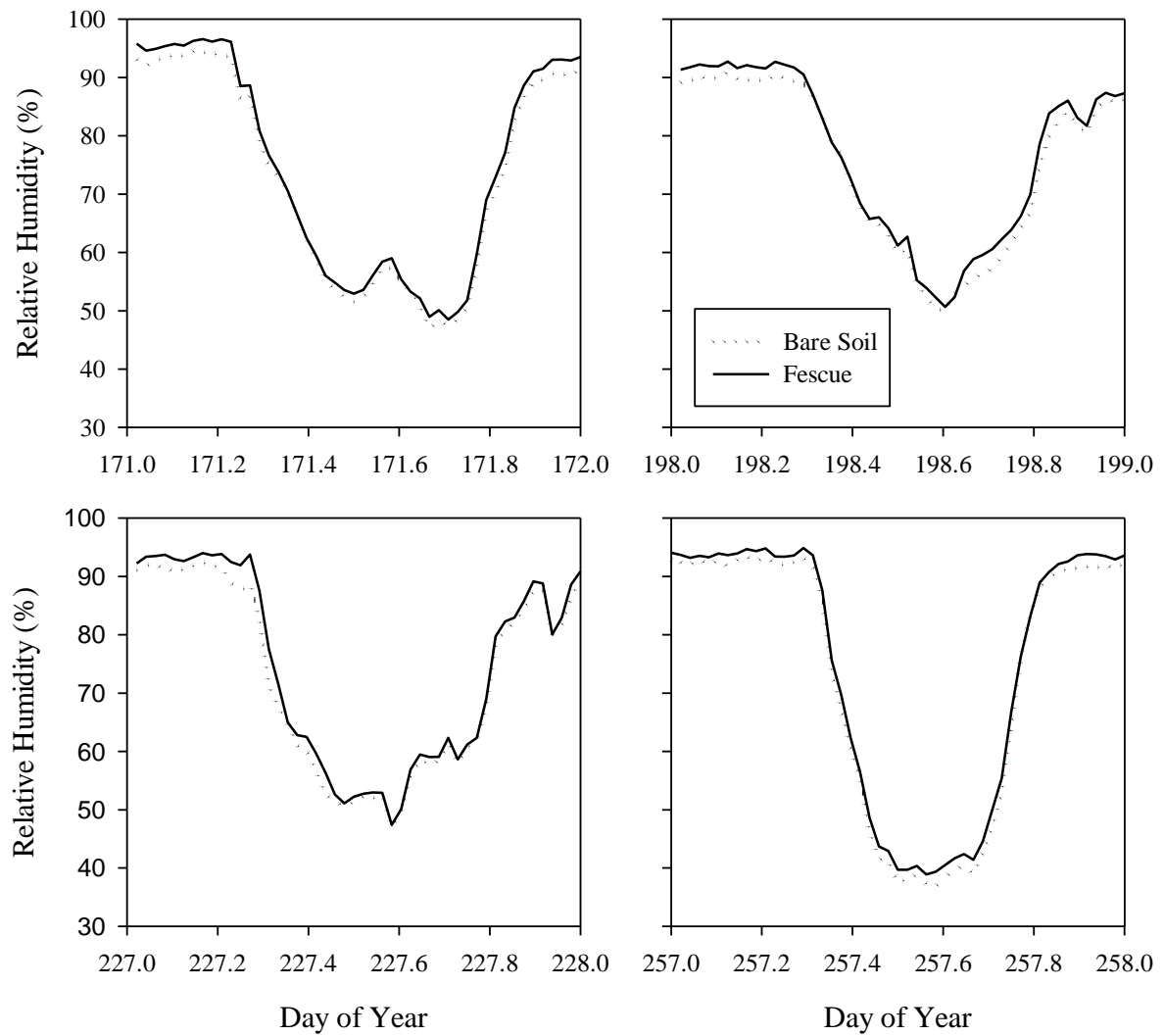
Figure 3.5. Relative humidity at 30 cm height above surface for representative days throughout the grape growing season (March – October).
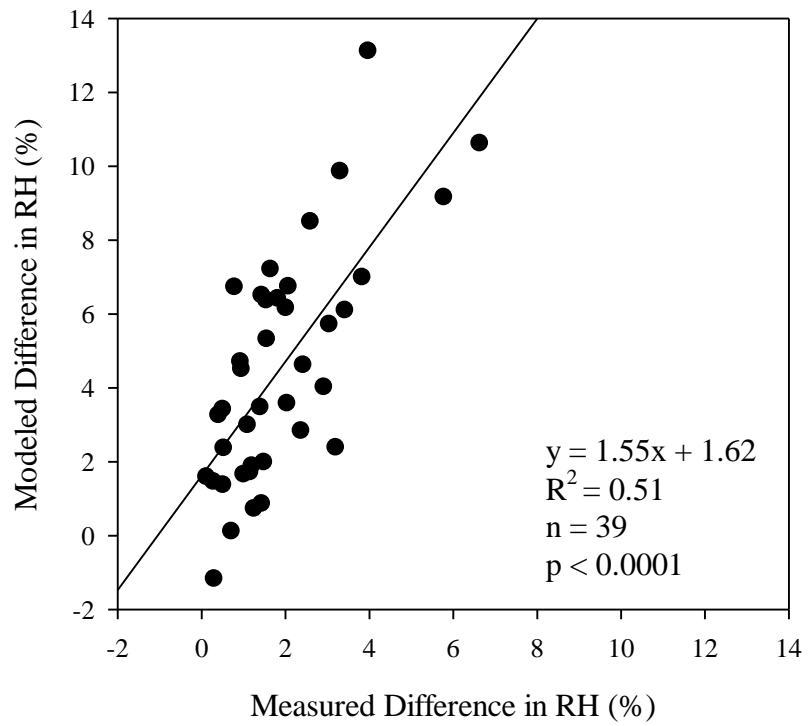
Figure 3.6. Measured vs. modeled difference in relative humidity (RH) between fescue and bare soil inter-row conditions at the vineyard site.