Leaf wetness: implications for agriculture and remote sensing

by

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ABSTRACT

Information regarding leaf wetness duration (LWD) has been used in disease management schemes for decades by researchers in the plant disease and agricultural meteorology communities. LWD is currently measured predominantly by electronic leaf wetness sensors or through the use of a model that represents latent heat transfer. Studies have been conducted that examine the placement, orientation and treatment of leaf wetness sensors. Some studies have compared empirical and physical models to LWD measurements obtained from leaf wetness sensors. However, an article that summarizes all aspects of leaf wetness sensors and models, addressing the benefits and disadvantages, has not been provided to extension personnel that need to provide accurate information to growers regarding disease risk associated with LWD. It is recommended that LWD should be estimated using a relative humidity $\geq$ 90% for operational use.

The vertical variability of dew has been examined for a variety of crops. Studies regarding the horizontal spatial variability of dew amount and duration has been limited to small areas, on the order of a few meters. Traditionally, information regarding LWD for disease warning systems has been obtained from a single sensor at a single point in a field. We sought to examine whether or not this provided accurate information regarding LWD, but also sought to determine if dew amount varies within a field. Our study examined how the spatial variability of both dew amount and duration differ within a field by examining locations that were hundreds of meters apart. Dew amount was measured manually, and simultaneously, at three locations within the field on seven mornings. The three sampling locations were chosen based on changes in topography and

soil textures. Information regarding LWD was obtained by leaf wetness sensors placed at each of the three locations. It was hypothesized that there would be a significant difference in both dew amount and dew duration between the sites due to changes in the distillation contribution to the overall dew amount. The study found that there was high leaf–to–leaf variability regarding dew amount, and no variability between sites was seen. It was found that there was no significant difference in dew duration at the three locations.

The Soil Moisture Ocean Salinity (SMOS) satellite provides the first global estimates of soil moisture using microwave radiometry. This satellite makes passes at 6 pm and 6 am local solar time. The remote–sensing community have indicated that data from the 6 am pass time should be preferred over the 6 pm pass time for a variety of reasons, however land–based studies of soil moisture using microwave radiometry have indicated that the presence of free water on canopy can cause errors in the estimations of soil moisture. Evaluation of the influence of dew on vegetative canopies for satellite measurements has not previously been possible. Our study examined a region in north–central Iowa, where the land–cover is uniform consisting of row crops. We hypothesized that there would be no significant difference in brightness temperature or soil moisture between evening and morning SMOS passes. We examined the soil moisture product and found that there was a significant difference in soil moisture between evening and morning SMOS passes for days when precipitation had not occurred after noon prior to the evening pass, nor during the time period between the evening and morning pass time. The soil moisture product is obtained from measurements of brightness temperature, however no significant difference in brightness temperature was seen between evening and morning passes. We indicate that there may be issues with retrieved values of optical depth during the SMOS processing phase that is resulting in errors in soil moisture measurements. We also highlight the possibility that decreases in the polarization index (a normalization of brightness temperature) could falsely indicate a decrease in soil moisture when it may be the result of an increase either of the volumetric water content of a vegetative canopy or the presence of free water on the canopy surface.

CHAPTER 1. INTRODUCTION

1.1 Leaf Wetness Implications for Agriculture

Leaf wetness refers to the presence of free water on the canopy, and is caused by intercepted precipitation, dew, or guttation. Leaf wetness has been studied extensively for decades, especially by the plant pathology and agricultural meteorology communities because some plant dieases require the presence of free water on a crop canopy for infection. Investigations have included the use of leaf wetness sensors to determine duration of leaf wetness, placement of sensors in various crop canopies, and the use of models as an alternative to sensors. The second chapter of this dissertation addresses the use of sensors and models in the determination of leaf wetness duration. Regardless of how the duration of leaf wetness is determined, these values have been used in many disease warning systems. These warning systems are now used around the world by growers, particularly those involved with high–valued crops.

Disease warning systems were developed to provide growers with guidance on when to apply fungicides or antibiotics based on the weather conditions as opposed to a calendar schedule. Disease warning systems that use leaf wetness duration as an input include TomCast which was developed for control of early blight, Septoria leaf spot, and antracnose caused by *Alternaria solani*, *Septoria lycopersici*, and *Colletotrichum coccodes*, respectively, in processing tomatoes (Pitblado, 1988; Poysa et al., 1993; Gillespie et al., 1993). A similar model was developed for control of Alternaria leaf blight, caused by *Alternaria cucumerina*, in muskmelons (Latin and Egel, 2001). Models have been developed for control of sooty blotch and flyspeck in apples, and several have been developed for late blight in potatoes (Brown and Sutton, 1995; Fry, 1977; Wharton et al., 2008). Grape models have been produced to reduce the incidence of grapevine downy mildew caused by *Plasmopara viticola* (Lalancette et al., 1988).

Disease warning systems have an element of conservatism built in, but are flexible to the point that growers can interpret the suggested thresholds for spray applications and adjust to their region or their particular variety of the crop. Regardless of how leaf wetness duration was determined, it is assumed to be representative of the entire managed agricultural field. These models have moved beyond the research communities to use by individual growers and commercial producers. The need to save money on fungicidal or antibiotic applications and to meet higher environmental standards have inspired the development of integrated pest management (IPM) programs. However, failure of a program to protect a grower from financial set back should an outbreak occur will limit the success and future use of many pest management programs. While many of the disease warning systems will typically over–estimate the true number of spray applications required, failure is always a risk.

Disease warning models are empirically based with spray thresholds developed for a specific region, and in some cases for a particular crop variety. Should these models be implemented elsewhere, where meteorological or varietal differences may occur, performance of these programs may be disappointing unless new calibrations are made (Duttweiler et al., 2008). Regardless of how information about leaf wetness duration is obtained, whether it be from a physical sensor, or an empirical or physical model, thresholds need to be be re–examined. Using leaf wetness sensors to estimate leaf wetness duration (LWD) for developing and operating disease–warning systems creates interesting complications. As discussed in the second chapter of this dissertation, placement of a sensor within a crop canopy can drastically influence measured LWD values. Typically, only one sensor is utilized within a field for IPM implementation. However, given the importance of distillation (the contribution of water vapor that has evaporated from the soil surface) to overall dew amount, the assumption that a single point measurement is representative of the entire field, let alone a growing region is weak (Wilson et al., 1999). With the advancements of precision agriculture, and means for assessing spatially varying dew amount, it is possible that different regions of a field could be treated differently if the leaf wetness duration varies greatly. The topic of the second paper addresses such an opportunity.

1.2 Leaf Wetness Implications for Remote Sensing

On November 2, 2009, the Soil Moisture Ocean Salinity (SMOS) satellite was launched by the European Space Agency. This satellite represents years of research coming to fruition. Land–based measurements utilizing passive microwave remote sensing to measure soil moisture have been on–going; however, until technology advanced to the point that space–borne measurements were feasible, studies were limited to the foot–print of a land–based radiometer, typically on the scale of meters. SMOS provides estimates of soil moisture at a spatial scale of < 50 km (Kerr et al., 2010). Information regarding soil moisture at this scale will be of great importance to improving weather forecasting (Koster et al., 2004).

There is concern regarding how the presence of leaf wetness in crop canopies will influence these estimates of soil moisture over a 50 km region. Several crops have been investigated on a localized scale of a few meters. Wigneron et al. (1996) found that the brightness temperature (equivalent black body temperature) over a wheat field increased with intercepted irrigation water. Dew on a grass canopy was also found to increase the brightness temperature at the same frequency of measurement as the SMOS satellite (de Jeu et al., 2005). In contrast, Hornbuckle et al. (2006) found that the brightness temperature in maize decreased when dew was present on the canopy. Soybean canopies have been shown to behave similarly to wheat and grass canopies (Wigneron et al., 2004). Dew will increase the measured brightness temperature on a soybean canopy.

The SMOS satellite offers a unique opportunity for studying the potential effect of leaf wetness on soil moisture retrievals, as the satellite passes the same regions on the earth twice a day on several occasions in a month, sampling different dew regimes (morning verus evening). SMOS passes occur at 6 pm and 6 am local solar time. The third paper of this dissertation investigates whether the soil moisture product produced by SMOS differs between the evening and morning passes. Days were selected for analysis, so that intercepted precipitation would not cause an obvious change between evening and morning overpasses. The study region, in central Iowa, is comprised predominantly of row crops, with the presence of maize being slightly higher than soybean.

The radio astronomy protected band within L–band ($\sim$ 20 cm) is the lowest frequency band that is practical for earth remote sensing. Lower frequencies would be as sensitive, and would be sensitive to moisture at a greater emitting depth, but space–borne antennas that would be able to provide a reasonable spatial resolution would be too large and too expensive. Higher frequencies have been investigated, but as the wavelength decreases, the sensitivity to soil surface roughness and vegetation increases. The optical depth of the vegetation also increases with increasing frequency, reducing the ability to sense the soil surface. Changes in the volumetric water content of vegetation between the evening and morning are not well understood, but should advances be made in this area, the use of remote sensing at higher frequencies could be beneficial in the examination of leaf wetness. Microwave radiometry at higher frequencies is more sensitive to the vegetative canopy, and to the presence of dew. Should improvements be made to the resolution of measurements, e.g., down to the scale of 1 km^2, satellite information could be used to map leaf wetness at close to field–scale.

1.3 Dissertation Composition

This dissertation consists of three primary papers.

- Chapter 2: This paper is a comprehensive review of leaf wetness in regards to the concerns of the plant pathology community. This paper has planned submission to the journal *Plant Disease* as a Feature Article. The paper addresses topics including:
  - the nature of leaf wetness
  - the importance of leaf wetness for the plant pathology community
  - modeling and measurement of leaf wetness
  - use of leaf wetness sensors
- Chapter 3: This paper investigates the spatial variability of dew amount and duration within a soybean field. This paper will be submitted to *Agricultural and Forest Meteorology*. The paper addresses:
  - model sensitivity to variables associated with distillation that may have implications for field–scale variability of dew amount and dew duration
  - results of manual measurements of dew amount
  - sensor measurements of dew duration
  - variability of dew amount and duration within a field
- Chapter 4: This paper investigates the difference between evening and morning passes of the SMOS satellite over the north–central of Iowa. This paper will be submitted to *IEEE Transactions on Geoscience and Remote Sensing*.
  - examine differences in the soil moisture product between evening and morning estimates

  - investigate measurement and models results for expected change in soil moisture
  - examine measured brightness temperatures
  - compare results of changes in brightness temperatures to theoretical changes

- Chapter 5: Conclusions and Future Research

CHAPTER 2. AN EVALUATION OF LEAF WETNESS

T.L. Rowlandson, M.L. Gleason, B.K. Hornbuckle

Abstract

Leaf wetness is a concern for the development of risk of epidemics of many plant diseases. In the plant pathology community, the concern is generally with the duration of the time period during which the leaves are wet, referred to as leaf wetness duration (LWD). In this article, we will address the causes of leaf wetness, current measurement techniques for determining leaf wetness duration, and alternative modeling approaches. Previous reviews have focused on the measurement and use of LWD by the research community and have had an emphasis on single issues, such as sensors or models. We will provide a comprehensive review of all measurement of LWD and discuss operational uses. We will offer some insight into how to chose between using a sensor or a model, and address some of the limitations of each. Finally, we will conclude with recommendations for the measurement of leaf wetness by the research community to address the needs of growers.

2.1 What is Leaf Wetness?

Leaf wetness refers to the presence of free water on plant leaves, and can result from several factors, including precipitation intercepted by the canopy and dew. Dew forms as a result of the condensation of water vapor on a canopy that has experienced radiative cooling to the atmosphere, causing their temperature to drop below the dew point temperature of the surrounding air space. Examples of dew formation on a maize and soybean leaves are shown in Figures 2.1 and 2.2. On overcast nights, the occurrence of dew is less likely because longwave radiation emitted by clouds may keep the canopy temperature elevated above the dew point temperature.

There are two possible sources for the water vapor that condenses on the canopy. The first and most commonly noted and modeled source of water vapor is from the atmosphere. This contribution to the overall dew amount is referred to as dew fall. The second source is evaporation from the soil surface. This process is referred to as distillation, or occasionally, dew rise. Another natural source of free water on leaves is guttation, which occurs in some, but not all crops. In guttation water is exuded from the interior of the leaf onto the surface. This process is considered to contribute to only a small portion of the overall dew amount, and is typically ignored (Jacobs et al., 1994). A final source of leaf wetness is overhead irrigation, typically treated in a similar fashion to rainfall.

2.1.1 Importance of Leaf Wetness

The presence of water on the canopy, in the form of dew, intercepted precipitation or irrigation has an impact on the infection, germination and sporulation of many fungal diseases. Huber and Gillespie (1992) conducted a thorough literature review of studies conducted between 1985 and 1991 regarding the disease, crop affected and the range of the wetness duration that is required for the epidemiological variable indicated. The

Figure 2.1 Dew formation on a corn leaf.

Figure 2.2 Dew formation on a soybean leaf.

results are presented in Table 2.1. The range varies from a short period of time, as little as a half hour for infection of *Phytophthora cactorum* in strawberry fruits, to as much as 140 hours for the incidence of *Diaporthe phaseolorum* in soybean.

Information regarding the wetness duration is used as an input in disease warning systems, which aid growers in determining the appropriate time for the use of preventative measures, such as fungicide application. Examples of disease management schemes include TomCast (Tomato foreCaster) and MelCast (Melon foreCaster). TomCast was developed in southern Ontario for tomatoes, to control *Alternaria solani*, *Septoria lycopersici*, and *Colletotrichum coccodes*, which cause early blight, Septoria leaf spot and anthracnose, respectively. The model accumulates daily severity ratings that depend on the duration of wetness and the average temperature during the time period. These severity values accumulate daily until the suggested threshold is reached, at which time a grower should apply fungicides. The counter is then reset until the next threshold (Poysa et al., 1993). The threshold can be variable depending on factors such as fungicide type. MelCast operates similarly to TomCast. It was developed to time fungicides efficiently for management of *Alternaria cucumerina*, causing Alternaria leaf blight in muskmelon. This model also accumulates severity values until a threshold is reached (Latin and Egel, 2001); however, the maximum number of severity values that can be accumulated in a day differs from that of TomCast, as does the threshold for fungicide applications.

Fungus	Host	Epidemiological Variable	Range of LWD (hr)
Botrytis cinerea	strawberry flowers	disease incidence	6–32
Botrytis squamosa	onion leaves	number of lesions	6–32
Colletrotrichum acutation	strawberry fruit	disease incidence	3–40
Colletrotrichum coccodes	tomato fruit	severity	10–50
Diaporhe phaseolorum	soybean	disease incidence	2–140
Phakopsora pachyrizi	soybean	number of lesions	6–12
Phytophtora cactorum	strawberry fruit	infection	0.5–5
Puccinia arachidis	groundnut	lesion density	4–40
Puccinia recondita	wheat	infection hyphae	9–15
Puccinia striiformis	wheat	infection	3–6
Pyricularia grisea	ryegrass	number of lesions	6–48
Pyrenophora teres	barley	infection	3–24
Uromyces phaseoli	bean	number of pustules	4–25

Table 2.1 Wet period requirements for infection by several foliar pathogens (results published between 1985 and 1991). Reproduced and adapted from Huber and Gillespie (1992).

2.2 Measurement of Leaf Wetness

The technically simplest means of measuring leaf wetness duration is through visual observation. This is not the ideal method as it is time comsuming and difficulties arise when attempting to define when the onset of leaf wetness has occurred (is it the first droplet on a leaf? Is it when 50% of leaves are wet?). For many decades sensors have been used. Initially, duration was measured using sensors that measured the duration in dew by recording a change in the length, size, or weight of a device (for example, the measurement of the change in length of a human hair). Often the duration was recorded using a mechanically controlled pen (Gillespie and Kidd, 1978). Sensors have advanced since this time to provide electronic measurement of leaf wetness. Two commercially available electronic leaf wetness sensors(LWS) will be discussed in depth below.

The most commonly cited, commercially available, sensor is the flat-plate, printed circuit sensor (Model 237, Campbell Scientific, Logan, UT, USA), herein referred to as the Campbell sensor (Figure 2.3). The sensor was originally designed to mimic the size of a leaf. The printed grid is a resistance grid, where the circuit is complete when water on the sensor surface bridges the interlocking electrodes, and the electrical resistance drops as water accumulates (Campbell Scientific, Inc., 2005). Although these sensors have been discontinued by Campbell Scientific, many are still being used for research purposes, and the performance of this sensor has been extensively documented (Gillespie and Kidd, 1978; Sentelhas et al., 2005; Magarey et al., 2006; Sentelhas et al., 2007; Batzer et al., 2008; Kabela et al., 2009).

An alternative sensor is a flat, dielectric leaf wetness sensor (Model LWS-1, Decagon Devices, Pullman, WA, USA), herein referred to as the Decagon sensor (Figure 2.4). This sensor was designed to have a heat capacity similar to that of a natural leaf. The known impedance of the sensor is compared to changes in the measured electrical impedance resulting from the presence of water on the sensor surface.

There has been no suggested standard use for electronic sensors or any other LWS, and as such, the sensors have been used in research studies in a multitude of ways. This makes comparisons of results extremely difficult.

Monteiro and Gleason (2006) conducted a field trial to compare the wetness duration output from the Campbell sensor and the Decagon leaf wetness sensor. Sensors were placed at 30 cm over turfgrass, at an angle of 45° from the horizontal, as demonstrated in Figure 2.5. Four Campbell sensors were monitored along–side eight Decagon sensors from July 5th to August 20th, 2006. The Campbell sensors were painted with one coat of black latex paint and two coats off-white latex paint and oven dried overnight after each coat (treatment of sensors is discussed in Section 2.3). Figure 2.6 shows the response of the Campbell and Decagon sensors over this study period. During the initial few days, the Campbell sensors show more variability between the sensors than is seen with the Decagon sensors. However, both sensor types respond similarly to wetness events, in that the shape of the curves are similar.

During both precipitation and dew events, Campbell sensors had, on average, an earlier onset and a later dry–off, with longer LWD for dew events than precipitation. For the entire study period, the mean average error was 0.31 hours and 0.82 hours for the Decagon and Campbell senors, respectively when compared to visual observations of dew onset and drying. The authors did note that the surface of the Decagon sensors had a white powder and indicated signs of aging. This is an issue that has been noted by Decagon, resulting from degradation of the sensors due to ultraviolet radiation exposure. They have recommended a product, McNett UV Tech, that can be applied to the surface of the sensor to prevent this degradation (D. Cobos, Decagon Devices, pers. comm.).

Several other types of sensors have been used to measure LWD (Sentelhas et al., 2008; Wei et al., 1995). For example, cylindrical sensors were developed and investigated by Gillespie and Duan (1987) in an onion canopy. Sentelhas et al. (2007) conducted a comparison between cylindrical sensors and flat-plate sensors, over maintained turfgrass, maize, tomato, and soybean canopies. It was found that the cylindrical sensor overestimated the duration of dew in all situations, which was in contrast with findings by Gillespie and Duan (1987). The sensors in these studies were oriented differently, which appears to have a significant impact on their sensitivities.

Figure 2.3 Flat–plate resistance sensor produced by Campbell Scientific.

2.3 Sensor Preparation

Davis and Hughes (1970) determined that unpainted flat–plate resistance sensors may not be able to detect small droplets of water (especially at the onset of dew development) which may form between the interlaced fingers of a sensor but do not bridge the wires. Painting allows these droplets to be absorbed by the paint and spread out for detection. Lau et al. (2000) conducted a study that looked at both painted (with varying number of paint coats) and unpainted sensors. The painted sensors had an initial layer of flat black latex paint, followed by either two or eight coats of a white latex paint. Sensors were placed in a tomato field just above the top of the canopy, and deployed at angles of

Figure 2.4 Dielectric leaf wetness sensor produced by Decagon Devices.

0, 30, and 45°. The sensor responses to the onset and drying of dew were compared to visual observations. For sensors with a 45° deployment angle, sensors with three coats of paint performed the best when compared to visual observations. Although painted sensors responded to all dew events in this study, unpainted sensors deployed at 30° and 45° failed to respond to 15.4% and 30.9% of dew events, respectively.

Sentelhas et al. (2004c) conducted a similar study, but used 6 sensors which were unpainted for the first portion of the study, and then painted with two coats of white latex paint and heat treated. The sensors were deployed at an angle of 20° from the horizontal. Sensor treatments were compared using the coefficient of variation, the standard deviation of the leaf wetness duration of the sensors divided by the mean leaf wetness duration. During the study interval when the sensors were unpainted, the average coefficient of variation among the sensors was 67% when examining both dew and rain events. The average coefficient of variation was reduced to 9% for the period

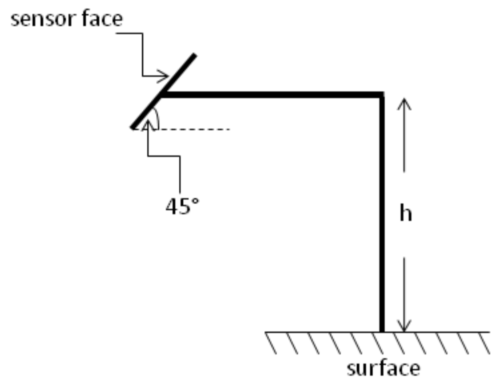

Figure 2.5 Diagram of a sensor deployed at 45° at a height, h, above a surface.

after the sensors were painted.

Gillespie and Kidd (1978) examined the effects of paint color and sensor performance in an onion crop using custom resistance grid sensors. The sensors were painted using a shades of off–white and three shades of gray. One sensor was painted dark green to match the color of the onion leaves. It was found that the drying rates increased with increasing darkness of sensor color, with the grenn sensor drying too quickly compared to visual observation, where that authors attribute this to being the result of the paint having a higher absorbtivity in the near infrared than an actual leaf. The very light gray sensor performed the best when compared to visual observations.

A study conducted by Wei et al. (1995) used sensors in a greenhouse to measure surface wetness. These custom resistance sensors were manufactured on a flexible copper-coated film. Similar to the Campbell sensors, droplets of water bridge the copper electrodes and the sensor resistance drops. These were designed to be flexible so they wrapped around the tomato fruits. Some sensors were left unpainted, and others were painted in varying rations of water to paint. The sensors that were painted indicated faster response to the onset of wetness, with the higher concentrations of paint showing the fastest response. However, the sensors remained wet for too long, overestimating the

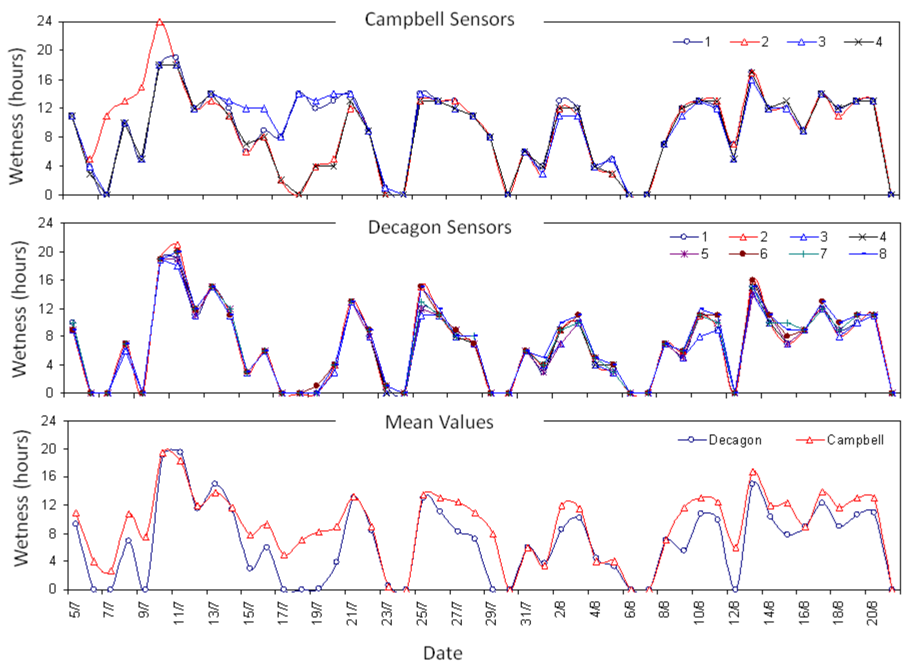

Figure 2.6 Sensor comparison of Campbell and Decagon sensors.

wetness period.

It is important to note that the study conducted by Wei et al. (1995) used resistance grid sensors, however they were not the flat–plate designed sensors used by Davis and Hughes (1970), Lau et al. (2000), Sentelhas et al. (2004c), and Gillespie and Kidd (1978). Additionally, this study was conducted in a greenhouse environment, where the flat–plate sensors have not been thoroughly examined. As such, it is difficult to compare the results of the study conducted by Wei et al. (1995) to the others.

2.4 Canopy Placement

There is high degree of spatial variability in leaf wetness duration within many crop canopies. This is evident from visual observations of individual leaves at difference points within a canopy. Placement of a LWS in a canopy should be considered carefully. Figure 2.7 shows profiles of dew measured in a maize canopy, defined as the product of the mean water density and the leaf area index (from Jacobs et al. (1990). In this study, dew measurements were made using Leick plates, which are circular disks molded from silicaecous earth and gypsum. The plates were massed an hour before sunset and placed within the maize canopy. The plates were massed again at sunrise, and the mass difference was determined to be the dew deposited. In the graph, z/h is a relative canopy height, where 1.0 represents the top of the canopy. This graph indicates that the greatest dew amount occurs at approximately 2/3 canopy height, where leaves are exposed to the cold sky at night, but are sheltered from influences of wind on the evaporation of dew. Similar results were reported by Sentelhas et al. (2005), and Kabela et al. (2009), who found that greater dew duration occurred at 2/3 canopy height than at 1/3 canopy height. Studies have been conducted to investigated that spatial heterogeneity of dew duration within a crop canopy for other crops, including apple (Sentelhas et al., 2005; Batzer et al., 2008), coffee (Sentelhas et al., 2005), grapes (Sentelhas et al., 2005), maize (Sentelhas et al., 2005; Jacobs et al., 1994; Jacobs and Nieveen, 1995), and soybean (Schmitz and Grant, 2009), using both field measurements and modeling. Results from Sentelhas et al. (2005) for apple, coffee, maize, and grape are presented in Table 2.2. Results indicate that crops such as coffee and grape, do not have a significant difference in wetness duration for different regions within the canopy. This is likely the result of the planting–style for grapes and coffee which allow all regions of the canopy to have similar exposure to the cold night sky and influences of wind speed. However, this is not the case for crops such as maize and apples (which have dense canopies), where there was a significant difference in wetness duration between the top of the canopy and within the canopy.

Schmitz and Grant (2009) investigated the variability of dew duration in a soybean canopy in western Indiana. They found that there was a vertical gradient of wetness during dew events, and the duration of wetness at the top of the canopy was longer for dew events than for rainfall events. In the middle of the canopy the frequency of wetting was also higher from dew than rain, but the duration of rain events lasted twice that of dew events. At the bottom of the canopy, wetness duration resulting from dew was rarely seen.

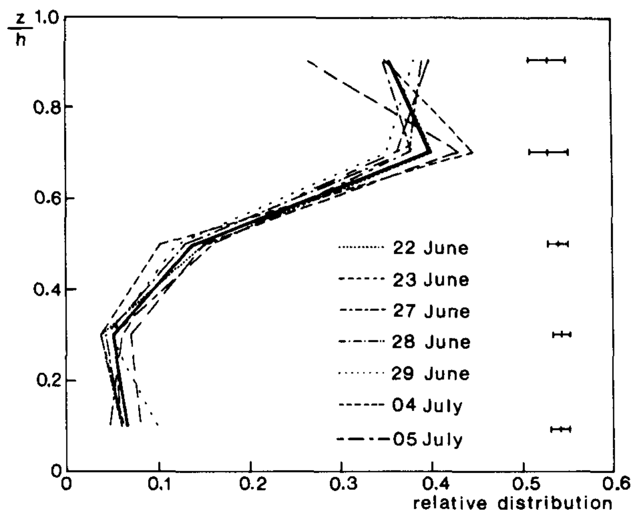

Figure 2.7 Relative distribution of dew in a maize canopy for 7 dew days. A z/h value of 1.0 represents the top of the canopy. Source: Jacobs et al. (1990).

From an operational stand point, it is not always convenient to place a sensor within a crop canopy due to field management requirements. The study conducted by Sentelhas et al. (2005) compared the duration of wetness within various crop canopies to durations measured with a sensor placed 30 cm above a turfgrass surface nearby. A sensor placed over a nearby stand of mowed turfgrass appeared to represent the duration of wetness occurring at the top of a crop such as maize, but not for a crop like coffee. Leaf wetness duration measured by a sensor over turfgrass compared to sensors within an apple canopy was 8% higher than the sensor at the top of the canopy, and 13% and 38% higher compared to sensors in the middle and bottom of the canopy, respectively. For a coffee canopy, the leaf wetness duration measured over the turfgrass underestimated the duration measured within the canopy with the highest underestimation occurring for the bottom of the crop. For maize and grapes, the sensor over turfgrass was able to

Source of Wetness	Crop	Canopy Position					
		Top	Middle	Middle-high	Middle-low	Bottom	Inside
Rain and dew	Apple	8.67[a]	8.25[a]	-	-	6.78[b]	-
	Coffee	7.84[a]	-	8.50[a]	8.63[a]	9.29[a]	-
	Maize	14.50[a]	-	-	-	-	13.53[b]
	Grape	8.48[a]	-	-	-	8.33[a]	-
Dew	Apple	8.32[a]	7.79[a]	-	-	6.14[b]	-
	Coffee	5.06[a]	-	5.64[a]	6.16[a]	6.65[a]	-
	Maize	13.05[a]	-	-	-	-	11.23[b]
	Grape	6.34[a]	-	-	-	5.88[a]	-
Rain	Apple	9.55[a]	9.38[a]	-	-	8.39[a]	-
	Coffee	12.39[a]	-	13.18[a]	12.66[a]	13.62[a]	-
	Maize	16.99[a]	-	-	-	-	17.43[a]
	Grape	12.41[a]	-	-	-	12.83[a]	-

Table 2.2 Average leaf wetness duration (hours) for different measurement positions in the crop canopies of apple, coffee, corn and grape resulting from different sources of wetness. Durations followed with the same superscript letter are not significantly different at $\alpha = 0.05$. Adapted from Sentelhas et al. (2004a).

capture the duration of wetness at the top of the canopies well, but overestimated the duration of wetness within the canopies. Placement of a LWS over a turfgrass surface would be more ideal for operational use. This eliminates the complication of where to place a sensor within a crop canopy as well as avoids conflict with field management practices.

2.4.1 Optimal Sensor Orientation

Sentelhas et al. (2004a) investigated the impact of orientation angle on painted flat–plate resistance sensors placed above a turfgrass surface. At an Elora, Ontario site, sensors were placed at angles of 0, 15, 30, and 45° from horizontal, 30 cm above the surface with the sensor face oriented north. In Piracicaba, SP, Brazil sensors were placed at a height of 150 cm at angles of 0, 30, and 45° from horizontal, also facing north.

The study found that the sensors placed at 0 and 15° experienced longer wetness duration, by 38 and 56 minutes for Elora and Piracicaba, respectively, than sensors placed at 30 or 45°. There was no significant difference in wetness duration between sensors at 30 and 45° at Elora. A mean duration difference of 25 minutes between the sensors at 30 and 45° in Piracicaba was deemed significant at $\alpha = 0.01$. It was acknowledged by the authors that sensors at Piracicaba should have been oriented facing south, given their Southern Hemisphere location.

The modeling results, such as those conducted by Rowlandson (2006), and field experimentation provide conflicting information as to how to orient sensors. There are aspects of leaf wetness sensors used in field measurements that cannot be accounted for when simulating orientation angles using models that investigate latent heat fluxes. Modesl are unable to account for actual characteristics of the sensor in terms of its heat capacity which would influence how quickly the sensor cools or how quickly water will evaporate from the surface of the sensor as the sensor begins to heat up from incoming solar radiation. In this situation, results from field experiments are more appropriate for indicating how a sensor should be oriented in a field.

2.5 Modeling Leaf Wetness

Models have been developed to estimate leaf wetness duration. These models are empirically–based or based on physical principles, with some models that bridge both concepts.

2.5.1 Empirical Models

Empirical models tend to require the fewest meteorological inputs. They range from the simplest models requiring only one meteorological input to much more complex models. The relative humidity (RH)≥90% model, initiates the onset of wetness when the relative humidity measured is greater than or equal to 90%, and the wetness period ends when the value drops below the 90% threshold. The sources of information regarding relative humidity may vary. Measurements may be made in an agricultural field or at a standardized weather station, such as at an airport. This particular model was examined by Kruit et al. (2004) and modified to form the extended relative humidity model (RH EXT). This model indicates that wetness occurs at RH values greater than 87%, but also examines the region of 70-87%. If the RH increases more than 3% in a 30 minute time period, and if the RH is within the range of 70-87%, the leaves are said to be wet. A decrease of 2% within a 30 minute period indicates that the leaves are dry. Another empirical model is the dew point depression model (DPD), which examines the difference between the measured air temperature and the dew point temperature (Gillespie et al., 1993). The model used a difference of 2°C or less as an indication of wetness onset, and a depression value greater than 4.3°C to indicate the end of a wetness period. The Classification And Regression Tree/Stepwise Linear Discriminant (CART/SLD) model requires a few more inputs such as windspeed, dew point depression, air temperature, and relative humidity (Gleason et al., 1994). The model identifies thresholds for each of these variabiles above which dew is unlikely to occur. The model first examines the threshold for dew point depression. If the conditions are satisfactory for dew development, then windspeed is examined next. Depending on the 10 m windspeed, the model either advances to look at the relative humidity or is directed to an empirically derived equation, which is a function of the temperature, relative humidity, windspeed and dew point depression. If the conditons of the equation are satisfied, dew is indicated. If the relative humidity is higher than the established threshold, then the user is directed to a final equation, also a function of temperature, relative humidity, windspeed and dew point depression.

One final model presented here is the Fuzzy Logic Model (Kim et al., 2004). This model is classified as an empirical model, but does incorporate some of the physical principles associated with leaf wetness. It requires inputs of windspeed, relative humidity, air temperature, and net radiation. The inputs of air temperature and relative humidity are used to determine the vapor pressure deficit. The user is required to classify each input into a set of categories. For example, windspeed can be classified into categories of 'slow' or 'fast,' and vapor pressure deficit and net radiation are categorized into 'low' or 'high.' A process referred to as 'fuzzification' determines the extent to which the variable fits within the category. The membership values range between 0 and 1. Rules regarding the conditions for wetness are established using physical principles. Rules can be based on a single variable, where one such example provided indicates that when net radiation is low, wetness is likely present. Alternatively, two or more variables can be combined, where their respective categorical membership numbers are multiplied. One such combination is the indication that the vapor pressure deficit is moderate, but the windspeed is fast, resulting in a conclusion that wetness is likely absent. When more than one rule is applied in order to finally determine if wetness is present, a process referred to as 'defuzzification' is conducted to determine an aggregated value between 0 and 1. A value of 0.5 is used as a threshold for wetness, where aggregated values greater or equal to 0.5 wetness indicate wetness.

Table 2.3 outlines the meteorological inputs required for the empirical models described. This is not an exhaustive list of possible empirical models. These models were selected for discussion as they appear to be the models that are most commonly cited by the literature within the plant pathology and agricultural meteorology research communities.

By definition, empirical models are only directly relevant to the region in which they were developed. Application of these models may not be successful if used in regions where the conditions for dew development, such as soil moisture, soil texture, or plant canopies, may differ. If an empirical model is required due to limited availability of data, then the model must be validated for the region, and the empirical coefficients or

	Variable				
Model	T	Td	RH	WS	Net Rad.
RH ≥90%			✔		
RH EXT			✔		
DPD	✔	✔			
CART/SLD	✔	✔	✔	✔	
Fuzzy Logic	✔	✔	✔	✔	✔

Table 2.3 Meteorological variables of temperature (T), dew point temperature (Td), relative humidity (RH), windspeed (WS) and net radiation (Net Rad.) required for the empirical leaf wetness models described. Note that if temperature and dew point temperature are available, relative humidity can be calculated and does not require a separate measurement. Likewise, dew point temperature can be obtained from measurements of temperature and relative humidity.

thresholds may require adjustment.

2.5.2 Physical Models

Physical models of leaf wetness have been developed to estimate dew duration by examining the exchange of latent heat, indicating condensation or evaporation from a surface, through the use of an energy balance approach. The benefit of physical models is that the physical principles used in the model do not change from region to region, and therefore the model does not require as many adjustments for use compared to empirical models. Within the physical models, there are either one-source or two–source models. One-source models examine energy and moisture exchange between the vegetative surface and the atmosphere (Sentelhas et al., 2004b; Rao et al., 1998; Jr. and Gillespie, 1982a,b). A commonly cited one–source model is the Penman–Monteith model, which has undergone several adaptations (Huber and Gillespie, 1992; Sentelhas et al., 2004b). Two–source models (Norman, 1979; Anderson et al., 2000) examine the exchange of moisture among the soil, vegetation, and atmosphere. Two–source models are able to differentiate between dewfall and distillation.

Physical models can be further divided into models that treat the vegetation canopy as a single-layer (Anderson et al., 2000), and those that break the canopy down into multiple-layers, where an energy balance approach is applied to each layer (Norman, 1979).

2.6 How to Choose Between Model and Measurement?

Several studies have been conducted that compare LWD measured by a sensor to model estimates. Sentelhas et al. (2008) conducted an experiment that examined leaf wetness duration measured over a turfgrass surface and the empirical models of RH≥90%, the DPD model, and the extended RH threshold model. The comparison between the models and the sensors was conducted in Ames, Iowa (USA), Elora, Ontario (Canada), Florence, Toscany (Italy), and Piracicaba, São Paulo (Brazil). It was found that the extended RH threshold model performed the poorest at all locations with the mean absolute error ranging between 2.89 (at Piracicaba) to 4.44 (at Florence) hours. At the Ames site, the model with the lowest mean absolute error in LWD was the DPD model at 2.43 hours. This model was also the most successful for the Elora site, where the model was initially developed. For the Florence and Piracicaba sites, the RH≥90% was the most successful with mean absolute errors of less than two hours. Kabela et al. (2009) compared the Atmosphere-Land Exchange model (ALEX) (Anderson et al., 2000) to measurements of duration in both corn and soybean canopies. The authors indicate that there was good comparison between the physical model and the measurements of the leaf wetness sensors, especially under heavy dew conditions, where the model indicated a dew onset a half hour earlier than the first sensor, but indicated drying at the same time as the sensor.

There are benefits and drawbacks for utilizing either models or measurement for estimation of leaf wetness duration. Models can be used when direct measurement is not possible, allowing estimation over larger regions. The use of a model can eliminate the concern over where to place a sensor in a canopy, and remove the need for regular maintenance. However, many models require several meteorological inputs that may not be available at all weather stations. In addition, the closest station where data is available may not be representative of the region for which the model is intended.

Sensors are beneficial because they provide information on leaf wetness duration for both dew, rainfall and irrigation events. They do not require the additional measurements needed for a model. However, sensors require calibration prior to placement in field, and ideally, need occasional visual observations for comparison of onset and drying along with regular maintenance. Like models, sensors are estimators of leaf wetness.

2.7 A Few Final Thoughts

When using leaf wetness sensors, regardless of wheather the sensor is a commercial product, a commercial product that is modified by painting, or a custom product produced by the researchers, placement within a crop canopy is important to consider. Sentelhas et al. (2005) found that within a grape and coffee canopies, placement is not as important as it is within a maize canopy or an apple tree. As a research community that utilizes leaf wetness sensors, it is important that we establish a standard for their use. Historically, sensors have been placed in a field at varying orientation angles, which prevents comparison between studies. Sentelhas et al. (2004a) and Lau et al. (2000) have suggested that orientation angles of 30 or 45° be utilized when using the Campbell sensors (although this orientation would apply for any sensor with a flat surface).

Based on the evidence, it is suggested that flat-plate sensors should be oriented at 45° with the sensor face facing away from the equator and toward the nearest pole. For the resistance-grid sensor produced by Campbell, studies support the theory that these sensors require painting. The Decagon sensor does not require painting, and may eliminate the potential discrepancy in results resulting from differing sensor treatments.

Leaf wetness has been studied for decades, and will continue to play a large role in management of plant diseases by the plant pathology community in the future. A researcher wanting to utilize leaf wetness estimates must carefully consider the purpose for the data. If they wish to have estimates that may be representative of a large region, and data from a weather station is available, it may be reasonable for them to proceed with a model. It is necessary, however, to consider the quality of the data that is being used. Gaps in data or data from a station lacking maintenance will not provide accurate estimates of leaf wetness. Should someone be more interested in a field measurement, it may be more appropriate to utilize a sensor. If multiple sensors are being used, they should be calibrated to ensure that they all react to wetness similarly. Once installed in a field, visual observations can ensure that sensors are performing as expected. It is important that sensors are maintained regularly. When installed in a field, they are subject to situations where the sensor data could be compromised. For example, rodents have an affinity for chewing wires, sensors may be impacted by farm equipment, or debris on the surface of the sensors could lead to the need for a new wetness threshold to be established. Sensors can not be placed in a field under the assumption that good data will be provided for the growing season if they are not maintained. It is the suggestion of the authors that estimates of LWD should occur from using the empirical model of RH $\geq$ 90%. Measurements of RH are generally more uniform over a growing region, and a single sensor could be used to provide a regional estimate of LWD for use in diease warning systems. Estimating LWD from this empirical model would provide results that are as accurate as the use of multiple leaf wetness sensors.

CHAPTER 3. SPATIAL VARIABILITY OF DEW AMOUNT AND DURATION

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Abstract

The vertical variability of dew duration and dew amount has been investigated within various crop canopies. Studies regarding the horizontal spatial variability of dew have been limited to aspatial scale of a few meters. Our study examines the spatial variability of dew at sites that are hundreds of meters apart. We investigated the spatial variability of dew amount and dew duration at three locations within a soybean field. Locations were chosen based on changes in topography and soil texture in an effort to determine if rates of distillation vary from one location to another. Dew was sampled on seven mornings at 1/3 and 2/3 canopy height. Dew measurements were also scaled to a canopy estimate through the use of leaf area index. It was found that the variability between 15 samples taken at one location was much higher than the variability seen between locations. At 1/3 canopy height, the variability between the samples was 30 times greater than the variability between the locations at 1/3 canopy height. For samples at 2/3 canopy height and for canopy–scaled mesaurements, the variability between sites

was 25 and 11.5 times greater than between locations at these heights, respectively. Overall, it was found that there is great leaf–to–leaf variability in dew amount. For dew duration, it was found that there was no significant difference in dew duration at 1/3 or 2/3 canopy height among the sites.

3.1 Introduction

Dew forms on a plant canopy from two predominant sources. One source is water vapor from the atmosphere, referred to as dew fall or dew deposition, and the second is water vapor from the soil surface, referred to as distillation or dewrise (Agam and Berliner, 2006; Jacobs et al., 1990). Guttation (also referred to as exudation) as a source of leaf wetness is noted in some literature, but is considered to be a minimal contribution to the overall amount of water on the surface of a leaf, and as such, will be ignored in this study (Jacobs et al., 1994).

The importance of leaf wetness duration, from either precipitation or dew, has been well documented in plant pathology literature, as the risk of infection for many fungal diseases has been shown to be related to the duration of leaf wetness. Many integrated pest management programs have been developed based on measurement or modeling of leaf wetness duration (e.g. Pitblado (1992); Latin and Egel (2001)).

Previous studies have examined the spatial vertical variability of dew deposition in various canopies (e.g. Sentelhas et al. (2005); Jacobs et al. (1994); Magarey et al. (2006)), but the context of the studies have been limited to examination of only dew duration or limited to one location. Kabela et al. (2009) measured and modeled dew amount and duration, however the study was limited to one location within the field. Schmitz and Grant (2009) examined the horizontal variability of leaf wetness duration within a soybean canopy. Leaf wetness sensors were placed randomly within an experimental circle with a 9.1 m radius. Sensors were placed within this circle at either 25, 55, or 85 cm heights. It was found that for dew events, there was a large variability in sensor response between the low, medium and high sensors. Wilson et al. (1999) conducted an experiment in a potato canopy that combined both measurement and modeling of dew amount. They utilized the Cupid model (Norman, 1979) to model the contribution of dewfall and distillation to the overall dew amount, as compared to measurements taken.

Our study sought to determine the variability of dew amount and duration between three locations in a soybean field. In this situation, a field is defined as a region of a continuous, homogeneous canopy that has experienced the same management practices. These locations were located hundreds of meters from each other, as shown in Figure 3.1, with the shortest distance between two sites was still greater than 600 m. We attempted to determine if a measurements taken at in a small region of a field is representative of the entire field. Information regarding leaf wetness duration is important for the management of many plant dieases which require the presence of free water on a plant canopy for infection. Disease warning systems have been developed to aid growers in determining the ideal time for application of fungicides or antibiotics for disease management.

We chose locations based on differences in topography and soil texture, where there may be variations in soil temperature and soil moisture that would impact rates of distillation. Wilson et al. (1999) conducted an experiment in a potato canopy that combined both measurement and modeling of dew amount. They utilized the Cupid model (Norman, 1979) to model the contribution of dewfall and distillation to the overall dew amount, as compared to the measurements taken. During the days investigated, on average, the contribution of distillation was over 85% of the total dew amount, indicating that water vapor from the soil surface is an extrememly important component. This was further verified by examining the days the dew was sampled to simulations of situations

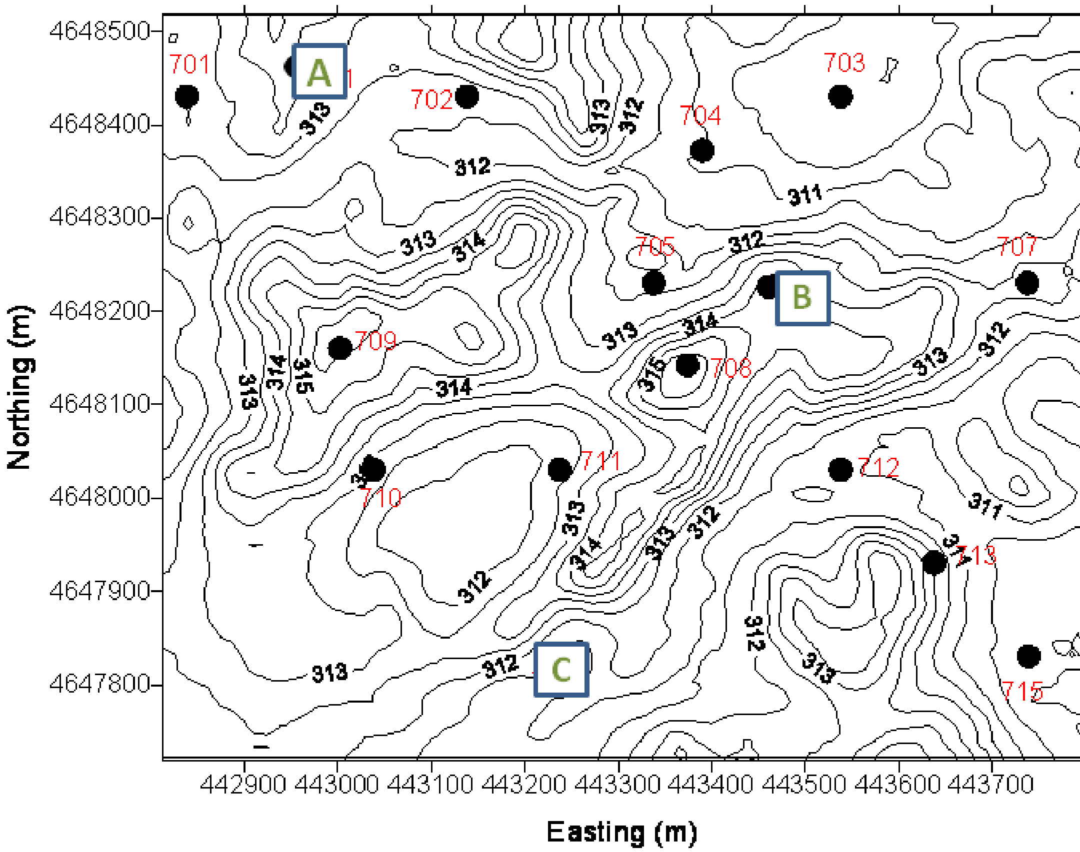

Figure 3.1 Topographic map of Iowa Validation Site. The locations A, B, C, outlined by boxes, are the sites where measurements of dew amount and dew duration were made. The black dots on the map indicate where additional soil moisture measurements are made. The contour lines show the variations in elevation within the field in meters.

where the soil was dry and when the soil wet. Total dew on the canopy was three times higher for wet soil scenarios than for dry. It was hypothesized that there would be a statistically significant difference in dew amount and dew duration between the sites. As dew is formed via dewfall or distillation, we the expected variability in the amount of dew and its duration because of the variation in distillation between the sites.

3.2 Sensitivity Analysis

The Atmosphere-Land EXchange model (ALEX) (Anderson et al., 2000) was utilized to describe the sensitivity of dew amount and dew duration to characteristics that make the sites we used in this study unique. ALEX is a two-source model that incorporates both a canopy and soil component and their interactions (Figure 3.2). The model examines the exchanges of heat, water and carbon between the soil surface, the in-canopy air-space, and the atmosphere above the canopy. As the model is capable of examining the exchanges between the soil and the canopy air-space, it is able to account for both dewfall and distillation. The model requires the meteorological inputs of windspeed, temperature, vapor pressure, incoming solar radiation, incoming longwave radiation and precipitation. The soil component of the model requires a description of soil properties by depth including hydraulic conductivity, air entry potential, and bulk density. The initial profile of soil moisture and lower boundary conditions in soil temperature must be specified. The movement of water and heat within the model are solved in conjunction using the Richards' equation. Total latent heat estimates are calculated by solving for the latent heat contribution from the canopy and the latent heat contribution from the soil surface. The latent heat from the canopy is further divided into components representing the evaporation of free water on the leaf surfaces and the transpiration. ALEX has been used in prior dew studies, such as Kabela et al. (2009); Hornbuckle et al. (2007, 2006), and Anderson et al. (2001).

We conducted a sensitivity analysis to investigate the inputs required for the soil component of the model, to determine if the model, when run using data from the three separate field locations, would predict variability of dew amount and duration at the field–scale. A time period of five days was used to test different components of the ALEX model. Datum from overnight of the fourth day to morning of the fifth day were used for comparison.

A sensitivity analysis was focused on variations in soil characteristics, as it was not expected that atmospheric conditions would vary greatly within our field. The sensitivity of dew amount and dew duration was tested against a range of soil textures. The proportions of sand, silt, and clay for each soil texture classification were taken from Campbell and Norman (1998). Associated average values for the air entry potential, exponent of the soil moisture release curve, and saturated hydraulic conductivity were also obtained from Campbell and Norman (1998). For each soil texture, an average bulk density value associated with that soil texture was used to run the model (Saxton et al., 1986). Finally, soil moisture values were examined. We tested the sensitivity of soil moisture values ranging from 0.1 to 0.4 m^3m^{-3} from the soil surface to a depth of 30 cm. Soil moisture from 30 cm to 2 m was kept at 0.2 m^3m^{-3}. This range of values spans dry soil conditions to values close to saturation. For this sensitivity analysis, all other components of the model were held constant.

The sensitivity of dew amount and duration to varying values of soil moisture to a depth of 30 cm are shown in Figure 3.3. In order to obtain the relative values of dew amount and duration, values were related to the value obtained at the mid–value soil moisture of 0.25 m^4m^{-3}. Values of dew amount and dew duration are similar for soil moisture values less than 0.25 m^3m^{-3}. Dew amount increases for the higher range of soil moisture, with dew amount at a soil moisture value of 0.4 m^3m^{-3} being 20% higher. Dew duration was not impacted by changes in soil moisture, as expected given that the duration of dew is driven predominantly by atmospheric conditions. These results are similar to results obtained by Wilson et al. (1999), where it was found that volumetric soil moisture of 0.25 m^3m^{-3} resulted in dew amount that was three times higher than the dew amount that occurred with 0.07 m^3m^{-3}. The results are further validated by Campbell (1985) who indicate that the rate of evaporation of water from the soil surface for wet soil conditions is driven by the difference in vapor pressure between the soil and the atmosphere. As the soil becomes drier, the rate of evaporation is controlled by how quickly water is supplied to the the surface.

Dew amount and dew duration appeared to be sensitive to changes in soil texture. The results from this analysis is shown in Figure 3.4. On the graph the soil textures are indicated on the x–axis in order of average bulk density. For this analysis, dew amount and dew duration obtained from each soil texture are related to the values obtained from the clay loam soil texture. Values for dew amount for loamy sand is 16% higher than for clay loam. The dew amount for sandy clay and silt clay was the lowest at approximately 5% less than for clay loam. Although dew duration appears to be influenced more by soil texture than soil moisture, it is likely the result of the lower dew amount values, which would evaporate faster. Soil texture influences both the movement of heat within the soil profile, due to different soil heat capacities and thermal conductivities, as well as the movement of water.

3.3 Materials and Methods

3.3.1 Study Location

Our study was conducted at the Iowa Validation Site, southwest of Ames, IA, in a soybean field approximately 1 km^2, during 2010. A topographic map of the site is shown in Figure 3.1. Three sites within the field were chosen based on variations in characteristics such as topography and soil texture . Site A was selected because it was located on one of the highest points in the field and has a loam soil texture for the first 10 cm and sandy clay loam from 10 cm to approximately 1 m. Site B is a location that is prone to ponding of water, with a soil texture of silty clay from the surface to a depth of 50 cm, and then a texture of silty clay loam to a depth of approximately 1 m. The last site, Site C, is considered to be the average topography of the field, with the soil texture of clay loam to a depth of 50 cm, with a loam texture beneath to a depth of approximately 1 m. The variation in soil texture and topography within our field is representative of other fields in central Iowa.

3.3.2 Measurement of Dew Amount

We sampled dew to determine dew amount on seven days during July, beginning around sunrise. Dew was sampled on mornings when preciptiation had not occurred the prior day to ensure that intercepted prepcipation was not identified as dew. The experiment was designed to capture the maximum dew amount of a dew event, a half hour to hour following sunrise (Kabela et al., 2009), and to witness some drying of the dew during the sampling period. Samples were taken at the three pre–selected locations within the field. A dry, 28 × 28 cm, paper towel (Bounty Basic, Proctor and Gamble, Cincinnati, OH) was folded and placed in a ziptop bag and and its mass was determined prior to sampling. For each leaf sampled, one paper towel was used to remove the water from the top surface of the leaf, and another used to remove the water on the bottom surface. One leaf at 1/3 and another at 2/3 canopy height was sampled (Sentelhas et al., 2005; Jacobs and Nieveen, 1995; Kabela et al., 2009; Schmitz and Grant, 2009). Once a leaf had been sampled, the leaf was removed and placed in a paper bag with the appropriate site identification, sample number, and canopy location. The leaf at 1/3 canopy height was always sampled first, followed by the leaf at 2/3 canopy height. This process was repeated 5 times. After 5 leaves at 1/3, and 5 leaves at 2/3 canopy had been sampled, a delay of 30 minutes was imposed. The sampling process was repeated two additional times, with a 30 minute delay between them. The entire sampling procedure required, on average, 2 hours. Samples were taken at the three locations within the field simultaneously, with a team of two people situated at each location. Teams were rotated between the sites each sampling day and team members where changed in order to minimize sampling error. Prior to each set of 5 samples, a control paper towel, with a known mass, was removed from a ziptop plastic bag and exposed to the air for 10 seconds to determine if there was any absorption of water vapor by the paper towel from the air that may affect the values obtained from the samples. This control paper towel was massed after exposure to determine if absorption of water vapor had occurred. Any mass change was indicated as a source of error in the sample.

Upon completion of sample collection, the paper towels in the ziptop bags were massed to determine the amount of water collected from each leaf (a sum of the mass collected from the top and bottom of the leaf). The sampled leaves were scanned to determine leaf area. Leaves were scanned using an Epson scanner at 600 dpi (dots per square inch), and were scanned as a black and white image. The images were then scaled to 92 dpi using Olympus Master 2 program to allow for manageable file sizes, but still maintain image integrity. Images were then imported into Scion Image (Scion Corporation, Frederick, MD) to determine the leaf area in square meters. Specific directions for determining leaf area using Scion Image can be found in Kabela (2006).

The amount of dew per unit two–sided leaf area was determined for leaves sampled at both 1/3 and 2/3 canopy height, by taking the mass of water collected from the top and bottom of the leaf and dividing it by two times the leaf area (the scanning of the leaf only provides the surface area of one side of the leaf). Additionally, dew amount sampled at 1/3 and 2/3 canopy height were averaged and multiplied by two times the canopy leaf area index (LAI) to scale measurements from single leaves to the canopy level. LAI measurements were taken throughout the summer using both and LAI–2000 (LI-COR Biosciences, Lincoln, NE) and AccuPAR LP–80 (Decagon Devices, Pullman, WA).

3.3.3 Dew Duration

Leaf wetness duration was measured using leaf wetness sensors (Decagon Devices, Pullman, WA). Prior to installation of sensors at the field location, the sensors were calibrated over turf grass in order to determine an appropriate threshold for the onset of leaf wetness. Although the suggested threshold from Decagon Devices (2009) is a threshold of $\geq$274 mV, it was found for some sensors in a field study the previous year that unique sensor thresholds were necessary due to aging of the sensor. After calibration, the sensors were placed in the field with a total of four sensors, at each of the three locations in the field where manual sampling of dew amount occurred. Two of the sensors at each location were placed at 1/3 canopy height, and two were placed at 2/3 canopy height. Sensors were positioned facing north, with one pair located one meter from the other pair, within the same cropping row. Sensors were sampled every minute and averaged over a 15 minute period using Campbell Scientific dataloggers (Campbell Scientific, Logan, UT). Examination of the data for dew duration indicated that one sensor (at 1/3 canopy height) at Site A was non-operational, as partway through the season it began to provide some mV readings that were negative. Due to a loss of data at Site B resulting from a datalogger change, dew duration analysis was conducted on 8 days beginning July 29 until August 30, 2010. The two sensors at 1/3 canopy height were averaged at each location and then compared to the two sites. The same procedure was used for the sensors at 2/3 canopy height.

3.4 Results

3.4.1 Dew Amount

A mixed effects model was utilized to examine the the variability of dew amount between the three sites for leaves sampled at 1/3, leaves at 2/3, and a canopy-scaled measurement of dew. For all three situations, the date samples were taken and the time they were taken were considered fixed effects. The times that samples were taken were normalized to minutes after sunrise, where information regarding time of sunrise was obtained from the USNO (2010). The dew measurement values, for 1/3 canopy height, 2/3 canopy height, and canopy-scaled dew amount for the seven days are presented in Figures 3.5–3.7. The mean, standard deviation (std. dev.), minimum and maximum dew amounts for the three sites at 1/3 canopy height, 2/3 canopy height, and canopy-scaled measurements are presented in Tables 3.1 - 3.3, respectively. The minimum values were all obtained on July 14, 2009, where atmospheric conditions were not conducive to the development of dew, being overcast and preventing the canopy from cooling. The mean values of dew amount are similar to what would be considered a moderate dew (Kabela et al., 2009).

At 1/3 canopy height, the mean dew amount for Sites A and B were similar. Site C, the site prone to ponding, experienced the highest mean dew amount and the highest maximum value. At 1/3 canopy height, the mean values of dew amount per unit leaf area was much smaller than the mean dew amount sampled at 2/3 canopy height. At 2/3 canopy height, the site at the highest elevation, Site B had the lowest mean value and the lowest maximum value. This trend does not hold true when scaling to the canopy level, where Site B had the highest mean dew amount. This is the result of higher leaf area index values through the growing season used to scale the measurements. It is important to note that regardless of sample location within the canopy or in the canopy-scaled values, the standard deviations of the measurements are very large, on the same order of magnitude as the mean values themselves. This is reflected in the analysis of variance, shown in Table 3.4, where the values for the variability between sites is very small compared to the variability between samples taken at one location. The variability between samples at one location is typically more than 10 times higher than the variability seen between the sites.

Table 3.5 indicates that for the fixed effect of day, a p-value of <0.0001 deemed day to be significant at an α of 0.05. Time was determined to not be significant for samples taken at 1/3 or 2/3 canopy height, nor when samples were scaled to the canopy.

Site	Mean (mm)	Std. Dev.	Minimum (mm)	Maximum (mm)
A	0.026	0.022	0.003	0.143
B	0.027	0.026	0	0.123
C	0.034	0.035	0	0.164

Table 3.1 Mean, standard deviation, minimum and maximum values for measurements of dew amount from leaves at 1/3 canopy height.

Site	Mean (mm)	Std. Dev.	Minimum (mm)	Maximum (mm)
A	0.108	0.057	0.004	0.220
B	0.088	0.054	0	0.193
C	0.098	0.060	0	0.208

Table 3.2 Mean, standard deviation, minimum and maximum values for measurements of dew amount from leaves at 2/3 canopy height.

3.4.2 Dew Duration

Dew duration for the three locations was examined separately at the 1/3 and 2/3 canopy heights. A simultaneous multiple comparison was made using a Tukey-Kramer test. It was found that there was no significant difference in dew duration between the three locations, with p–values greater than 0.1 at an α of 0.05. At 2/3 canopy, the results were similar, with no significant difference in dew duration between the measurement sites.

3.5 Conclusions and Discussion

The results from the mixed effects model for dew amount indicate that there is great variability among samples taken at one location, regardless of the site location. If there was variability between sites as hypothesized, it was not seen using the sampling technique utilized in this study. Statistically, day was deemed to be significant for dew amount, which was expected given that atmospheric and soil conditions change day-to-day, influencing the amount of dewfall and distillation, respectively, on any given day. Time was determined to not be significant. The sampling technique was established in

Site	Mean (mm)	Std. Dev.	Minimum (mm)	Maximum (mm)
A	0.329	0.195	0.0250	0.800
B	0.444	0.259	0	0.870
C	0.399	0.232	0.017	0.875

Table 3.3 Mean, standard deviation, minimum and maximum values for canopy-scaled measurements of dew amount.

Measurement	Between Sites	Within Site
1/3 canopy	$3x10^{-5}$	$6x10^{-4}$
2/3 canopy	$8x10^{-5}$	0.002
full canopy	0.002	0.023

Table 3.4 Variability (mm^2) found in measurements between sites and measurements within a site.

order to see the drying of dew during the sampling period, by implementing delays in sampling. It appears as though either this was a flaw in the sampling design as there was not enough of a time delay to discern the impact of time on dew amount, or else the leaf to leaf variability in dew amount overshadowed any effect of time on the sample. Similarly to there being no significant difference in dew amount, there was no significant difference in dew duration between the three locations.

Fungicide spray scheduling (Pitblado (1992); Latin and Egel (2001)) provides information regarding the ideal time for fungicide application based on leaf wetness duration. The results of this study indicate leaf wetness duration estimates in a field with minimal topography and a uniform crop canopy can be measured at a single point within the field, and perform as well as measurements taken at multiple location. It is important to note that placement of a leaf wetness sensor in a crop canopy is important. Previous studies have investigated how the vertical variability of dew amount and dew duration varies within several crops (e.g. Jacobs et al. (1990, 1994); Jacobs and Nieveen (1995); Sentelhas et al. (2005); Batzer et al. (2008)).

Measurement	Day	Time
1/3 canopy	<0.0001	0.6225
2/3 canopy	<0.0001	0.2365
full canopy	<0.0001	0.8335

Table 3.5 p-value for fixed effects of Day and Time for $\alpha = 0.05$.

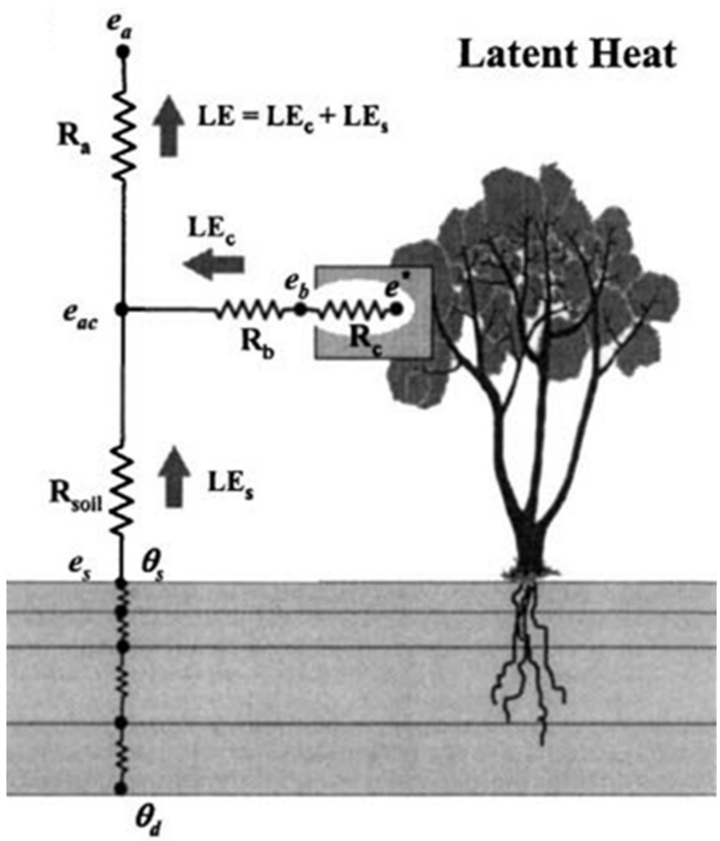

Figure 3.2 Schematic of the latent heat exchange component of the ALEX model. Source: Anderson et al. (2000). The total latent heat flux, LE, is a sum of the latent heat flux contribution from the canopy, LE$_c$, and the latent heat flux from the soil, LE$_s$. R$_a$, R$_b$, and R$_c$ are the aerodynamic, boundary layer, and effective stomatal resistances. R$_{soil}$ is the resistance through the boundary layer at the soil surface. The vapor pressure within the stomatal cavity is indicated by e*, with e$_s$, e$_{ac}$, e$_a$, representing the vapor pressures at the soil sruface, within the canopy airspace and above the canopy, respectively. The volumetric soil moisture at the surface is represented by θ_s, and at the lower boundary, by θ_d.

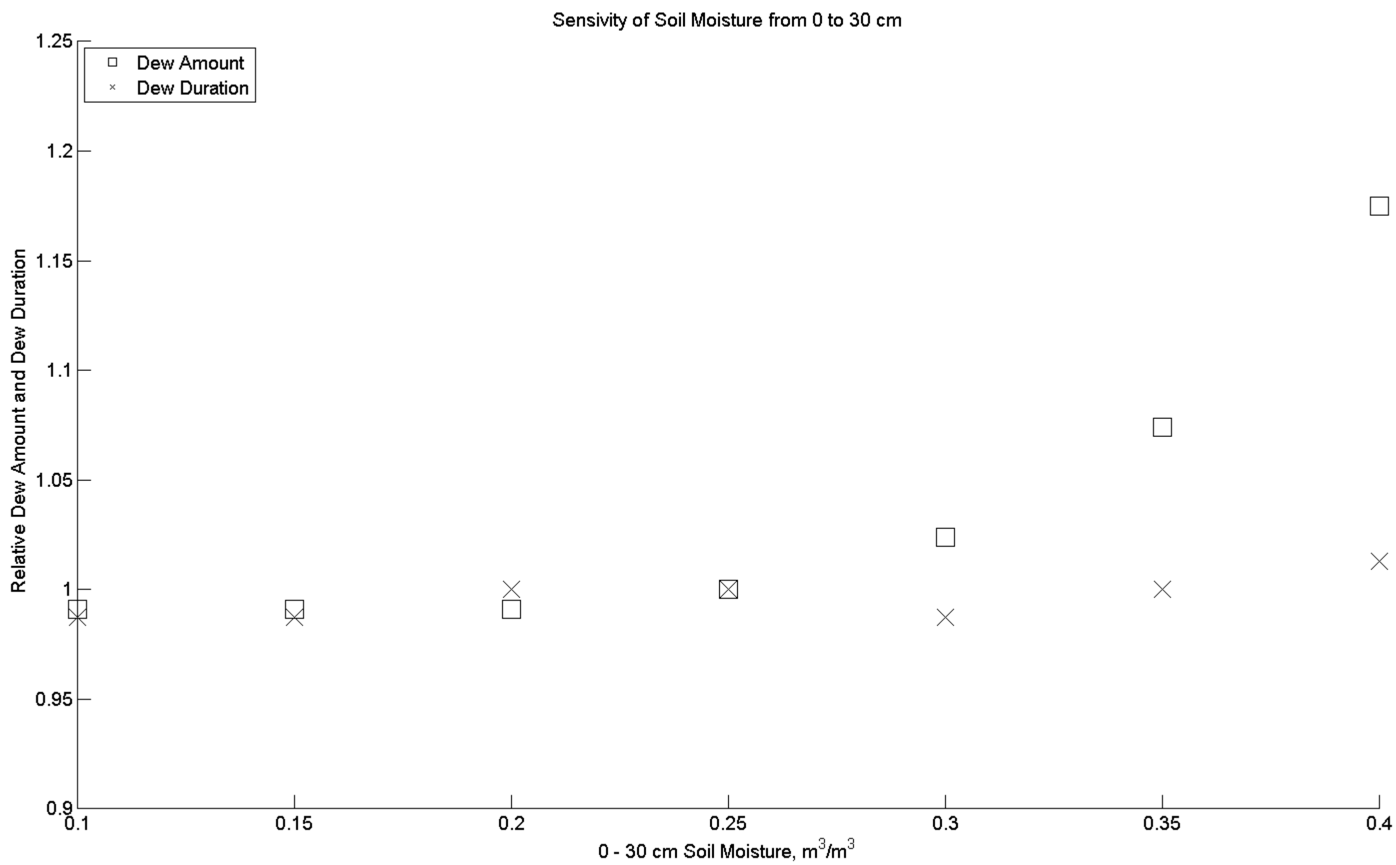

Figure 3.3 Sensitivity analysis of dew amount and dew duration to soil moisture, $m^3\ m^{-3}$, within the top 30 cm of the soil profile. The values of dew amount and dew duration are relative to the mid point value of 0.25 $m^3\ m^{-3}$.

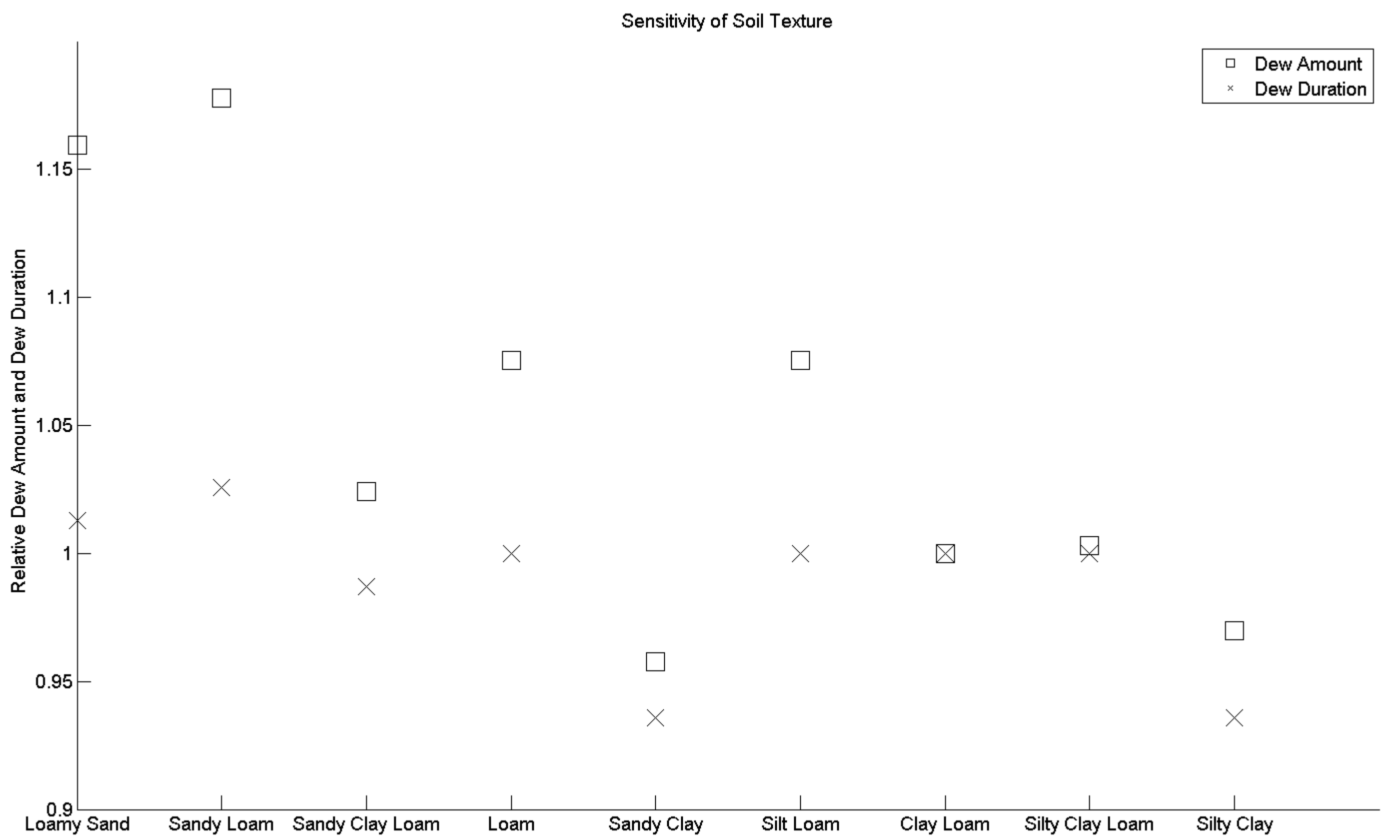

Figure 3.4 Sensitivity analysis of dew amount and dew duration to a variety of soil textures, each having unique soil characteristics. Dew amount and dew duration are relative to the values obtained for the clay loam soil texture.

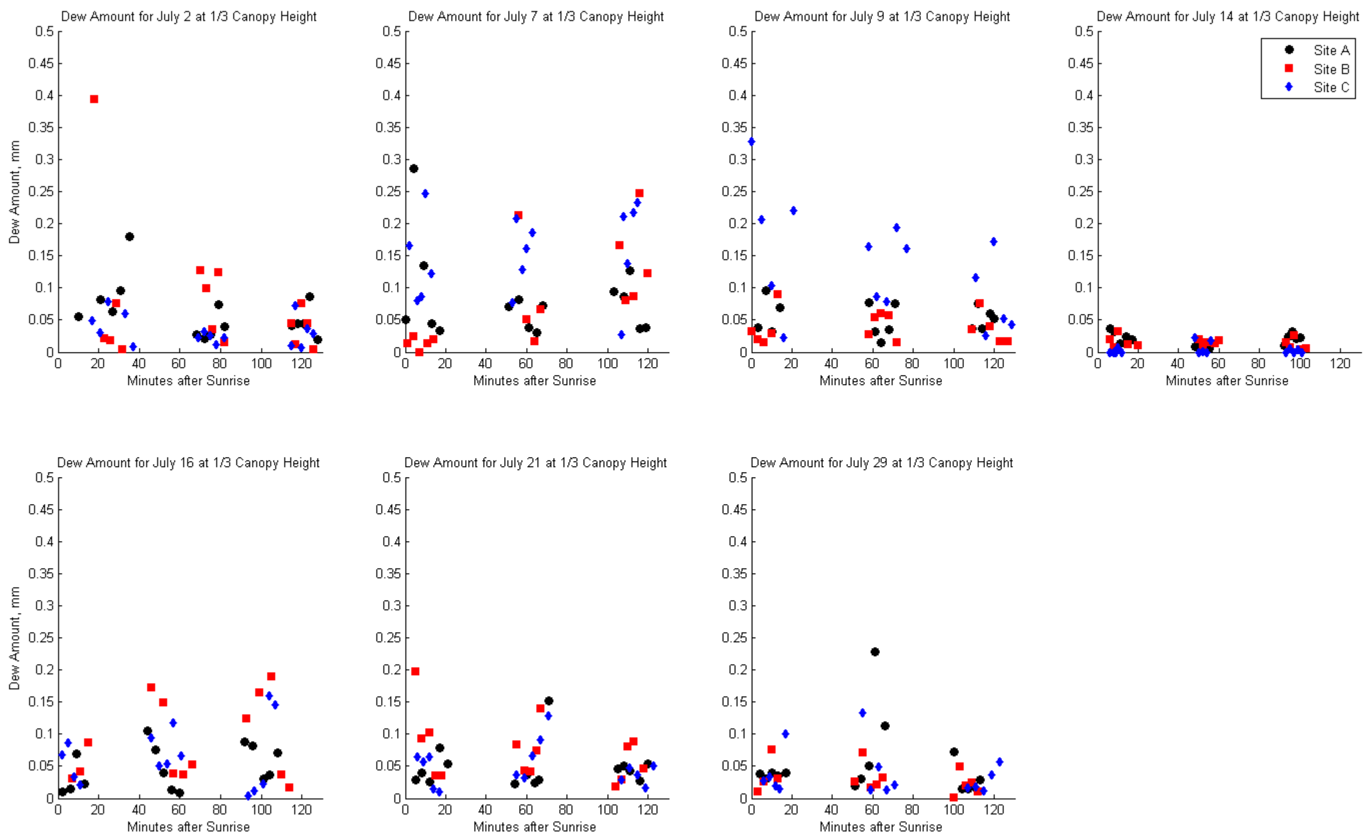

Figure 3.5 Dew amount measurements at 1/3 canopy height.

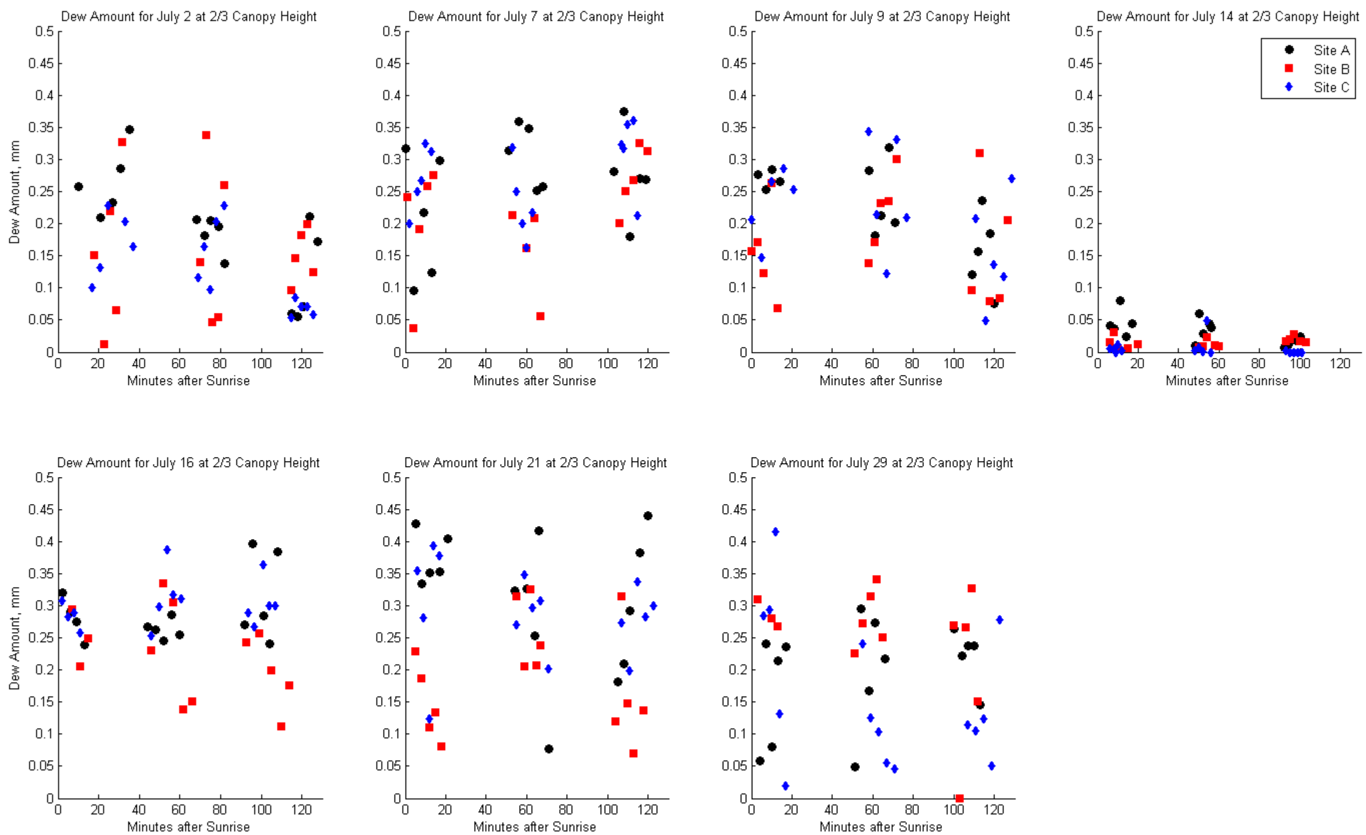

Figure 3.6 Dew amount measurements at 2/3 canopy.

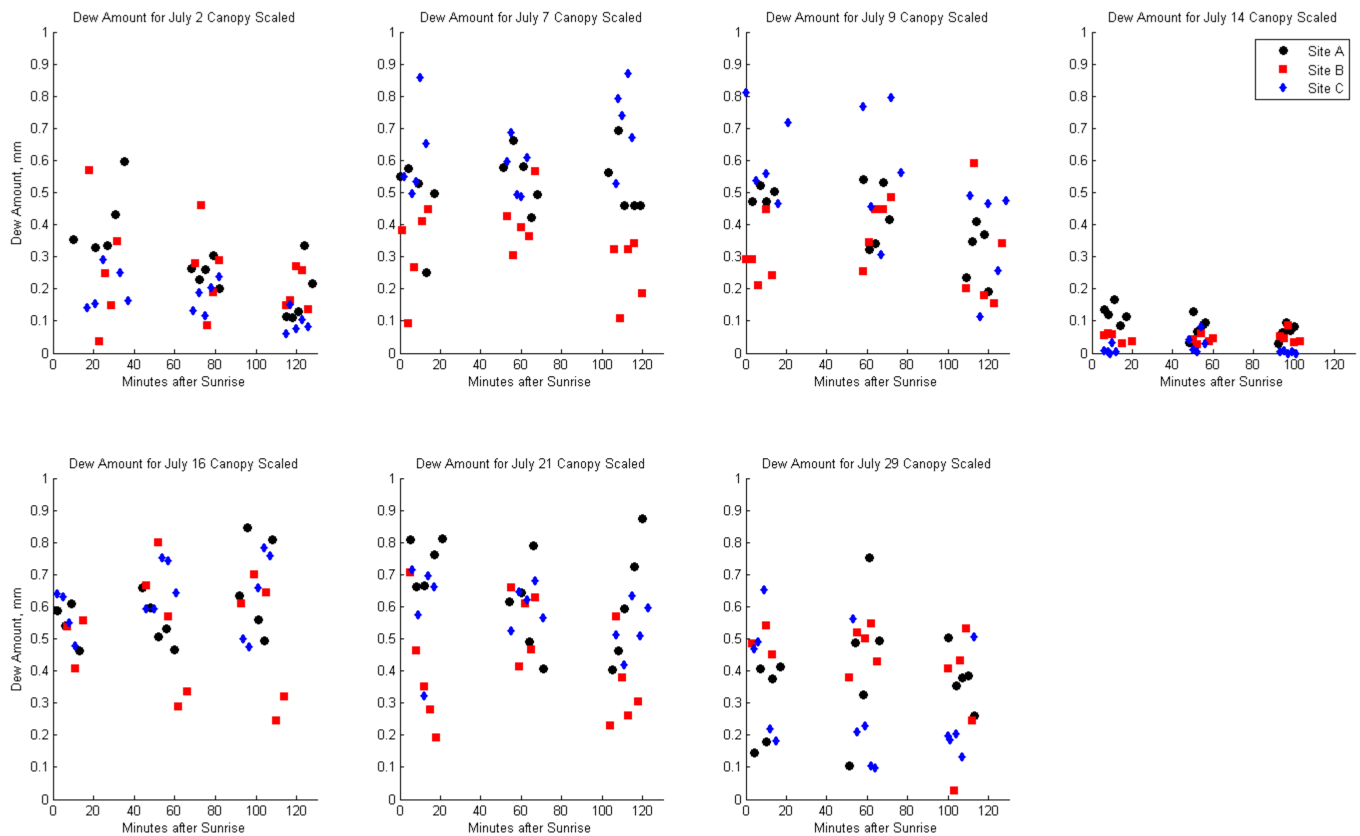

Figure 3.7 Canopy–scaled dew amount measurements.

CHAPTER 4. COMPARISONS OF EVENING AND MORNING SMOS PASSES OVER THE MIDWEST UNITED STATES

T.L. Rowlandson, B.K. Hornbuckle, J.C. Patton, S. Logsdon

Abstract

This study investigates differences in the soil moisture product and brightness temperatures between 6 pm and 6 am local solar time SMOS passes for a region in north–central Iowa. This region consists of 69 SMOS pixels and has uniform land–cover, consisting of maize and soybean row crops. The comparison was restricted to periods with no rainfall after noon prior to the evening pass and no rainfall between the evening and morning passes. There were 19 days available for analysis of the soil moisture product. It was found that there was a significant difference in the soil moisture between evening and morning SMOS passes for all 19 days, with the soil moisture being lower in the morning for a majority of the days. The difference between the soil moisture measurements on some days exceeded the allowable error for SMOS of 0.04 m^3 m^{-3}. *In–situ* and model results indicate that there should be virtually no change in soil moisture between the

evening and morning. In order to investigate this discrepancy, measured brightness temperature was converted to a polarization index (PI) and evening and morning values were compared. Investigation of the measured brightness temperature was limited to five days where a large range in incidence angles was available for both the evening and morning passes. It was found that there is no significant difference between evening and morning measurements of PI for any of the five days. We found that there was an unexplainable large spread in data at low incidence angles which will hopefully be resolved with the reprocessed SMOS data. The PI values also indicate that there may be a decrease in soil moisture for the morning, but we suggest that given the *in–situ* and model measurements that this could be attributed to an increase in the volumetric water content of the vegetation.

4.1 Introduction

Soil is important in understanding surface-atmosphere exchange. It is a reservoir of water which has the potential to evaporate back into the atmosphere. This is an important component of the surface-atmosphere energy budget, as the evaporation of water from the soil surface requires energy which will influence the other components of the energy budget. This energy exchange is a key component that is missing in many weather forecasting models, as measurements over larger regions have not been available to date, and traditional *in situ* measurements are very site–specific (Pardé et al., 2004; Koster et al., 2004).

The Soil Moisture Ocean Salinity (SMOS) satellite was launched by the European Space Agency on November 2, 2009. SMOS measures the natural emissions from the Earth's surface within the L–band. SMOS takes advantage of the fact that the microwave emissivity of the earth's land surface depends on the soil moisture, and the microwave emissivity of the oceans depends on the surface salinity. SMOS aims to provide global estimates of soil moisture with accuracy of at least 0.04 m^3 m^{-3}, with a spatial resolution of less than 50 km. SMOS has a polar sun–synchronous orbit providing measurements at 6 am and 6 pm local solar time on a revisit time of at lease 3–5 days (Kerr et al., 2010).

At L-band, the atmosphere has minimal influence on measurements, vegetation is semi–transparent, and measurements of soil moisture can be made to a depth of approximately 5 cm (Jackson et al., 1982). The general remote sensing community has indicated that the ideal time for measurement is at the 6 am time when Faraday rotation in the ionosphere is minimized, there is thermal equilibrium within the soil profile (within the first five centimeters) and within the vegetation canopy, and an effective temperature can be used to represent both the soil surface and canopy temperatures. The soil moisture profile gradient is also considered to be smallest at 6 am (Kerr et al., 2010). While these factors that influence the brightness temperature are all plausible concerns, there has never been an opportunity to actually test these assumptions at the satellite scale. SMOS provides this opportunity.

SMOS passes over the agricultural Midwest region of the United States on a schedule that is more frequent than the 3-5 day revisit time first envisioned for the satellite. Additionally, on several occasions a month, the satellite passes over this region at approximately 6pm and 6am the following morning, local solar time (LST). This provides a unique opportunity to investigate if there are changes in the measurement brightness temperature between the evening and morning. These back-to-back passes provide an opportunity to determine how changes in soil moisture and vegetation over a short period of time influence these measurements.

Our study investigates the SMOS brightness temperature and soil moisture product for a region in north–central Iowa. We investigate periods where there is no precipitation after noon prior to the evening SMOS pass nor during the time between the evening pass and the following morning pass. We hypothesize that there will be no significant difference in measured brightness temperature or soil moisture between the evening and morning SMOS passes, because changes in soil moisture and volumetric water content of the vegetation between evening and morning SMOS passes will be minimal, when changes in surface temperature have been accounted for.

4.2 Background

The overall brightness temperature measured by the SMOS satellite is comprised of the contribution from the soil and the contribution from the vegetative canopy as described by the τ–ω radiative transfer model, as shown in (4.1).

$$T_B = T_{Bsoil} + T_{Bcanopy\uparrow} + T_{Bcanopy\downarrow} \tag{4.1}$$

where

$$T_{Bsoil} = T_{soil}(1 - R_{soil})e^{-\tau/cos\theta} \tag{4.2}$$

$$T_{Bcanopy\uparrow} = (1 - \omega)(1 - e^{-\tau/cos\theta})T_{canopy} \tag{4.3}$$

$$T_{Bcanopy\downarrow} = (1 - \omega)(1 - e^{-\tau/cos\theta})T_{canopy}R_{soil}e^{-\tau/cos\theta} \tag{4.4}$$

The model is simple but useful in that it contains only two parameters, the single scattering albedo, ω, and the optical depth, τ, which must be specified along with the temperature of the soil and vegetation, T_{soil} and T_{canopy}. The brightness temperature emitted by the soil is a function of the soil temperature and the emissivity of the soil. By Kirchoff's law (and assuming thermal equilibrium) soil surface emissivity is equal to $1 - R_{soil}$, where R_{soil} is the soil surface reflectivity. The brightness temperature is attenuated by a vegetative canopy ($e^{-\tau/cos\theta}$), as shown in expression (4.2). The amount of attenuation that occurs is related to the incidence angle of the measurement, θ, and the optical depth of the canopy. The reflectivity of the soil is related to the soil moisture – as soil moisture increases, the reflectivity increases (Dobson et al., 1985). The reflectivity of the soil surface, R_{soil}, is also impacted by the soil surface roughness (Wigneron et al., 2001a). The vegetative component of the model represented by expressions (4.3) and (4.4). The brightness temperature emitted upward from the canopy(4.3), a function of the canopy temperature, is scattered by the canopy according to the single–scattering albedo. The brightness temperature is also attenuated by the canopy. The canopy also emits radiation downward which is reflected by the soil surface and attenuated by the canopy.

The single scattering albedo, ω is a function of the canopy type. Although some canopies have been shown to have values of ω as high as 0.13, such as for corn, crops like soybean and grasses have been shown to have ω values that are zero (Wigneron et al., 2004). SMOS has opted to use a single scattering albedo of zero for regions of low vegetation, such as grasslands and crops.

The optical depth, τ, is related to the column water density, or vegetative water content of the crop and a parameter, referred to as the b–parameter. Recent studies have shown a relationship between τ and leaf area index (LAI) (Saleh et al., 2006; Wigneron et al., 2007). The entire optical depth of a vegetative canopy is a combination of the optical depth of the standing vegetation, the optical depth from a litter layer, and the optical depth resulting from intercepted water. SMOS has opted not to account for the optical depth resulting from a litter layer in the operational processor. Days with large precipitation events will be flagged to indicate that soil moisture cannot be retrieved as estimates of intercepted precipitation are unavailable globally. Only the optical depth from the standing vegetation will be accounted for at this time. For processing, initial estimates of τ are provided from an external source. A line of best fit is applied the measured brightness temperature using information for all incidence angles. A line of best fit is also applied to the model estimates of brightness temperature. The model goes through an iterative process, adjusting values of τ and soil moisture until the difference between the modeled and measured brightness temperatures is minimized in order to find the optimal values of soil moisture and optical depth.

4.3 Study Region

The region used in this study is located in north–central Iowa, as shown in Figure 4.1. It is defined by the latitude and longitude limits of 42.6 and 43.6°N and 95.0 and 93.5°W. According to the National Agricultural Statistics Service, 47.9% of the total land use is maize and 36.4% is soybean (NASS, 2011). The total land area for row crops in this region is 84.4%. This uniformity is important as all 69 SMOS pixels contained in this region have essentially the same characteristics. The distribution of maize and soybean over the study region is shown in Figure 4.1. This region is part of the Des Moines lobe and has similar soil textures throughout. The land experiences very few changes topography, with the maximum change in elevation being 125 m. It is an ideal location to investigate the data obtained by the SMOS satellite as there are minimal complications from factors other than the presence of a vegetative layer.

There are four dominant factors that could influence changes between measurements made in the evening and morning: changes in surface temperatures; changes in soil moisture; changes in the volumetric water content of vegetation tissue; and the presence of free water on the vegetation, such as dew or intercepted precipitation. Changes in the volumetric water content of the vegetation between evening and morning are not well understood, and the contribution to changes in SMOS measurements are unknown.

The influence of free water on a crop canopy has been investigated in a variety of crops. For example, intercepted irrigation water increased the brightness temperature of wheat (Wigneron et al., 1996). Dew on a grass canopy was found to increase the brightness temperature (de Jeu et al., 2005). In a maize canopy, dew decreased the brightness temperature, with v–pol being affected more than h–pol (Hornbuckle et al., 2006). However, many of these studies were performed in the early morning when dew was present on the canopy and not during evening hours, so no comparison between measurement times can be made. Also, they are limited to a small spatial scale of a few meters. Airborne campaigns, such as the SGP97 campaign provide a larger footprint than ground based measurements, but very often do not fly during the period when dew is present on the canopy. Of the 30 flights during SGP97, only two occurred prior to 8am CDT (Jackson et al., 1999). The frequency of occurrence of dew at 8 am CDT is only 10% (Kabela et al., 2009) .

4.4 SMOS Soil Moisture Product

4.4.1 Analysis

The SMOS L2 soil moisture product was examined to determine if evening and following morning soil moisture values were different. We chose to examine days between July and October, 2010 as a result of dates when the SMOS soil moisture data was available. Days were also restricted to days precipitation had not occurred after noon prior to the evening pass nor during the time period between consecutive evening and morning passes. There were 19 days that satisfied this criteria. Pixels in which soil moisture could not be retrieved for either the evening or morning pass were eliminated. Although data for all 69 pixels were available for most of the days, there were always at least 36 pixels that we examined. A paired t–test was conducted to determine if the difference between evening and morning mean soil moisture values was significant. The

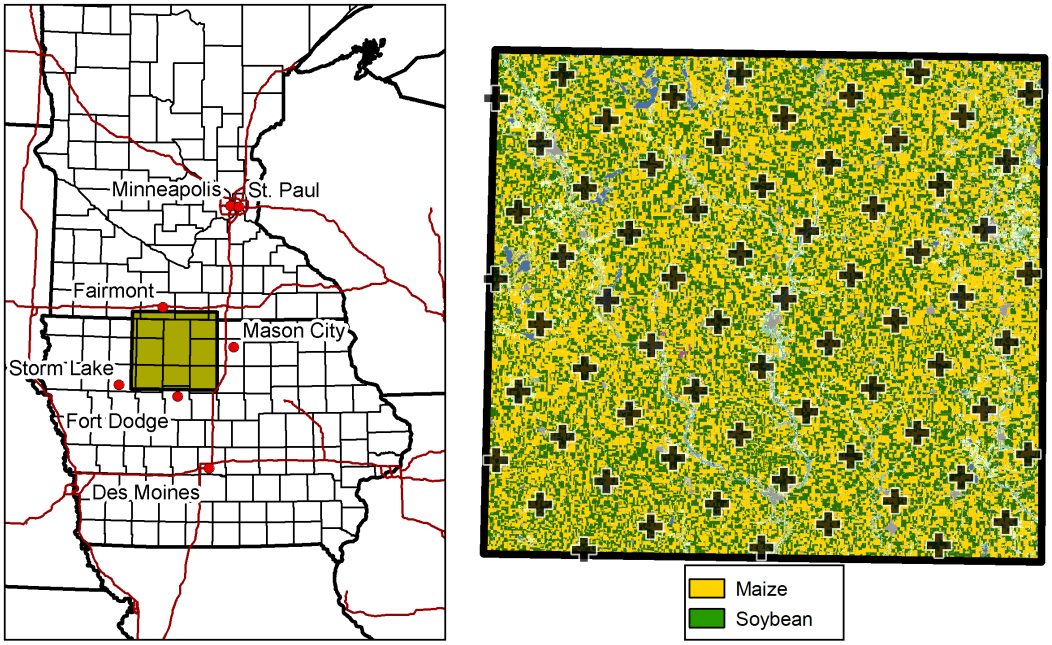

Figure 4.1 The study region in north–central Iowa is highlighted in the image on the left. The image on the right is an enlargement of the study region as outlined in the map on the left and indicates the distribution of maize and soybean within the study region. The center point of each SMOS pixel in this region is indicated by the + symbols.

data was examined to determine if normality was satisfied prior to the analysis since a t–test is not appropriate for conditions of non–normality.

4.4.2 Results

The results from the paired t-test for differences in means for soil moisture are presented in Table 4.1. The paired t-test indicated that there is convincing evidence that there is a significant difference in soil moisture between the evening and morning passes for all days. This evidence is indicated by p–values less than 0.1 at a probability of 95%. The results for the soil moisture data for the passes of October 21–22 should be viewed with caution as the condition of normality was not satisfied for the paired t–test. The mean difference in these passes on October 21 and 22 also results in the largest mean difference in soil moisture, with the morning soil mositure values being higher than the

Pass Comparison	Mean Diff (m^3 m^{-3})	SM p–value
July 26 PM and July 27 AM	0.0005	0.0583
Aug. 16 PM and Aug. 17 AM	0.0217	<0.0001
Aug. 18 PM and Aug. 19 AM	0.0213	<0.0001
Aug. 21 PM and Aug. 22 AM	0.0541	<0.0001
Aug. 28 PM and Aug. 29 AM	-0.0203	<0.0001
Sept. 2 PM and Sept. 3 AM	-0.0069	0.0130
Sept. 5 PM and Sept. 6 AM	0.0235	<0.0001
Sept. 26 PM and Sept. 27 AM	0.0623	<0.0001
Sept. 28 PM and Sept. 29 AM	0.0290	<0.0001
Oct. 1 PM and Oct. 2 AM	0.0531	<0.0001
Oct. 3 PM and Oct. 4 AM	-0.0073	0.0015
Oct. 6 PM and Oct. 7 AM	0.0118	<0.0001
Oct. 8 PM and Oct. 9 AM	-0.0054	0.0010
Oct. 11 PM and Oct. 12 AM	0.0108	<0.0001
Oct. 14 PM and Oct. 15 AM	0.0255	<0.0001
Oct. 16 PM and Oct 17 AM	0.0189	<0.0001
Oct. 21 PM and Oct. 22 AM	-0.0719	<0.0001
Oct. 24 PM and Oct. 25 AM	0.0167	<0.0001
Oct. 29 PM and Oct. 30 AM	0.0196	<0.0001

Table 4.1 Comparison of soil moisture (SM) differences between evening and morning passes, p–value at $\alpha = 0.05$. The mean difference is an average for the study region.

previous evening. The results indicate that the soil moisture for 14 of the 19 days was lower for the morning pass than the evening pass, as indicated by a positive difference (difference calculated as evening soil moisture minus morning soil moisture). The majority of the mean soil moisture difference between the evening and morning SMOS passes is within 0.02 m^3 m^{-3}, however on four occasions the mean difference was larger than 0.05 m^3 m^{-3}.

4.4.3 Are These Differences in Soil Moisture Realistic?

In order to evaluate the L2 soil moisture product, we examined what the typical measured change in soil moisture would be for August, September and October beneath a soybean and maize canopy. The data was collected in a 1 km^2 field in central Iowa for

2007-2009, which has a maize and soybean rotation. This field has similar topography and texture to the study region. Days were chosen where there was no rainfall between the evening and morning soil moisture measurements. Measurements were made using CS616 water content reflectometers at seven sites within the field at depths of 1.5, 4.5, and 5 cm. The CS616 is essentially a transmission line that is inserted horizontally into the soil. The output is a square wave whose period corresponds to the length of time it takes an electrical pulse to travel the length of the rods of the instrument which form the transmission line. The period depends on the relative permittivity of the soil:

$$\frac{P}{S_f} - 2t_d = \frac{4L\sqrt{\epsilon_a}}{c} \tag{4.5}$$

where P is the output period in ms, S_f is the standardized period for a CS616, t_d is a time delay, $\sim$ 5.12 ns, L is the length of the instrument rods, $\sim$ 0.26 m, $\sqrt{\epsilon_a}$ is the index of refraction (also referred to as n_{soil}), and c is the speed of light in a vacuum (Kelleners et al., 2005).

Many investigators have found that the volumetric water content of a soil is linearly related to the index of refraction of the soil (Topp et al., 1980; Whalley, 1993; White et al., 1994; Curtis, 2001):

$$\theta = a \times n_{soil} + b. \tag{4.6}$$

We corrected the index of refraction to account for the diurnal temperature effect and assumed a linear relationship:

$$n_{adj} = n_{soil} - jT \tag{4.7}$$

where n_{adj} is the adjusted index of refraction, j is an empirical factor, and T is temperature. We calibrated for water content using gravimetric samples. To avoid bias, we used the same a and j for all depths across sites, but allowed the intercept, b, to vary to match the measured data, because surface probes are removed and reinserted each year. Change in water content will not vary with intercept but absolute calculated water content will vary.

Data from sensors at 1.5, 4.5 and 5 cm depths were averaged to obtain an estimate of the change in soil moisture to a depth similar to the emitting depth of SMOS measurements. There was a decrease in soil moisture between the evening and morning for August, September and October, where the largest decrease in soil moisture, 0.002 and 0.003 m^3 m^{-3} for maize and soybean fields, respectively, occurred in September.

Output from the Agro-IBIS land surface process (LSP) model was used to determine the mean overnight 0-5 cm soil moisture change for the same field as the *in–situ* soil moisture measurements. Agro-IBIS (Kucharik, 2003) is among the few LSPs that are able to simulate agricultural field types (i.e. maize, soybean) that are prevalent throughout the study region. Agro-IBIS was configured with a maize land surface type and driven with soil profile and hourly meteorological data collected in 2009 when the field was planted with maize. On days during the August–October period where no precipitation fell between 1200 LST and 0600 LST (the following morning), the change in 0-5 cm soil moisture between 1800 LST and 0600 LST averaged -0.0030 m^3 m^{-3}.

With the exception of 5 days, the SMOS measurements indicate a decrease in soil moisture for the morning pass. This change is supported by our measurements. However, the magnitude of the change indicated by SMOS is much larger, with differences between the evening and morning SMOS measurements being at least 10 times higher than field measurements or model estimates.

4.5 Analysis of SMOS Brightness Temperature

We determined through our analysis of the SMOS soil moisture product that soil moisture derived from morning measurements is often significantly different than soil moisture derived from the measurement made the previous evening even when there is no precipitation. However, we found that both in–situ soil moisture measurements and modeled soil moisture indicate that essentially *no change* in soil moisture occurs over the 12 hours between evening and next–morning SMOS measurements in the absence of precipitation.

Why are evening and morning SMOS soil moisture products different? We believe that there are two possible explanations. One, there are actual differences in the SMOS brightness temperatures measured in the evening and the following morning, and these differences are being attributed to a change in soil moisture by the SMOS soil moisture algorithm. Two, the SMOS soil moisture algorithm itself is producing different estimates of soil moisture because of inaccurate ancillary data. In this section we investigate whether there are actual differences in evening and next–morning SMOS brightness temperatures that can be attributed to soil moisture.

4.5.1 Polarization Index

We desire to determine if SMOS brightness temperature measurements made in the evening and the following morning are in fact different and if this difference can be attributed to a change in soil moisture. In order to do this, we must use a method that isolates the effect of a potential change in soil moisture on the SMOS brightness temperature. There are only three variables in (4.1) that can possibly change over the 12 hours between an evening and morning SMOS brightness temperature measurement: surface temperature (either the soil temperature, vegetation canopy temperature, or both); soil surface reflectivity (a function of soil moisture and soil surface roughness); or the optical depth (a function of the water content of the vegetation canopy). Of these three changes, changes in surface temperature and soil surface reflectivity are likely the most significant. Furthermore, any change in soil surface reflectivity over a 12–hour period can not be attributed to a change in soil surface roughness if there has been no precipitation (Zobeck and Onstad, 1987). Therefore in order to determine if a change in soil moisture has caused a change in SMOS brightness temperature, we must use a method that is not sensitive to changes in surface temperature.

One variable that is insensitive to surface temperature is the polarization index, defined as:

$$PI = \frac{T_{Bv} - T_{Bh}}{\frac{1}{2}(T_{Bv} + T_{Bh})}. \tag{4.8}$$

A change in the PI is caused by a change in the difference between the vertically–polarized brightness temperature, T_{Bv}, and the horizontally–polarized brightness temperature, T_{Bh}. Normalizing $T_{Bv} - T_{Bh}$ by the mean value of T_{Bv} and T_{Bh} eliminates the effect of surface temperature on the PI as indicated by (4.1). Because of the different sensitivities of T_{Bv} and T_{Bh} to soil moisture, a change in soil moisture will result in a change in $T_{Bv} - T_{Bh}$. Hence the PI is ideal for determining if differences in the SMOS evening and morning brightness temperature measurements can be attributed to a change in soil moisture.

What values of the PI do we expect to see in SMOS brightness temperatures? And how much does the PI change when soil moisture changes? Theoretical estimates of the variation of the PI with incidence angle are shown in Figure 4.2 for four surface conditions: a bare and specular soil surface; a bare but rough soil surface; a rough soil covered by an amount of vegetation that would be expected for both July and September in our study region; and a rough soil covered by vegetation that would be expected in our study region in August. For each surface condition, three curves of the PI are shown. The solid line in each of the four groups indicates the PI for a uniform soil moisture content of 0.28 m^3 m^{-3}, a typical soil moisture content. The dashed line closest to the solid line in each group indicates the PI for a uniform soil moisture content of 0.26 m^3 m^{-3}, 0.02 m^3 m^{-3} less than the soil moisture content represented by the solid line. The last dashed line indicates the PI for a uniform soil moisture content of 0.24 m^3 m^{-3}, 0.04 m^3 m^{-3} less than the soil moisture content represented by the solid line.

We made estimates of the PI for the bare and specular soil surface with a soil dielectric model (Mironov et al., 2009) for a clay loam soil and assuming Fresnel reflectivities. The estimate for a bare but rough soil was made using a rough soil surface model (Wigneron et al., 2001b) and assuming an rms soil surface roughness of 25 mm (Hornbuckle et al., 2003) and a correlation length of 60 mm (Wigneron et al., 2001b). To estimate typical values of the PI when the soil is covered by vegetation, we used (4.1), the model $\tau = b \times M_w$ (Jackson and Schmugge, 1991), and assumed the fraction of the land area covered by maize and soybean indicated earlier in this paper. For soybean, we assumed $\omega = 0$ (Jackson and Schmugge, 1991). For maize, we used values of ω specifically determined for a maize canopy (Hornbuckle et al., 2003). Maize and soybean crops planted in early spring grow over the summer, peak in biomass in August, and then gradually lose their water content in September and October before they are harvested. In July and September we assumed vegetation water column densities of 2 and 4 kg m^{-2} for soybean and maize, respectively. In August, we assumed vegetation water column densities of 3 and 5 kg m^{-2} for soybean and maize, respectively (Hornbuckle et al., 2003).

Note the following characteristics of the PI in Figure 4.2. For an incidence angle of $\theta = 0°$, $T_{Bv} - T_{Bh} = 0$ and the $PI = 0$ for all isotropic surfaces. For the range of SMOS incidence angles, as θ increases the difference between T_{Bv} and T_{Bh} generally increases, and hence the PI increases. The PI is sensitive to soil surface roughness and the presence of vegetation. The highest values of the PI are associated with a bare and specular soil surface. Soil surface roughness decreases the PI. Vegetation further decreases the PI, and larger amounts of vegetation (as measured by the vegetation water column density) result in smaller values of the PI. These changes occur because an increase in soil surface roughness decreases the difference between T_{Bv} and T_{Bh}. Vegetation also decreases the difference between T_{Bv} and T_{Bh}, and in the limit as τ becomes large $T_{Bv} - T_{Bh} = 0$.

Also note that although the PI generally increases as the incidence angle increases, the shape of the curve depends on the conditions of the surface. For bare soil surfaces, the curve is concave up (for incidence angles less than the Brewster angle, which include the incidence angles measured by SMOS). For surfaces with vegetation, the curve is concave down. This concave down shape occurs because at larger incidence angles the vegetation begins to decrease the difference between T_{Bv} and T_{Bh}. The incidence angle at which the slope of the curve for vegetated surfaces is zero decreases as the amount of vegetation increases.

Most importantly, because T_{Bv} and T_{Bh} have different sensitivities to soil moisture, changes in soil moisture result in a change in the PI: a decrease in soil moisture results in a decrease in the PI. Although the change in the PI with soil moisture appears small, a microwave radiometer with a precision of 2 K (comparable to the SMOS radiometer) would be able to distinguish a change of at least 0.01 in the PI if it is assumed that T_{Bv} and T_{Bh} in (4.8) are normally–distributed and independent random variables (Beers, 1962). At small incidence angles, there is essentially no variation in the PI with soil moisture. At large incidence angles, Figure 4.2 illustrates that for vegetated surfaces a change in soil moisture of about 0.02 $m^3\ m^{-3}$ produces a change close to 0.01 in the PI. Hence it appears that if we examine SMOS evening and morning PI, we should be able to determine if differences in the evening and morning PI could be attributed to a change in soil moisture of greater than 0.02 $m^3\ m^{-3}$.

4.5.2 Analysis

In an effort to use the data from a wide range of incidence angles, on average 10–60°, and the limitation of days with no rainfall, the study was limited to 5 evening and morning pass comparisons. These passes occurred on the evening of August 18 and morning of August 19, evening of September 5 and morning of September 6, the evening of September 28 and morning of September 29, the evening of October 11 and morning of October 12, and the evening of October 16 and morning of October 17, 2010. For the evening and following morning of SMOS passes, we evaluate each pixel individually. For each day and time (evening or morning) there were 69 pixels. We converted measurements of brightness temperature to a PI value. As discuss earlier, the use of PI removes the complication of differences in temperature between evening and morning SMOS passes but is still sensitive to changes in soil moisture. We treated the PI as the response variable (y) and the incidence angle as the explanatory variable (θ). Upon examination of plots of the PI values versus incidence angles, a quadratic relationship between the two variables was most appropriate. This choice of a quadratic function is also consistent with our theoretical predictions shown in Figure 4.2. The quadratic functions given in (4.9) and (4.10) were fit to the data (for each day and location separately) via ordinary least squares regression.

$$\mu_{y_{pm}}(\theta_{pm}) = \beta_0 + \beta_1\theta_{pm} + \beta_2\theta_{pm}^2 \tag{4.9}$$

$$\mu_{y_{am}}(\theta_{am}) = \beta_0 + \beta_1\theta_{am} + \beta_2\theta_{am}^2 \tag{4.10}$$

Here the subscripts pm and am denote evening and morning passes, respectively. Using a level of significance of $\alpha = 0.05$, a quadratic relationship was found to be significant. A cubic function was also fit to the data, however, a significant cubic relationship was not found in any of the locations over all days.

The difference between the evening and morning curves was then computed as:

$$d(\theta) = \mu_{y_{pm}}(\theta) - \mu_{y_{am}}(\theta) \tag{4.11}$$

Note that the difference between the two functions was only computed for the range of incidence angles that were observed in both the evening and morning data for each location. Specifically, this range of θ values for each location's difference curve is defined as:

$$\{\theta \mid \max[\min(\theta_{am}), \min(\theta_{pm})] \leq \theta \leq \min[\max(\theta_{am}), \max(\theta_{pm})]\} \tag{4.12}$$

where θ_{pm} and θ_{am} are vectors of all observed incidence angles for the evening and morning data, respectively, for a given location. We wished to examine whether the difference between morning and evening PI values were significantly different from zero for a given incidence angle. In order to evaluate this question over all considered incidence angles, we conduct a randomization test for the two groups of observations from evening and morning. Given all observed pairs of data from the evening, $\{(\theta_{pm,1}, y_{pm,1}), (\theta_{pm,2}, y_{pm,2}), ..., (\theta_{pm,m}, y_{pm,m})\}$ and observed pairs of data from the morning, $\{(\theta_{am,1}, y_{am,1}), (\theta_{am,2}, y_{am,2}), ..., (\theta_{am,n}, y_{am,n})\}$, the data was pooled and labels of morning/evening data were ignored. A random sample of n pairs from the pooled data were assigned to be from the morning and thus, the remaining m pairs of data were randomly assigned to be from the evening. Given the randomly assigned data the functions in (4.9) and (4.10) were fit via ordinary least squares regression and the corresponding difference curve given by (4.11) was computed. This randomization process was repeated 1000 times for a given location. If the original difference between evening and morning PI data have a statistically significant difference for a set of incidence angles, the original difference curve will have a distinct vertical location that is different from the difference curves computed via randomization.

4.5.3 Results

The PI values obtained from the L1c data for August 18 and October 16, 2010, are shown for one SMOS pixel within our study region in Figure 4.3. The red line and data points are from the evening SMOS pass, and the black line and data points are from the morning pass. Histograms of $\hat{\beta}_2$ for the quadratic functions for the evening and morning passes of August 18 and October 16 are shown in Figures 4.4 and 4.5. Negative estimates correspond to a concave downward shape and positive estimates correspond to a concave up shape. The pixel shown for August 18 is representative of all the pixels for that day, but also for the pixels for passes prior to September 28 in terms of both the magnitude of the PI values and in the shape of the quadratic function, with the shape being concave down. As of the evening pass of September 28 the shape of the quadratic function transitioned to concave up, and the pixels for September 28 and 29, and October 11 and 12 are similar to those shown for October 16 and 17 passes. The magnitude of the PI values for all pixels on all days are within the expected range indicated by Figure 4.2 for scenarios with vegetation present. All of the pixels on all of the days experienced a large spread in the PI values at low incidence angles which can not be physically explained, as the PI values at low incidence angles should be similar regardless of the surface conditions, as seen in Figure 4.2. Additionally, many pixels indicate negative PI values at low incidence angles which are also not physically justified (Figure 4.2).

The difference curves between the evening and morning passes for each pixel on August 18 is shown in Figure 4.6. The largest difference between evening and morning PI values occurs at the incidence angles less than 30°. This is the result of the large spread in the data at these low incidence angles, as seen in Figure 4.3. There is also a larger difference between the evening and morning PI values at incidence angles greater than 55°. The differences seen at larger incidence angles is consistent with the theory indicated in Figure 4.2, if the soil moisture conditions are actually drier in the morning.

The results from the randomization process for one pixel on August 18 is shown in Figure 4.7. The randomization process was conducted for each pixel individually. The black line is the difference curve for one pixel (the same pixel that shown for August 18 in Figure 4.3), and the gray lines are the difference curves that resulted from 1000 repetitions of the randomization process for that same pixel. For all pixels on all days, the actual difference curve is contained within the band of the curves created from the randomization process, however some of the difference curves are close to the edge of the band at incidence angles that are less than 20° and greater than 60°. The fact that the difference curves are contained within the band indicates that there is no significant difference in the PI values between measurements of the evening and morning SMOS passes.

4.6 Discussion

The results of the SMOS brightness temperature data agrees well with the modeled PI. We see a transition from the concave down shape of PI values seen in August and the start of September, to a concave up shape beginning September 28. This is reflective of changes in the vegetative canopy in this region as they begin to senesce and be harvested. As of October 3, in the north-central region of Iowa, 60% of the soybean and 21% of the corn had been harvested. By October 24, 99% of soybean and 95% of corn had been harvested. These results are indicated in Figures 4.4 and 4.5, where the values of the parameter for the quadratic function transition from negative to positive and we transition from a vegetative surface to bare soil. The soil moisture product indicates a decrease in soil moisture for the morning pass compared to the evening pass, and this is reflected in decreased values of the PI for the morning. However, these changes in the PI at larger incidence angles are much smaller than the changes in the PI at smaller incidence angles. It is unknown if the spread in the data at low incidence angles may change with the reprocessed SMOS data, which has recently become available.

4.6.1 SMOS Processing

As noted earlier, there are four factors which can could influence changes in measurements between the evening and morning: changes in soil moisture, the presence of free water on the vegetation canopy, changes in the volumetric water content of the vegetation and changes in surface temperature. If these factors were significant for the days investigated, they would have been reflected in the measured brightness temperature, where it was found that there was no significant difference between evening and morning SMOS passes. However, there is a significant difference between evening and morning soil moisture, according to the soil moisture product. Although many of these differences are within the allowable error of 0.04 m^3 m^{-3}, there are several occasions when it is larger. This leads us to believe that the issue may reside in the processing of the soil moisture product, where the error could be associated with the estimates of optical depth or the assumption that an effective temperature can be representative for both the soil surface and canopy temperatures.

There are two possible options for estimating surface temperature with a region of low vegetation used by the SMOS processor. The first is the two use two separate temperatures, one for the soil surface and another for the temperature of the vegetative canopy. The alternate is through the use of an effective temperature which assumes that the temperature of the soil surface and the vegetative canopy are approximately equal (ESA, 2010).

In order to evaluate the validity of this assumption, we again examined *in–situ* data recorded at the same site as the *in–situ* soil moisture. Canopy temperatures were measured using an infrared thermometer (IRT). Although there may be error associated with measurement of the canopy temperature using an IRT, the error is small, with the maximum error being 0.9 K (Hornbuckle and England, 2005). Soil temperatures were measured at depths of 1.5 and 4.5 cm. A linear regression analysis (forced through zero) was conducted to compare canopy temperature to soil temperatures. Data presented in Figure 4.8 are measurements taken at 6 pm LST and 6am LST from July 29th to September 27, 2010. Figure 4.8 indicates good agreement between canopy surface temperature and soil temperatures at each depth both in the evening and in the morning. A linear regression (forced through zero) was also conducted over the same time period to investigate the use of air temperature to represent canopy and soil temperatures. Figure 4.9 shows that there is good agreement using air temperature, with R^2 values for canopy, soil temperature at 1.5 cm, and soil temperature at 4.5 cm of, 0.9956, 0.9949 and 0.9948, respectively for 6 pm LST, and R^2 values that are slightly lower for 6 am LST. These results support the use of an effective temperature to represent the canopy and soil temperatures, at both 6 pm and 6 am LST, is suitable for this region and therefore this is likely not a source of error in the SMOS processing.

An investigation into the values of retrieved optical depth indicated that there was a significant difference in retrieved optical depth between evening and morning pases for the 19 days that the soil moisture product was investigated, with the exception of three pass comparisons, October 6 and 7, October 14 and 15, and October 16 and 17. It was found that on 10 of the 19 days there was a decrease in optical depth, indicating that the value for the optical depth was higher in the morning than in the evening. Land–based studies have indicated that dew can influence measurements of brightness temperature, causing error in soil moisture estimates through its contribution to the total water column density of the vegetation. A simple empirical model of relative humidity $\geq$ 90% was used to determine which days had dew present (Sentelhas et al., 2008). Dew was present on eight of the 19 mornings, but there did not appear to be a pattern in the difference in optical depth between the evening and morning for days with dew, with five of the eight days showing a decrease in optical depth. It can be noted that there was no dew present on the three days when the optical depth was not significant different between the evening and morning. Significant differences between evening and morning optical depth values were seen into mid–October, where the majority of the vegetation had been harvested in this region.

4.7 Conclusions

The fact that the soil moisture product is significantly different between the evening and morning SMOS passes for periods of no rainfall is interesting. On several occasions these differences exceed the allowable error in soil moisture associated with SMOS of 0.04 m^3 m^{-3}. These differences are not seen statistically in the measured brightness temperature, according to the randomization process, which led us to believe that there may be an issue in the SMOS processing. The two possible sources identified were in the estimation of surface temperature and optical depth. Data of air, canopy surface, and soil temperatures would indicate that the simplest form of estimating surface temperature, using an effective temperature, would be acceptable as there is good agreement between these measurements at both 6 pm and 6 am LST. Concern in the retrieval of optical depth still remains. It has been noted that the use of LAI may underestimate the optical depth of some vegetation during periods of senescence or for vegetation that has a greater vertical height (and larger volumetric water content) that can not be accounted for by using LAI as a substitute for estimates of volumetric water content of the vegetation. Values of LAI should be less sensitive to changes over such a short time period, and one would expect that changes in optical depth between the evening and morning SMOS passes would not be different. This has been shown to not be the case, with 16 of 19 comparisons showing a significant difference in optical depth.

The study of brightness temperature was limited to 5–pass comparisons due to constrictions on days with no precipitation after noon prior to the evening pass nor between the evening pass and the corresponding morning pass, but also due to days where there was a large range of incidence angles. Many of the days that satisfied the precipitation restriction (there were 19 in total) had at least one pass with a low range of incidence angles, and in some situations both passes were limited. For the 5 days with a suitable range of incidence angles for both the evening and morning passes, the soil moisture product was within the acceptable error range for SMOS. Days with larger differences in soil moisture were produced from brightness temperatures that spanned a narrower range of incidence angles. This finding may have implications on the Soil Moisture Active Passive (SMAP) satellite that is designed to use a single incident angle for estimates of soil moisture.

The measured brightness temperature (converted to PI) by SMOS follows closely with the patterns seen with changes in modeled PI. The measurements transitioned from concave down for periods when the vegetation canopy in this region would be close to its maximum growth and highest volumetric water content to concave up when harvest of the vegetation began, with the shape becoming more reflective of a bare soil surface. However, there was a large spread in PI values at low incidence angles which can not be described by physical processes. Larger spread was seen for most pixels at incidence angles closer to 55° which would be expected and is confirmed with the modeled values for PI if it is indeed true that soil moisture is lower in the morning. Notice that Figure 4.2 also indicates that a decrease in PI can result from an increase in volumetric water content of vegetation. Volumetric water content of a vegetation will increase overnight (Hay and Porter, 2006), although the magnitude of that increase is unknown. It is possible that a decrease in the PI values between evening and morning SMOS passes could be mistaken for a decrease in soil moisture, when it could actually be cause by an increase in volumetric water content of the vegetative canopy.

Although it has been noted that the ideal time for measurement of soil moisture via satellite microwave radiometry has been assumed to be at 6 am LST for various reasons, excluding the error possibly associated with Faraday rotation in the ionosphere, data from the 6 pm LST pass is valuable. Our analysis at this point (before the reprocessed data) has found that there is no statistically significant difference between evening and morning brightness temperature measurements. On the other hand, if the data at low incidence angles are neglected and assumed to be a correctable error, the SMOS brightness temperatures do appear to indicate a *decrease* in soil moisture from evening to morning. However, this decrease is too large according to our *in–situ* and model results. This trend in the data could also, however, be explained by an increase in the volumetric water content of the vegetation overnight. If these issues can be resolved, using data from the 6 pm pass, in conjunction with data from the 6 am LST passes would provide twice as many values of soil moisture and may even provide reassurance that values measured at 6 am LST are accurate.

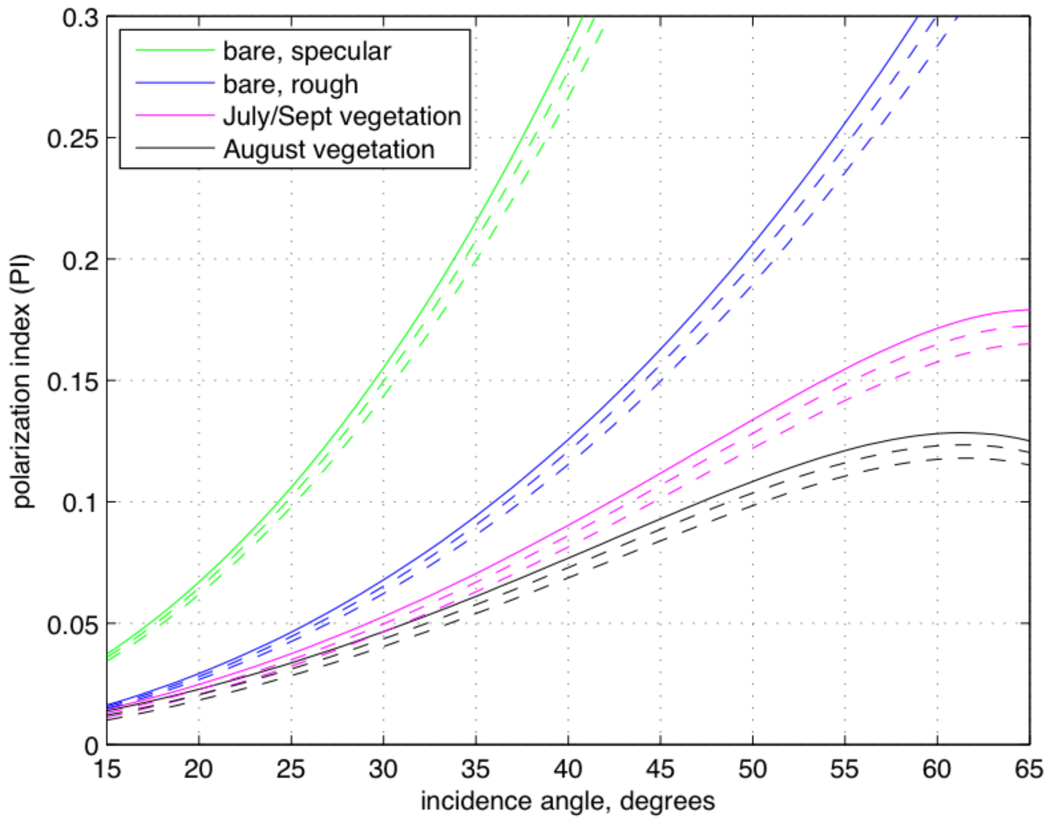

Figure 4.2 Polarization index (PI) as a function of incidence angle for four surface conditions: a bare and specular soil surface; a bare but rough soil surface; a rough soil surface covered with vegetation expected in July and September; and a rough soil surface covered with vegetation expected in August. The solid line of each of the four groups is for a wet soil. The dashed lines indicate the PI for soils that have water contents 0.02 m^3 m^{-3} and 0.04 m^3 m^{-3} less than the wet soil.

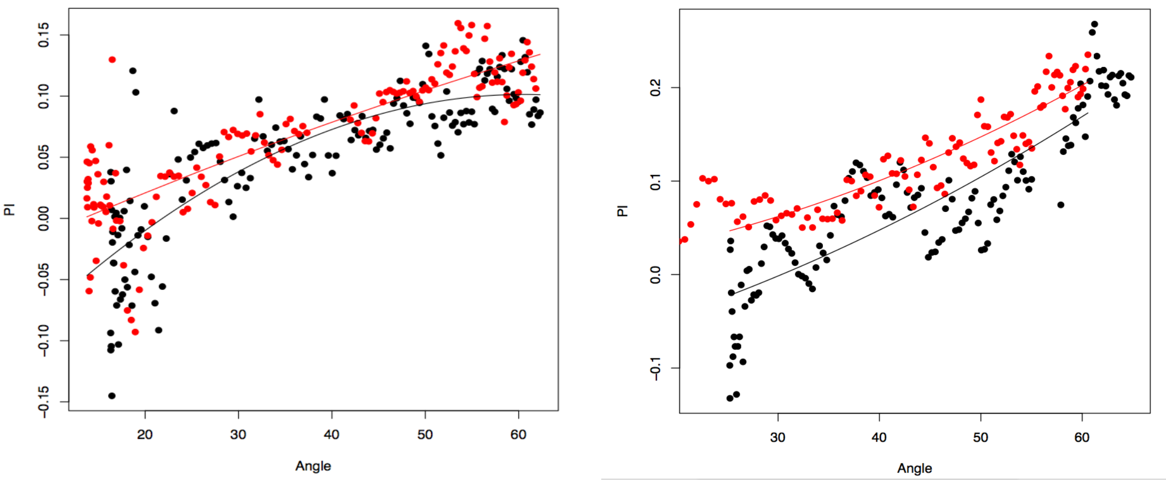

Figure 4.3 PI values for one pixel in the study region for the passes of August 18 and 19, 2010 (left) and October 16 and 17, 2010 (right). The red line and data points represent the data for the evening SMOS pass, and the black line and data points for the morning pass. The angle on the x-axis is the measurement incidence angle in degrees.

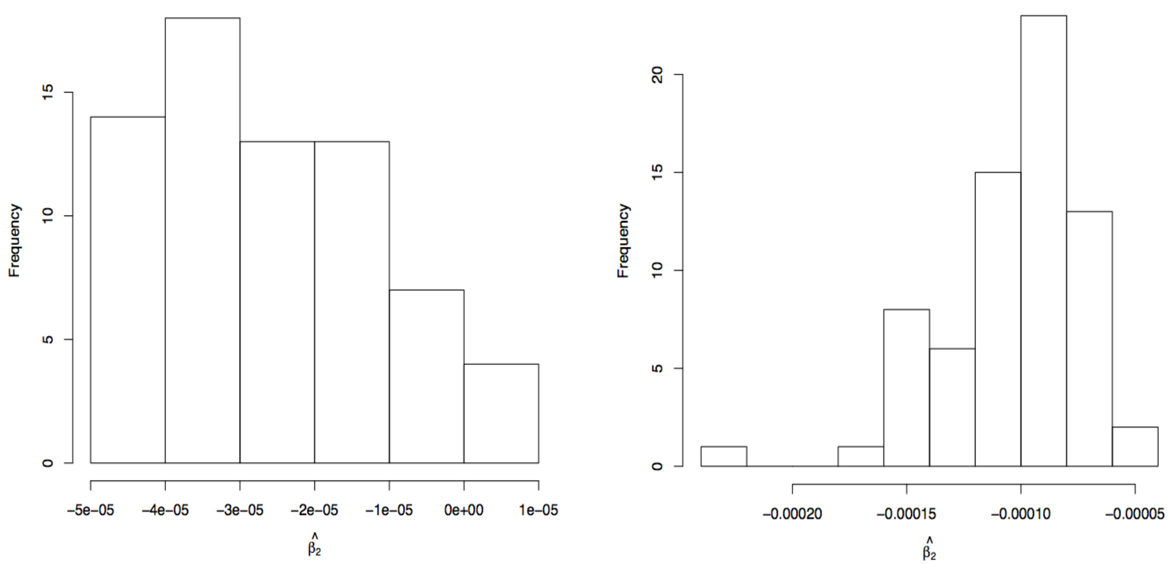

Figure 4.4 Histogram of the parameter estimates for the quadratic function fit to the data from the evening pass (left) on August 18, 2010 and the morning pass on August 19, 2010 (right).

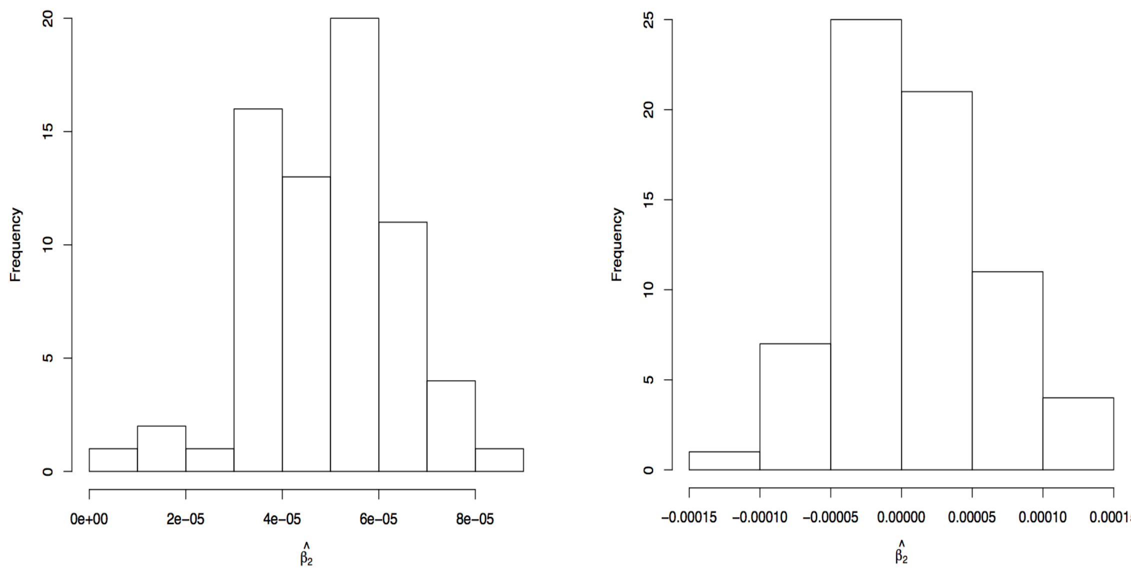

Figure 4.5 Histogram of the parameter estimates for the quadratic function fit to the data from the evening pass (left) on October 16, 2010 and the morning pass on October 17, 2010 (right).

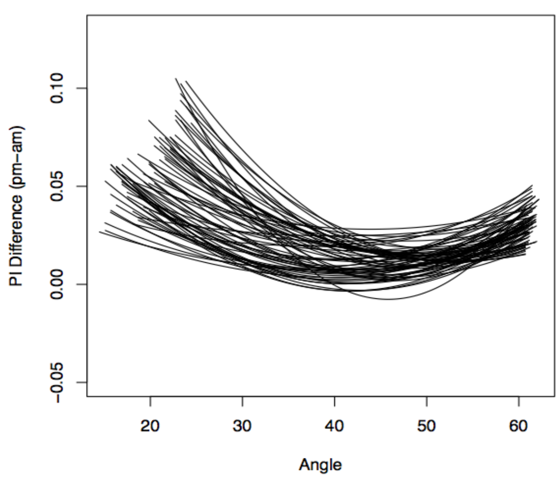

Figure 4.6 The difference curves for all 69 pixels in the study region for August 18, 2010. The angle on the x-axis is the measurement incidence angle in degrees.

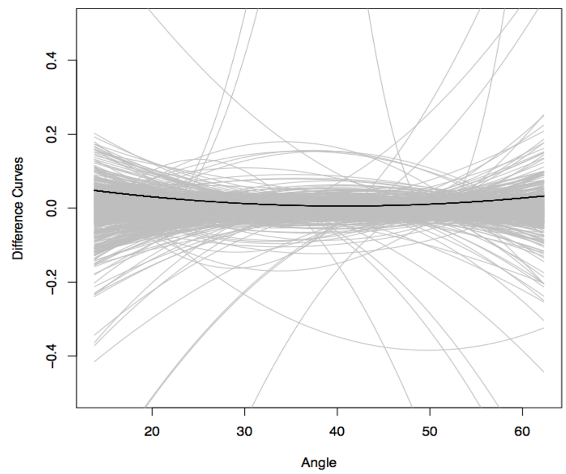

Figure 4.7 The difference curves for all 69 pixels in the study region for August 18, 2010. The angle on the x-axis is the measurement incidence angle in degrees.

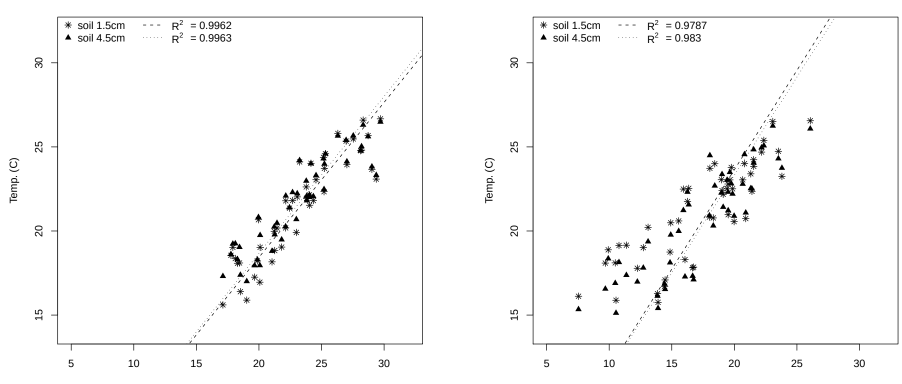

Figure 4.8 Comparison of canopy temperature (°C) and soil temperatures measured at 1.5 and 4.5 cm depths (°C) for measurements at 6 pm LST (left) and 6 am LST (right).

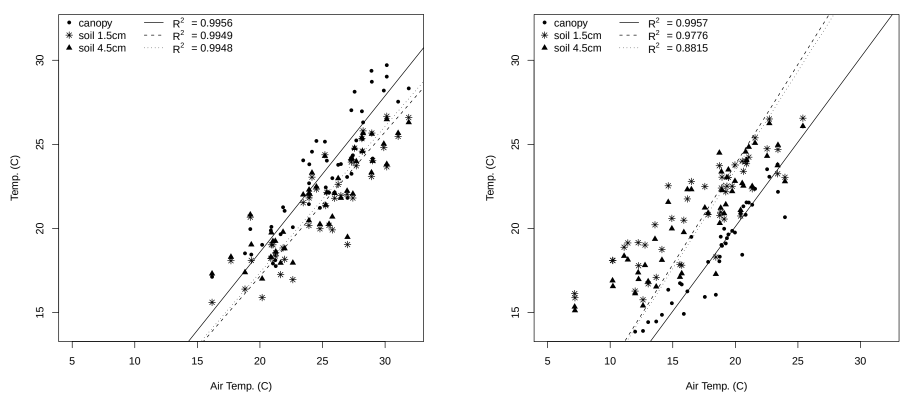

Figure 4.9 Comparison of air temperature (°C), canopy temperature, (°C), and soil temperatures measured at 1.5 and 4.5 cm depths (°C) at 6 pm LST (left) and 6 am LST (right).

CONCLUSIONS AND FUTURE WORK

4.8 Conclusions

The ability to monitor or model leaf wetness is an integral component to the management of many plant diseases. Regardless of how leaf wetness is determined, the limitations of the technique must be acknowledged. Sensors require labor. They require careful placement within a canopy, they need to be treated to optimize sensitivity and precision in some cases, but equally important, they need to be maintained. It is not always convenient for a sensor to be placed within a grower's field, especially if it needs to be removed frequently for crop management. To date, there has been no standardized use for leaf wetness sensors, and this has led to an unfortunate inability to compare results among studies. The use of these sensors in disease warning systems may not be suitable for a variety of reasons, including the inconvenience associated with having a sensor in a field that requires crop management. Studies have indicated that there is good agreement between simple, but useful empirical models such as RH $\geq$ 90%. Given the uniformity of a measurement such as relative humidity in some growing regions, regional estimates of LWD with the use of a single RH sensor may provide results that are as accurate as sensors.

The results from the study examining the spatial variability of dew amount and dew duration in a soybean field may provide some justification for measurement of dew duration and dew amount at any one location within a field. Nevertheless, it is still important to consider where in the crop canopy that the sensor is placed when measurements of LWD are required, because literature has shown that the profile of dew amount and duration varies within the canopy. Leaf to leaf heterogeneity of dew amount was found to be so substantial that no location to location differences could be seen. As such, one measurement location of dew amount would be suitable if there are minimal variations in topography and soil type. When sampling for dew amount, although it can be conducted at one location, several leaves should be sampled to get an average representation.

An investigation into the SMOS soil moisture product found that there was a significant difference in soil moisture between 6 pm and 6 am LST passes over a region in north–central Iowa. The difference in soil moisture values could not be justified by measurements of soil moisture or by model estimates. Examination of the brightness temperature measurements indicated that there was no significant difference between evening and morning passes. This raised questions regarding the SMOS processing of brightness temperature to obtain soil moisture estimates. An investigation of using a single temperature to represent both the canopy and soil surface temperature was found to be suitable for both 6 pm and 6 am LST passes. There is concern regarding the retrieved values of optical depth, a representation of the volumetric water content of a vegetative canopy, as significant differences in optical depth were seen once the vegetation in this region had been harvested. Decreases in the values of PI should not entirely be attributed to a decrease in soil moisture, but increases in the volumetric water content of a vegetative canopy should be considered as well. The results of this study, particularly with the measured brightness temperature indicate that although the preference by the remote sensing community is to use data obtained only from 6 am LST passes, that the data collected at 6 pm LST should not be excluded.

4.9 Future Research

- Attempt to quantify variability of dew in a two crop canopies in fields of similar topography and soil texture for the same dew periods to see if the variability in dew amount is seen for both canopies. Measurement of soil moisture with microwave radiometry with footprint sizes of meters to a kilometer require estimates of dew amount. For airplane campaigns for soil moisture measurements, it would be important to know if measurements of dew amount were needed for each unique crop, or if one measurement in the region would be suitable.

- Quantify the changes in the volumetric water content of vegetative crops changes between the evening and morning. Currently, decreases in the PI values of SMOS (and other forms of microwave radiometry) may be associated with decreases in soil moisture when the decrease in PI could be dominated by changes in the volumetric water content of the vegetation.

- Quantify the error that may be associated with using LAI as a substitute for volumetric water content of a vegetative canopy during periods of senescence. Measurements of soil moisture are closely tied with optical depth. Measured brightness temperature would be higher than modeled brightness temperature if the model is underestimating the optical depth. As a result, the model will under predict the soil moisture.

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