Soil Moisture, Vegetation and Surface Roughness Impacts on High Resolution L-Band Microwave Emissivity from Cropped Land during SMAPVEX12

by

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ABSTRACT

The SMAPVEX12 (Soil Moisture Active/Passive Validation Experiment 2012) was carried out over the summer of 2012 in Manitoba, Canada. The goal of the project was to improve the accuracy of satellite-based remote sensing of soil moisture. Data were gathered during a 42-day field campaign with surface measurements on 55 different agricultural fields in south-central Manitoba. The extended duration of the campaign, contrast in soil textures, and variety of crop types over the study region provided an excellent range of soil moisture and vegetation conditions. The study fields ranged from bare to fully vegetated, with volumetric soil moisture levels spanning a range of almost 50%. Remotely sensed data were collected on 17 days by aircraft at 1.4 Ghz with a microwave radiometer at two different resolutions. Observed brightness temperatures from the radiometer showed a typical inverse relationship to the near simultaneous soil moisture measurements from the field. Field-by-field relationships using all sampling dates with both soil and emissivity data were all shown to be significant with the exception of two of the pasture fields and a soybean field. Linear regressions across multiple fields and by flight lines also had statistically significant slopes. The significance of all these relationships improved with the removal of pasture fields from the analysis. On most fields, the sensitivity (slope) of the relationship and correlation coefficient (R^2) between emissivity and observed soil moisture increased when vegetation and roughness effects were taken into account. The *b* parameter that relates vegetation water content to optical depth in the tau-omega model was optimized using the collective slope and R^2 values of the individual fields. A b parameter value of 0.06 for horizontal polarization and 0.13 for vertical polarization were found to be optimal across the range of all fields in this analysis.

Keywords: Passive microwave, soil moisture, SMAP, radiometer, L-band, agriculture

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1 INTRODUCTION

1.1 INTRODUCTION TO REMOTE SENSING OF SOIL MOISTURE

1.1.1 The Case for Soil Moisture Monitoring

Surface soil moisture is an important part of the environment, creating a link between land and atmosphere by allowing an exchange of heat and moisture (Owe, et al., 2001). It has an important role in weather and climate modeling, due to its influence on processes that lead to flooding (Ojha, et al., 2014). Spatial variation in soil moisture has also been linked to the development and intensity of deep convection in the atmosphere (Kang, et al., 2007) which leads to development of severe weather events such as hail or tornadoes (Raddatz & Cummine, 2003). Understanding soil moisture is also critical to agriculture, where knowledge of the spatial and temporal variations in surface moisture can be used to properly direct irrigation practices (Vereecken, et al., 2008), determine the emergence of weeds (Bullied, et al., 2012), estimate crop yield and quality (Mkhabela & Bullock, 2012), and quantify the risk levels for outbreaks of insects and pathogens (Dufault, et al., 2006).

Despite its importance to a host of critical environmental conditions, soil moisture is difficult and expensive to measure over large scales on the ground (Pan, et al., 2014). In situ networks comprised of numerous automated soil moisture monitoring stations may cover large areas, but only provide actual soil moisture information about a very limited area surrounding each measurement site (Brocca, et al., 2010). Furthermore, the variable nature of surface moisture means attempting to average point measurements over large distances will often introduce considerable error (Owe, et al., 2001). More detailed moisture surveys are labour intensive and expensive to conduct, and are not practical over an extended period of time or large area.

Soil moisture conditions vary greatly both spatially and temporally, due to the large number of factors that affect the surface moisture content (Merlin, et al., 2008). Remote sensing provides a unique opportunity to directly measure soil moisture frequently and on a large scale. However, at the spatial resolution typical of passive satellite based sensors (>10 km), landscape heterogeneity within the sensor footprint is likely to be high (Anderson, et al., 2004; Njoku & Entekhabi, 1996). While this landscape-scale retrieval is useful for climate or environmental modeling, it is too coarse for any field-scale agricultural applications. Smaller scale aircraft-based retrieval can accurately estimate soil moisture at scales appropriate for agricultural applications; however it is considerably more limited in coverage and not useful for long term monitoring.

1.1.2 Previous Passive Microwave Research on Soil Moisture Monitoring

The use of passive remote sensing in soil moisture retrieval goes back nearly 40 years (Njoku & Kong, 1977; Choudhury, et al., 1979; Ulaby, et al., 1986; Jackson, 1993; Schmugge, et al., 1986). During this time, the methods for soil moisture retrieval have been refined, and contributing factors to brightness temperature have been measured. The reason that remote sensing can be used to measure soil moisture is that emission from the Earth in the microwave spectrum is particularly sensitive to soil moisture (Champagne, et al., 2010). Soil moisture is linked to radiometer observed brightness temperature through the reflectivity (r) and emissivity ($e = 1 - r$) of the surface. The reflectivity is related to the complex dielectric constant of a smooth soil surface using the Fresnel equations. There is a large difference in the dielectric of water (80), and dry soil (3.5), at frequencies less than 5 GHz (Njoku & Entekhabi, 1996). This difference creates a substantial range in the emissivity of dry (>0.9) and wet (~0.6) soils, when observed by a microwave radiometer.

Passive microwave sensors can be mounted to spaceborne platforms which have the capability of measuring soil moisture on a global scale, however, the passive emission of microwave radiation from the earth's surface is faint. Therefore, satellite-based soil moisture retrieval using passive remote sensing utilizes very coarse measurements with footprints hundreds of square kilometers in size. Since passive microwave satellite retrievals have very coarse resolution, they are not useful for field level soil moisture estimates. The European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellite launched in 2009 (Barre, et al., 2008) uses a radiometer which provides output with a spatial resolution of 43 x 43 km. This is achieved only because the sensor exploits the interferometry principle to measure phase differences of the incident radiation (Crow, et al., 2005).

Early research, such as Njoku and Kong (1977), focused on multi-frequency, dual-polarization retrievals. It was built upon the understanding of microwave emission from the Earth's surface and its correlation to soil moisture through the use of radiative transfer models and surface emissivity calculated from the dielectric constant of the soil. The study offered a step toward a better understanding of the contributions to recorded brightness temperature, but specifically noted that surface roughness posed, "…a continuing problem in the remote sensing of natural terrain." (Njoku & Kong, 1977). A study by Choudhury et al. (1979) examined the effects of surface roughness and developed a surface parameter (*h*) that would be used in dozens of subsequent soil moisture experiments over the next three decades. The roughness parameter relies on measureable surface variables to account for the effect of roughness on microwave emission. Specifically, these variables are the RMS of surface heights (δ) and correlation length

(l_c) which can be used to statistically describe the vertical and horizontal components of roughness, respectively (Choudhury, et al., 1979). These surface variables are used to modify the smooth surface reflectivity as defined by the Fresnel equations.

Other research has focused on the contribution of vegetation to the observed brightness temperature, as vegetation both attenuates the emitted ground radiation and adds its own to the total observed (Ulaby, et al., 1983). Accounting for the influence of vegetation on surface microwave emission is primarily done with the vegetation opacity (also referred to as optical depth) parameter, τ (Schmugge, et al., 1986). The vegetation opacity was initially calculated using dielectric and structure parameters of the crops, but was later simplified as a linear correlation to vegetation water content (Jackson & O'Neil, 1990). Another variable in understanding the influence of vegetation is the single scattering albedo, ω. The single scattering albedo describes the emitted power lost inside the vegetation canopy, and is generally determined by variables like plant structure and water content (Kurum, 2013). However, it is often ignored and assumed to be near 0 for longer wavelengths such as L-band (Jackson, 1993). While this simplifies the soil moisture retrieval, it can also introduce error in the final soil moisture product, especially under dense vegetation canopies (Kurum, 2013). The presence of water gathered on the vegetation components from dew or rain has not been investigated in depth with passive retrievals. The effects of this water on microwave emission and scattering are assumed to be taken into account in the model by the existing vegetation parameters described above.

Generally, soil moisture retrieval experiments have focused on solving for soil moisture based on observed brightness temperature. However, it is possible with sufficient knowledge of ground variables to use a two parameter retrieval that simultaneously solves for the vegetation optical depth as well as soil moisture (Wigneron, et al., 2004). This approach relies on an inversion of the radiative transfer model, knowledge of the soil dielectric properties and the model developed by Dobson et al (1985). The two parameter retrieval of soil moisture and optical depth is used by the SMOS satellite (Wigneron, et al., 2007).

The SMOS satellite was the first spaceborne passive sensor to operate in L-Band (Merlin, et al., 2008). Compared to higher frequency measurements in C- (~6 GHz) or X- (~10 GHz) band, the L-band (1-2 GHz) offers several advantages for remote sensing of soil moisture. L-band observations have a large range of emissivity values in response to changes in soil moisture, reduced atmospheric effects and lower vegetation attenuation and remain sensitive to soil moisture up to about 5 kg/m^2 of vegetation water content (Entekhabi, et al., 2012). Additionally, the longer wave L-band emission is less affected by surface roughness effects (Escorihuela, et al., 2007), and is sensitive to moisture in the top 5-10 cm of soil, depending on moisture and texture (Njoku & Kong, 1977).

1.1.3 Soil Moisture Model

At lower microwave frequencies, the emission from the surface is well described by the τ-ω (tau-omega) model from radiative transfer theory (Njoku & Entekhabi, 1996; Entekhabi, et al., 2012; Ulaby, et al., 1986; Jackson, et al., 1982) due to a lack of complex multiple scattering effects inside the vegetation canopy (Wigneron, et al., 2001; Ulaby, et al., 1986). The τ-ω model is given as:

$$T_{B_P} = \left[\left(1 + r_{g_P}\right)\gamma_P\right](1 - \gamma_P)(1 - \omega)T_v + \left(e_{g_P}\gamma_P T_s\right) \qquad (1.1)$$

Where:

T_B - brightness temperature

e_g - ground (rough surface) emissivity

r_g - air-surface reflectivity (= $1 - e_g$)

γ_p- vegetation transmissivity

ω - vegetation single scattering albedo

T_s and T_v - soil and vegetation physical temperature, respectively

Subscript p denotes polarization (H or V)

The above equation breaks surface emission into three distinct terms: vegetation emission, vegetation emission reflected by the soil surface, and the emission from the soil that is attenuated by the canopy (Wigneron, et al., 1995). The vegetation layer is the dominant factor affecting microwave emission from soil (Jackson, et al., 1982; Ulaby, et al., 1983; Schmugge, et al., 1986).

The emissivity of the surface can be calculated from the observed brightness temperature and surface temperature as:

$$e_p = \frac{T_{B_p}}{T_{IR}} \qquad (1.2)$$

where T_B is the brightness temperature and T_{IR} is the physical temperature of the scene from the thermal infrared sensor, and subscript p denotes polarization (H or V).

The predominant influence on the brightness temperature from vegetation is from the vegetation water content. Vegetation water content has been found to be linearly related to vegetation opacity, which is the vegetation attenuation of emitted microwave radiation.

Equation (1.1) can be simplified by assuming that scattering albedo (ω) is near 0 for L-band wavelengths, because the wavelength is larger than the majority of vegetation components. Furthermore, due to the early morning sampling time, it can be assumed that vegetation and physical temperature can be considered equal ($T_v \approx T_s$) (Jackson, 1993).

With these assumptions, (1.1) can then be reduced, and ground emissivity calculated as:

$$e_{g_P} = 1 - (1 - e_P)/\gamma_p^2 \qquad (1.3)$$

Where e is the observed emissivity calculated as in equation (1.2) at p polarization, and e_g represents the modeled emissivity of a bare, rough surface. The effect of vegetation on the surface, and its influence on emissivity, is accounted for in the vegetation transmissivity parameter, γ, defined as:

$$\gamma_P = \exp[-\tau_P(\sec\theta)] \qquad (1.4)$$

The observation angle from surface normal is represented by θ, and τ is the vegetation opacity and relates the vegetation water content, W_v (in kg/m^2) to a vegetation parameter, b:

$$\tau_P = b_P\, W_v \qquad (1.5)$$

The b parameter linearly relates vegetation water content to optical depth, and is generally influenced by vegetation type, frequency and vegetation dielectric constant. Polarization dependency in b is the result of the vertical orientation of plant stalks, which affect horizontal and vertically polarized emission differently (Crow, et al., 2005).

For the purposes of the model detailed in equations (1.1) - (1.5), the vegetation layer is simply considered to be a single lossy layer above the soil surface (Ulaby, et al., 1983), and scattering is ignored. The vegetation canopy can be modeled as a series of discs (leaves) and cylinders (stalks) with varying dielectric and scattering effects (Kurum, 2013), having a similar effect on both polarizations (Njoku, et al., 2002). Absorption dominates vegetation with components smaller than the wavelength, whereas scattering effects increase as the vegetation components approach and exceed the wavelength (Kurum, 2013). While the model used does not account for the varying effects of vegetation components, the changing effect of increased vegetation component size should be kept in mind.

Equations (1.3) - (1.5) account for the vegetation contribution to brightness temperature, and allow for a modelled bare surface emissivity to be compared to soil moisture. In order to calculate a smooth surface emissivity for comparison, the contribution of surface roughness must also be modeled.

Surface roughness is described by a roughness parameter, h, which is dependent on measured surface RMS heights (σ), and the wavelength (λ) (Choudhury, et al., 1979).

$$h = \left[2\sigma\left({}^{2\pi}/_{\lambda}\right)\right]^2 \qquad (1.6)$$

Using the h parameter, roughness effects on the emissivity from the soil can be accounted for as:

$$\mathrm{e}_{\mathrm{s}_\mathrm{p}} = 1 + \left(\mathrm{e}_{\mathrm{g}_\mathrm{p}} - 1\right)\exp(h\cos^{N_\mathrm{p}}\theta) \qquad (1.7)$$

where N_p is an empirical, polarization dependant parameter, and e_{s_p} represents the modeled emissivity of a smooth soil surface at polarization p. θ is the angle of observation from surface normal.

Generally the value of N_p ranges from 0 – 2, though following the work of Escorihuela, et al. (2007), a value of N_H = 1 was used for horizontal and N_V = -1 for vertical in order to account for differing effects of polarization on roughness.

After accounting for vegetation and roughness effects, the emissivity from a modeled smooth soil surface can be compared to observed soil moisture (Jackson, 1993). The model detailed by the above equations is used for all data in this work at both low and high altitude.

1.1.4 Previous Validation Experiments for Combined Active/Passive L Band Sensors

There have been several experiments designed for validation of microwave data in comparison to soil moisture over the years, such as the Soil Moisture Experiment 2002 (SMEX02), Soil Moisture Active/Passive Validation Experiment 2008 (SMAPVEX08), Cloud and Land Surface Interaction Campaign (CLASIC), the Southern Great Plains 1999 experiment (SGP99) and the Canadian Experiment for Soil Moisture 2010 (CanEx-SM10 (Colliander, et al., 2012; Jackson & Le Vine, 1996; Bindlish, et al., 2009)). These experiments were designed to test soil moisture retrieval models using smaller scale aircraft-based systems and high-resolution ground sampling. In each of these experiments, the remote sensing systems used a combined passive/active L-band sensor.

The number of flights and flight lines varied by experiment, depending on the size of the study area and the number of test fields contained within the region. Smaller experiments like SGP99 needed only four flight lines to cover its fields (Njoku, et al., 2002), while the much larger CanEx10 used 16 (Magagi, et al., 2013). Generally, the experiments used an arrangement of flight lines that were designed to create maximum coverage of the study fields, passing directly over measured fields whenever possible. When brightness temperature data were available for sampling sites on the ground, observations from the radiometer were averaged to create field averaged brightness temperatures (Bindlish, et al., 2009).

Field sampling methods have varied from experiment to experiment depending on the purpose of the experiment; ranging from in-field variability to satellite scale validation. Generally satellite scale measurements focus on large *in situ* networks spaced several kilometers apart (Crow, et al., 2012), while sub-field level experiments using aircraft data utilize a large number of samples placed to account for the topography of each field (Jacobs, et al., 2004). Field level soil moisture experiments have often measured soil moisture and vegetation in multiple fields using regular sampling transects. In the case of several of the experiments listed previously, sampling transects were arranged to cover as much of the field as possible and equidistant from field edges (Colliander, et al., 2012). Vegetation measurements were done directly and then interpolated for the remainder of sampling dates (Bindlish, et al., 2009), or estimated based on a vegetation index such as NDVI (Normalized Difference of Vegetation Index) (Anderson, et al., 2004; Jackson, 1993).

1.1.5 The SMAP Satellite Mission

The Soil Moisture Active/Passive (SMAP) satellite is an Earth observational satellite developed and built by the National Aeronautics and Space Administration (NASA). SMAP was developed to monitor soil moisture and freeze/thaw states from space on a global scale with a high degree of accuracy and frequency. The SMAP satellite has global applications for hydrology, climatology, ecology and other environmental sciences (Entekhabi, et al., 2012), and was successfully launched on January 31st, 2015 (NASA 2015). The goal of SMAP is to estimate soil moisture to 4% accuracy using a combined active/passive product at a resolution of 9 km by 9 km (Entekhabi, et al., 2012). This resolution is possible due to the combination of strengths from the two different sensors. The higher resolution of the radar is mitigated by its higher sensitivity to vegetation and surface roughness effects; while the radiometer's coarse spatial resolution maintains a strong relationship to soil moisture with increased vegetation and roughness effects (Entekhabi, et al., 2012). The end result is high resolution soil moisture retrieval that maintains the accuracy of a passive only system. Despite the higher spatial resolution, the 9 x 9 km footprint of the combined soil moisture product will still be too coarse for field-scale use. However, it will be quite valuable for broader scale applications such as flood risk estimation, crop disease risk and the development of severe weather from deep convection. SMAP operated very well during the first 10 weeks of testing until July 2015 when the active sensor failed. The test phase was sufficient to demonstrate the capability of a combined active/passive sensor. The mission is now shifting to incorporate active radar data from other satellites in order to maintain its design goal to achieve higher resolution soil moisture measurements from the combination of passive and active retrievals.

The Soil Moisture Active/Passive Validation Experiment 2012 (SMAPVEX12) campaign was part of a series of field experiments used to refine models and algorithms that will be used in the SMAP mission. The most unique aspect of SMAPVEX12 was its extensive time duration (6 weeks), which was longer than previous similar experiments (Colliander, et al., 2012). The extended duration allowed SMAPVEX12 to cover multiple stages of vegetation growth, from early development to full maturity (McNairn, et al., 2015). The campaign also covered a wider range of vegetation types than most other campaigns and was spread across contrasting soil textures that created wide variation in soil moisture levels. These physical conditions for the SMAPVEX12 campaign were coupled with extensive, high-resolution, ground sample collection to provide a unique opportunity to test the response of the microwave instruments across a broad range of soil, vegetation and moisture conditions. The SMAPVEX12 campaign was designed to be one of the most spatially and temporally extensive soil moisture campaigns ever conducted. During SMAPVEX12, transects were arranged to allow for good field coverage while still facilitating field teams sampling several fields per day.

During the 43-day experiment, a range of conditions were observed. Very wet conditions in the opening week of the experiment preceded a steady dry-down as the campaign went on. Scattered precipitation was recorded in the final two weeks of the experiment that lead to a slight rise of observed soil moisture values on some of the fields. Recorded vegetation biomass was extremely varied, with a majority of fields beginning in a near bare state to fully mature high biomass crops such as corn and canola.

The final result of SMAPVEX12 was a comprehensive and detailed dataset of airborne emissivity data at two different spatial resolutions with corresponding measures of field-based soil moisture, vegetation characteristics and surface roughness (Université de Sherbrooke, 2012). These data provided an unprecedented opportunity to validate the theory behind microwave remote sensing of surface soil moisture in an agricultural setting.

1.2 OBJECTIVES

This research focused on the effects of surface soil moisture, vegetation and surface roughness on passive microwave emissivity from agricultural fields. The high resolution of the passive microwave data from SMAPVEX12 provided an opportunity to validate its application in this type of environment using relatively homogeneous field-scale ground data, rather than the heterogeneous pixels normally utilized with airborne passive microwave sensor campaigns. The wide variety of vegetation cover and surface soil texture provided an ideal scenario to test the technology over a range of conditions representative for most of western Canada, all within a reasonably compact footprint, where ground crews could efficiently collect data on a large number of fields very quickly.

Thus, the goal of the research was to explore the linear relationship between emissivity and soil moisture using the tau-omega model detailed in equations (1.1) - (1.7). The extensive data gathered during the campaign allowed for the use of primarily directly measured variables in the model. The overall objectives of this work were:

1) To calculate emissivity values for the measured sites and use observed parameters to correct for vegetation and roughness effects;

2) To examine the strength of the linear relationship with the application of the corrected emissivity values compared to observed soil moisture; and

3) To apply the corrections to larger, less heterogeneous areas and groups to test if the relationship between emissivity and soil moisture remains linear

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2 SOIL MOISTURE, VEGETATION AND SURFACE ROUGHNESS IMPACTS ON HIGH RESOLUTION L-BAND MICROWAVE EMISSIVITY FROM CROPPED LAND AT FIELD SCALE

2.1 ABSTRACT

During the SMAPVEX12 validation campaign, radiometer data were gathered by aircraft at two different altitudes. Low altitude (1 km) passes were flown on three north-south lines directly over 22 ground measured fields. The brightness temperature was recorded from the Passive/Active L-band Sensor (PALS) radiometer at 1.41 GHz in both horizontal and vertical polarization at a spatial resolution of approximately 600m. The aircraft also measured surface temperature using a passive thermal infrared sensor. These overpasses were done early in the morning so were near simultaneous with soil moisture measurements by ground teams. Soil moisture was sampled on two transects of eight locations spaced 75 m apart. Vegetation measurements were carried out on alternate sampling dates to soil moisture and brightness temperature in order to measure vegetation water content. The high resolution soil moisture measurements were plotted against emissivity values calculated from observed brightness and thermal infrared temperature. Corrections for vegetation and roughness effects on emissivity were calculated using the well-established tau-omega model. Analysis of the sensitivity to soil moisture (slope) and strength (R^2) of the linear relationship was conducted for both polarizations for the emissivity values observed by the radiometer, and those corrected for vegetation and roughness effects from the model. It was expected there would be an increase in the sensitivity to soil moisture with corrections to vegetation and roughness effects applied by the model. The slope of each regression was tested for significance at 95% confidence to ensure a significant response in emissivity values with changing soil moisture. Results showed strong linear correlations on a field-by-field basis that were weakened with the inclusion of multiple fields. Aggregated regressions were attempted for multiple fields with similar vegetation and soil conditions in order to assess the linear relationship over larger areas. These aggregations showed an increase in the strength of the relationship, but were still considerably weaker than any individual field relationships.

2.2 INTRODUCTION

The passive emission of microwave radiation from the earth's surface is faint, therefore a much larger area is required to retrieve a useable signal than for its active counterpart. Large scale, high resolution passive retrieval from satellite altitudes is not possible, since the only way to increase the radiometer's resolution is to move it closer to the target. Typically, high resolution passive retrievals have been done by the use of localized truck or tower mounted radiometers in local experiments (Choudhury, et al., 1979; Escorihuela, et al., 2010; Schmugge, et al., 1986), or low altitude aircraft-based observations in validation campaigns such as the Soil Moisture Active-Passive Validation Experiment in 2012 or SMAPVEX12 (Bindlish, et al., 2009; Colliander, et al., 2012; Jackson & Le Vine, 1996).

The SMAPVEX12 campaign provided an excellent opportunity to analyze high resolution radiometer data with detailed ground measured soil and vegetation data. Four low altitude lines were arranged directly over study sites, which allowed for radiometer footprints that fit completely inside individual agricultural fields. These low altitude flights created the opportunity to isolate the relatively homogenous footprint of the fields with both spatially and temporally representative soil moisture measurements from the ground. Furthermore, the detailed vegetation sampling within each study field and field specific roughness measurements meant that the key variables that influence the observed brightness temperature were directly measured. This negated the need to use indices, estimates or proxies when calculating the passive microwave model parameters. While a handful of previous similar experiments summarized by Colliander et al. (2012) have used a similar design, none have had the duration or variety of conditions that were present during SMAPVEX12.

The data gathered during SMAPVEX12 represents possibly the "best case" for passive microwave retrieval. The homogenous radiometer footprint and detailed soil and vegetation sampling provided an ideal opportunity to examine the relationship between radiometer observed brightness temperature and ground measured soil moisture. It has been found previously that the relationship between moisture and brightness temperature is essentially linear (Du, et al., 2000; Jackson, et al., 1982; Wigneron, et al., 2003). Both the quantity and quality of data from SMAPVEX12 facilitated a comprehensive assessment of the relationship between these variables, and the degree of influence from vegetation and soil roughness on the strength of the relationship.

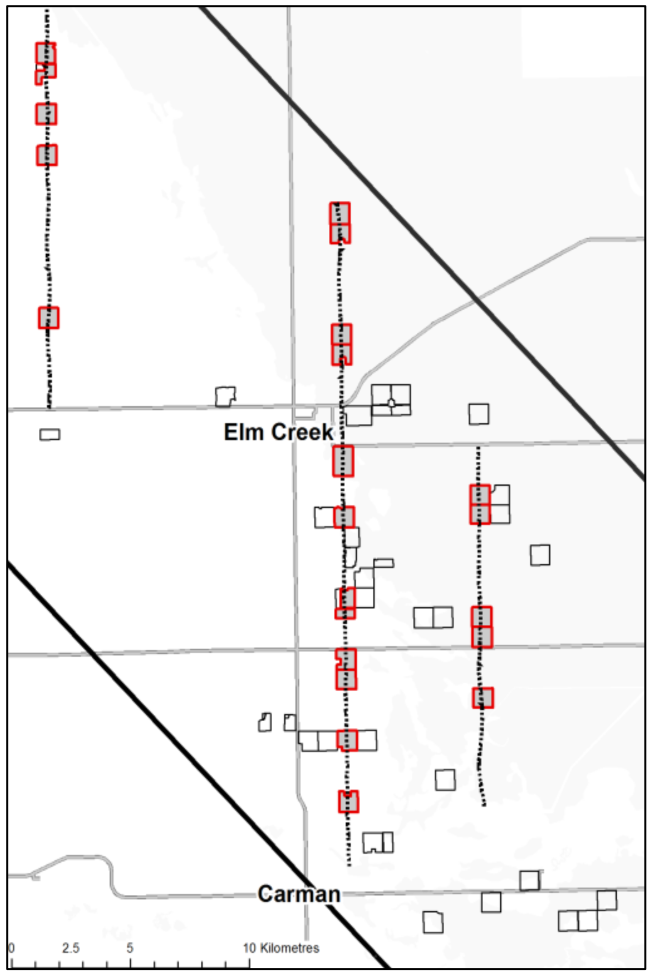

Figure 2.1- SMAPVEX Agricultural fields.

Fields highlighted in red are those included in this chapter. Dotted lines represent general flight paths of PALS radiometer for low altitude flights. Shaded area denotes clay soils.
Forest sites in the north-east not shown.

2.2.1 Objectives

The goal of this chapter was to examine the strength of the relationship between soil moisture and emissivity, along with the sensitivity of the sensor to soil moisture over a variety of crop and soil types. The sensitivity of the sensor to soil moisture is the degree of change in sensor signal in response to observed changes in moisture (Njoku, et al., 2002). Sensitivity is expected to be reduced in the presence of vegetation and roughness; however corrections can be applied to account for these effects and create a more accurate estimate of soil moisture from the passive microwave sensor. These corrections, discussed in detail in section 1.1.3, were each examined to determine their effect on the sensitivity and strength of the soil moisture - emissivity relationship.

The objectives of this chapter were:

1) To assess the strength of the linear relationship between soil moisture and emissivity using high resolution remotely sensed data and field measured values from the SMAPVEX12 field campaign;

2) To examine the effect of corrections on the relationships using existing models for vegetation and roughness; and

3) To determine the optimal values of the *b* parameter which most accurately characterize the range of vegetation types in the study.

2.3 METHODS

2.3.1 Study site

The study area for SMAPVEX12 was an approximately 70 x 12 km area oriented in a northwest to southeast direction and located in southern Manitoba, Canada. The town of Carman lies just outside the southernmost extent and the town of Elm Creek is near the centre of the area (Figure 2.1). The region was chosen for several reasons: its existing monitoring network of in situ soil moisture sensors, contrasting soil texture from west to east, a wide range of agricultural crops and the presence of mostly forested and undeveloped land in the northern portion.

One of the unique features of the study area is the extreme gradient of soil textures present. The study area lies within a region called the Manitoba Escarpment, which corresponds to the shoreline of an ancient glacial lake (Lake Agassiz). The eastern side of the study area lies at the bottom of the escarpment, and is characterized by dominantly clay soils (~60% clay). The western, uphill part of the region, however, is covered by extremely sandy soils (>80% sand). The sharp change occurs over just several metres in parts of the region.

Within the study area, 55 agricultural fields and 5 forest sites were chosen for ground data collection. Of these 55 total fields, 22 of them were located along three low altitude flight lines which are shown in Figure 2.1.The agricultural fields sampled represented the major crop types in the area, and included soybean, corn, spring wheat, winter wheat, canola, oats, pasture and forage. The pasture fields were characterized by a wide variety of ground cover: various species of grasses and brush, bare soil, along with small forested areas and ponds. The typical agricultural field size in the area is one full quarter-section of approximately 800 x 800 m. With few exceptions, detailed later, each field was planted with a single crop-type.

2.3.2 SMAPVEX12 background data

Spatial background data from the SMAPVEX campaign were provided in the geodatabase, available from the SMAPVEX data warehouse (Université de Sherbrooke, 2012). Included in the geodatabase were shapefiles for the boundaries of each of the 55 test fields and 5 forest sites, as well as point files for the transects of ground sampling points on each field. Once these layers were loaded into GIS software (ArcMap 10.0, (Environmental Systems Research Institute (esri), n.d.)), the forest sites were removed from the layer, as they were not included in this analysis.

A small number of the agricultural fields in the study were planted with multiple crops. These fields were identified using the crop type attribute data included with the field layer. Both the area of the field and any transect points that fell within the area of the secondary crop type were discarded from future analysis. On two of the three fields where this occurred, the area was a small corner, and only caused the removal of one or two of the sample points. The third field, however, had fully half (8) of its sample points in corn, and half in canola. For this field, the larger canola crop was kept and used in the analysis, with the soil moisture, vegetation and Passive/Active L-band Sensor (PALS) measurements taken in the corn discarded from future analysis.

When the field boundary and sampling transect point data were displayed together, an issue was discovered on two adjacent fields both planted with winter wheat (identified as fields 41 and 42). The two northern-most points of the southern field were over the quarter-section boundary and were spatially located on the northern field. In order to remain consistent in calculating field average values, these two sample points were reassigned to the field on which they were spatially located, giving the northern field 18 ground sample points and the southern field 14 sample points.

2.3.3 Field Data Collection

Soil moisture was sampled by hand-held probe on 17 days between June 7th and July 19th, 2012 (Table 2.1). Each agricultural field was sampled on two ~500m long transects spaced 200m apart with eight sampling sites on each transect (Figure 2.2). Sampling sites were numbered 1-16 and

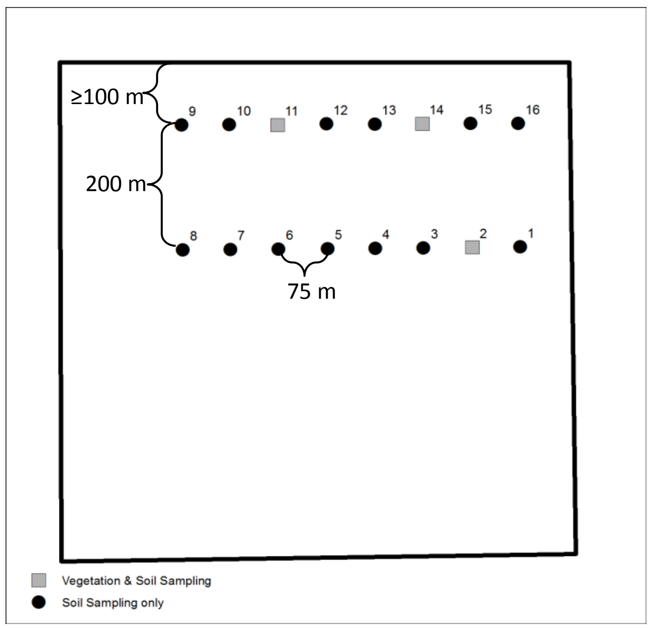

Figure 2.2- Example of transects for field sampling.

Black line denotes field boundary. Distances are to scale.

sampled in the same order on each day. Sites were created in GIS software by exporting the coordinates to handheld GPS units carried by the field teams. On the first day of sampling in each field, sampling sites determined to be atypical of the general conditions of the field were relocated to a nearby more representative location. Areas that were deemed atypical included unusually low lying areas with little or no crop, or in unplanted parts of the field.

At each sampling site, three readings were taken with a hand-held dielectric probe inserted vertically into the soil to measure volumetric soil moisture in the top 5 cm. Whenever possible, the three soil moisture measurements were recorded in the crop row, at ¼ row spacing and at ½ row spacing. At the sites at each end of the transects, temperature measurements were taken with a thermometer at 5cm and 10cm depths, as well as soil and vegetation surface temperature with a thermal infrared sensor. One soil core was gathered from each field on each sampling day for soil moisture probe calibration (Rowlandson, et al., 2013)' as well as bulk density and particle size analysis. The location of the core changed by one sample site along the transect each sampling day, so that cores were gathered from all locations at least once by the end of the campaign.

On approximately three-quarters of all measured fields, an *in situ* station was positioned at the first sample point to measure soil moisture hourly for the duration of the field campaign. The stations had a single probe inserted into the soil horizontally at 5cm depth. A quick examination of the sampling time measurements (7:00am – 12:00pm) revealed a change in soil moisture of generally 0.01 cm^3cm^{-3} on each sampling day (data not shown). Thus, the hand-held measurements of surface soil moisture were representative of the value at the time of the PALS flights which occurred within the 7:00am to 12:00pm time window on each sampling date.

Table 2.1- Sampling days during SMAPVEX12.

Each field day was dedicated to sampling either soil or vegetation. Radiometer data coincides with soil sampled dates.

Sample Date	Day of Experiment	Day of Year	Sampled
June 7, 2012	1	159	Soil
June 11, 2012	5	163	Veg
June 12, 2012	6	164	Soil
June 13, 2012	7	165	Veg
June 15, 2012	9	167	Soil
June 16, 2012	10	168	Veg
June 17, 2012	11	169	Soil
June 18, 2012	12	170	Veg
June 19, 2012	13	171	Veg
June 21, 2012	15	173	Veg
June 22, 2012	16	174	Soil
June 23, 2012	17	175	Soil
June 24, 2012	18	176	Veg
June 25, 2012	19	177	Soil
June 27, 2012	21	179	Soil
June 28, 2012	22	180	Veg
June 29, 2012	23	181	Soil
June 30, 2012	24	182	Veg
July 3, 2012	27	185	Soil
July 5, 2012	29	187	Soil
July 7, 2012	31	189	Veg
July 8, 2012	32	190	Soil
July 9, 2012	33	191	Veg
July 10, 2012	34	192	Soil
July 13, 2012	37	195	Soil
July 14, 2012	38	196	Soil
July 16, 2012	40	198	Veg
July 17, 2012	41	199	Soil
July 18, 2012	42	200	Veg
July 19, 2012	43	201	Soil

Surface roughness was measured once per field with a pin board at the beginning of the campaign and then assumed constant. Roughness measurements were taken during the first two weeks of the experiment with a 1m pinboard. The pinboard had 101 steel pins that were free to slide up and down to follow the vertical profile of the surface. The top of each pin was marked in red to highlight the surface profile which was captured with a digital photo. At two sites per field (generally sites #1 and #2 in Figure 2.2), three measurements were taken along a line parallel to the flight lines. The variable of primary interest was the root mean square (RMS) of surface heights which statistically describes the vertical component of roughness. The RMS of surface heights were calculated by digitizing the surface profile gathered in the field into height values at a set spacing (Ulaby, et al., 1982). RMS of the surface was calculated using the average surface height and the variance (Trudel, et al., 2010).

2.3.3.1 **Soil moisture data -** The field measured soil moisture values were calibrated using the field specific calibration described by Rowlandson et al. (2013). During calibration, some soil moisture values were removed due to probe errors or as part of the outlier analysis. Values above 60% volumetric soil moisture were flagged as high values and removed from field average soil moisture calculations for this analysis. The calibrated values were then collected in a table and sorted based on the sample date and location. With the exceptions detailed previously in Section 2.3.2, each field had moisture readings from 16 sample sites per sampling day with three readings per site. In order to maintain a spatially averaged soil moisture value, each site's average moisture was calculated before combining the 16 sites into a field average. This ensured that sites with measurements discarded were still represented equally as part of daily spatially-averaged soil moisture. However, any fields on any of the sampling dates that did not have more than half (24 of 48) of the measurements remaining were discarded from the analysis for the affected date. This was only the case for one date on each of three different fields: field 32 on June 27, field 41 on July 19 and field 42 on June 15. The loss of measurements on each of these fields on those particular days was likely the result of technical issues with the hand-held probe during soil moisture sampling.

2.3.3.2 **Vegetation sampling -** Vegetation was sampled 15 times during the campaign on days alternate to soil moisture sampling. Unlike the soil moisture sampling strategy, field teams measuring vegetation did not sample all fields on each date, but rather prioritized based on days since last sampling and vegetation type. This provided vegetation measurements between four and six times per field throughout the campaign. Sampling was done on the same transects as soil moisture, but used only 3 of the 16 points, with samples being taken at sites 2, 11, and 14 on each field (Sites marked with squares in Figure 2.2). The variable of primary interest in terms of influence on the passive microwave signal was vegetation water content (VWC) in mass per unit area (kg m^{-2}) (Jackson & Schmugge, 1991). Field measurements of plants per metre (in row) and row spacing from several locations around each field at the beginning of the campaign were used to estimate average plants per square metre. Vegetation sampling of ten plants at three locations per field were used to create average water content per plant. The average plant spacing and vegetation water content were then used to create an estimated field sampled VWC per square metre. For small leafed vegetation such as grass and cereals, vegetation sampling was done with a 0.5x0.5 m square. All plants within the square were removed and bagged to determine VWC. Additionally, stem diameter, plant height, and leaf area index were also measured at each sampling location.

Plants removed from the field were weighed wet and bagged before being placed in a drying room. Samples were air dried for 48 hours at 30 °C, then reweighed to obtain the dry-weight and the average air-dry vegetation water content. A subset of the air-dried vegetation samples were oven dried in order to determine the oven-dry weight of the vegetation samples. For all crop types except corn, it was determined that after drying for 48 hours at 60°C, the oven-dry weight was a very consistent average of 94.6% of the air-dried weight. This correction factor was applied to all of the air-dried weights (with the exception of corn) to calculate the final VWC from each field sample based on the oven-dry plant weight. Vegetation water content was calculated as the difference between the wet and oven-dry weights, and moisture content was calculated water content divided by wet biomass.

2.3.3.3 **Corn Oven-dry Weight** - The relationship between oven-dried and air-dried weights for corn gathered in the field was found to be highly inconsistent. This necessitated a follow-up experiment to determine the oven-dry moisture content of corn plants throughout their life-cycle. During the winter of 2012 a growth chamber experiment was set up at the University of Manitoba to determine values for converting corn wet weight to oven-dry weight by growth stage. At the beginning of the experiment, three corn seeds were planted into each of 30 pots containing topsoil and placed into a growth chamber. Fertilizer, consisting of 1g of S, 1g of P, and 1.5g of N, was added to the pots two weeks later following emergence of 75 of the 90 seeds. The first sample was taken several days later, when the plants were approximately 20cm tall. A subsample of the corn plants were clipped and removed at soil level, then cut into segments a few centimetres long and placed in three onion skin bags. The first samples contained four plants per bag with decreasing numbers on later sample dates as the plants increased in size. The bags containing the fresh corn biomass were weighed, placed into a drying oven at 60°C for 48 hours and then weighed again to determine gravimetric water content. This sampling procedure was repeated 10 times every 7-10 days with the final sample being taken 68 days after the first.

The experiment provided measurements of corn VWC throughout the BBCH growth stages (Agriculture and Agri-Food Canada, 2012) of corn plants observed during the field campaign. The BBCH stages observed for the corn plants during SMAPVEX12 were used to link the appropriate oven-dry weight conversion to the samples that had been collected in the field. The oven-dry weight of the field samples was essential to calculate VWC values for each sample from the field (Figure 2.3). Table 2.2 shows the results of the experiment using the mean value of the three bags for each sample date.

Table 2.2 – Results of the growth chamber experiment to determine corn oven-dried biomass and moisture content by BBCH stage.

Sample	Observed BBCH Stages	Plants / Bag	Wet Biomass (g)	Oven-Dry Biomass (g)	Water Content (g)	% Moisture
1	12-14	4	3.89	0.29	3.60	93.18%
2	14-15	4	12.70	1.18	11.52	90.67%
3	16-18	3	16.13	1.66	14.47	89.65%
4	18 & 30-31	3	43.01	4.38	38.63	89.79%
5	30-32	3	103.49	9.26	94.23	91.08%
6	30-36	2	252.32	23.24	229.08	90.83%
7	31-36	2	485.00	61.16	423.84	87.45%
8	33-38	2	613.46	87.14	526.32	85.88%
9	51-55	1	457.82	76.08	381.74	83.44%
10	67-71	1	539.01	115.09	423.92	78.76%

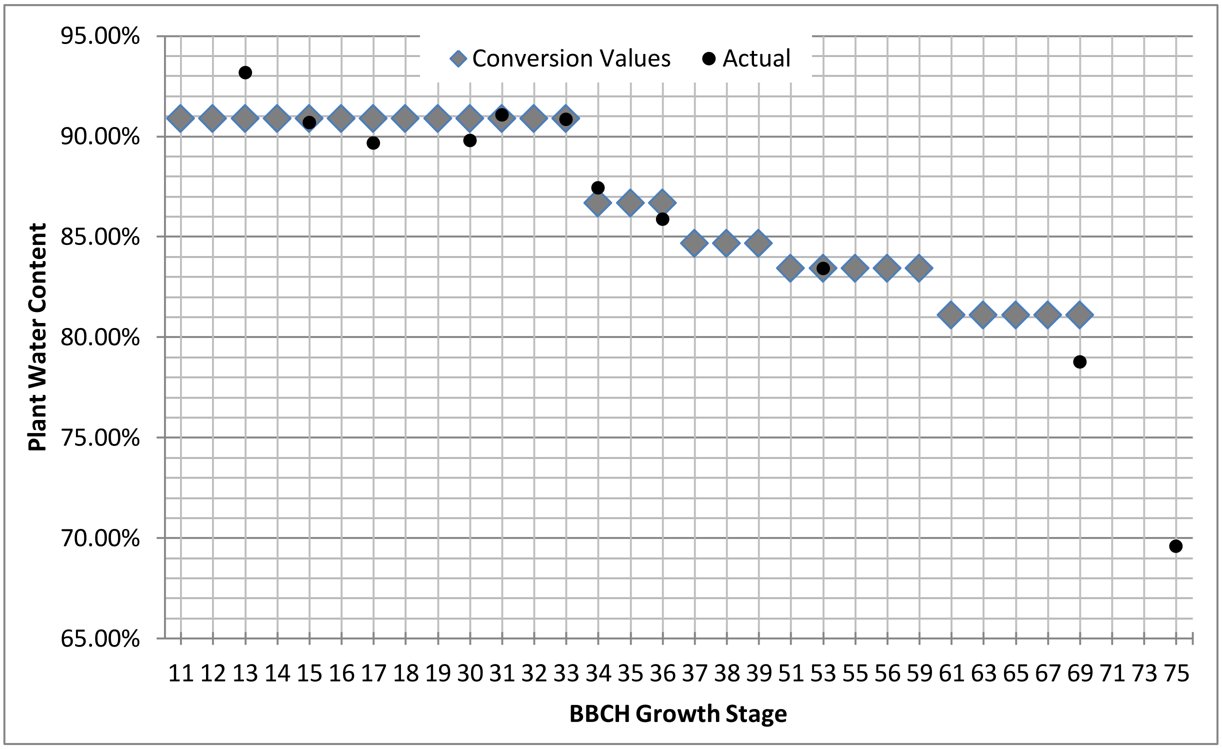

Figure 2.3 – Actual values of vegetation water content from corn oven-dry biomass experiment.

Values plotted with conversion values utilized at each BBCH stage to calculate oven-dry biomass for the field samples. Conversion values were held constant until BBCH stage 34 where a steady decline was observed. Vegetation water content was modeled to decrease in stages as an average of actual measurements based on growth stage. See Table 2.2

2.3.4 Vegetation data

Measurements of vegetation water content from the three sites per field were entered into a table and attributed based on date and location. For each site measurement the total vegetation water content, as well as the amounts from individual plant components (leaves/stem/flowers) was recorded. Only the total water content of the crop was considered in this analysis, as the model used does not differentiate between effects from the stem or leaves on the microwave emission.

Once daily field averaged VWC was calculated, estimates were needed for dates on which soil moisture and passive microwave data had been collected. Each soil sampling date was assigned an interval based on the vegetation date it preceded, so any date before the first vegetation sample was given a value of 1. Any soil sampling dates that occurred after the final vegetation date were assigned a value of one higher than the last interval on that field. The linear relationship between each two consecutive vegetation samples was calculated and applied to the corresponding time interval (Figure 2.4). The first and last intervals on each field used the same relationship as the next nearest interval (i.e. the first and second interval equations were identical). Estimated values for the VWC on dates when soil moisture was sampled were calculated based on the linear equation of the time interval for the soil moisture sample date. This piece-wise linear estimation has been used in the past, and is considered more accurate than fitting a polynomial curve to a limited number of data points (Anderson, et al., 2004).

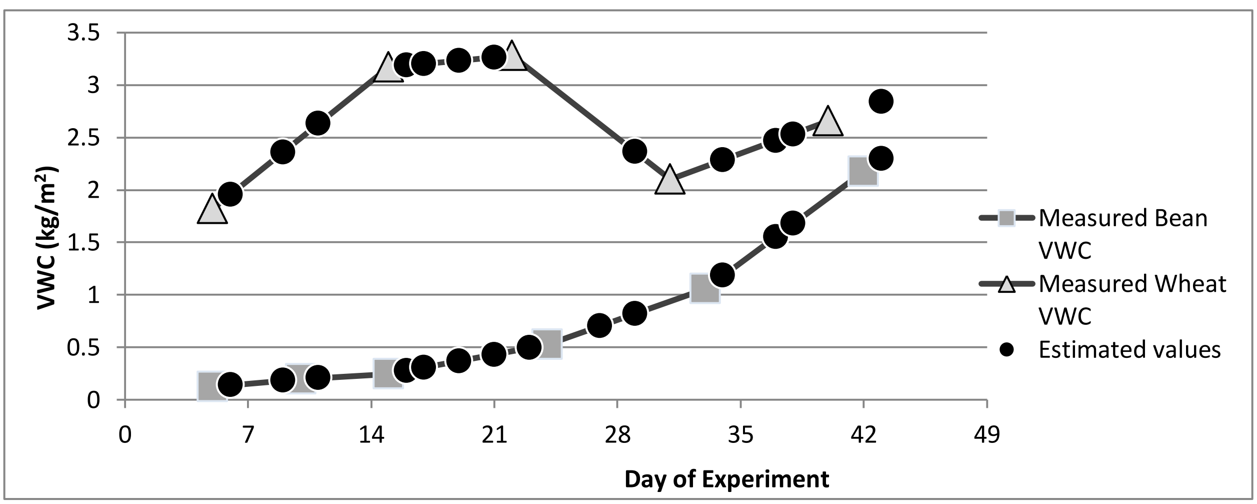

Figure 2.4- Examples of Vegetation Water Content (VWC) estimation on two different fields.

Squares and triangles represent field measured average values. Linear interpolation between sampling dates was used to assign VWC to soil sampling dates (circles)

Table 2.3- Summary of fields with low altitude data

Field ID	Crop Type	Flight Line	General Soil Texture	VWC Range (kg/m^2)	Max VWC (kg/m^2)	Mean SM (cm^3/cm^3)	RMS Height
11	Beans	West	Sand	0.32	0.33	0.16	0.395
12	Beans	West	Sand	0.14	0.18	0.14	1.04
13	Pasture	West	Coarse Loamy	0.32	0.37	0.27	0.550
21	Pasture	West	Sand	0.20	0.56	0.28	0.890
22	Pasture	West	Sand	0.20	0.32	0.30	1.195
31	Wheat	Centre	Clay	1.49	3.26	0.38	0.595
32	Wheat	Centre	Clay	0.92	2.88	0.36	1.315
41	Winter Wheat	Centre	Clay	2.96	4.28	0.36	1.135
42	Winter Wheat	Centre	Clay	1.73	3.40	0.39	1.005
51	Beans	Centre	Clay	2.16	2.30	0.20	0.475
52	Beans	Centre	Loamy	2.05	2.14	0.15	1.085
61	Canola	Centre	Loamy	2.73	3.56	0.13	0.790
62	Canola	Centre	Sand	2.58	2.71	0.12	0.570
71	Corn	Centre	Sand	3.15	3.19	0.11	0.550
72	Corn	Centre	Sand	3.40	3.45	0.12	0.460
81	Wheat	Centre	Loamy	0.87	1.96	0.19	0.740
91	Wheat	Centre	Loamy	1.88	3.28	0.16	1.055
102	Beans	East	Clay	0.57	0.59	0.33	0.670
103	Beans	East	Clay	0.56	0.58	0.34	0.695
111	Beans	East	Clay	0.87	0.90	0.27	0.645
112	Beans	East	Clay	0.51	0.55	0.31	0.550
113	Beans	East	Clay	0.48	0.51	0.30	0.905

2.3.5 Aircraft Data

Within the study area, four of the aircraft flight lines were low altitude and were situated to fly in a line directly over a subset of fields that could be covered with this flight pattern. One of the low altitude lines was over the forest sites in the north-west and was discarded from this analysis. The remaining three low altitude lines were over the agricultural portion of the study area oriented directly north-south over 22 of the study fields. The eastern- and western-most lines each passed over five fields, while the longer central line covered 12 fields (Table 2.3). There were also eight high altitude flight lines oriented parallel to the study area boundary and spaced approximately 1500 metres apart and to provide near total coverage of the area by the aircraft mounted sensors. The high altitude flight lines were not used in this analysis and are discussed in the next chapter.

During the SMAPVEX12 campaign, two different aircraft were used to gather the remotely sensed data. The first was a G3 jet equipped with UAVSAR (Unmanned Aerial Vehicle Synthetic Aperture Radar) (McNairn, et al., 2015). The UAVSAR system is an active radar, and was flown at 13 km altitude (Université de Sherbrooke, 2012) on 12 dates throughout the campaign using the high altitude flight lines. The second aircraft was a small twin otter aircraft with the PALS system onboard and described in the next section. The twin otter flew both low altitude (1 km) and high altitude (3 km) flight lines on the each day of soil moisture data collection by the field teams on 17 dates.

2.3.6 Low Altitude Microwave Data

The PALS radiometer was designed to simulate the instrumentation to be used on board the SMAP satellite. The instrument was set to a viewing angle of 40°, with a beam width of 20°, creating a ground footprint of approximately 600 m in diameter for the low altitude data (Colliander, et al., 2012b).

The data consisted of a series of points representing the centre of the radiometer boresight. The data were downloaded from the SMAPVEX12 data warehouse as a group of text files. Each data point along the flight line had several measurements associated with it; a time value (in UTC seconds), X & Y coordinates (in UTM), horizontal and vertical (H & V) polarized brightness temperature (in K), and a thermal infrared value (in °C). After the data were properly formatted as a table, the data were imported into GIS software and displayed as a point layer based on the X & Y position of each individual measurement. With all boresight points loaded into the GIS software, all dates were combined into a single file.

The boresight points were arranged along three north-south oriented flight lines shown in Figure 2.1. The shorter east- and west-most lines each covered five study fields, with the longer centre line passing over 12 study fields. These three flight lines were flown on each of the 17 flight days, though due to variations in the path of the aircraft, not all of the possible 22 fields were measured on every day.

Given that the low-altitude lines passed directly over the study fields, and that the ground footprint observed by the radiometer was smaller than the field itself (~600m diameter and 800x800m square, respectively); it was possible to retrieve a signal derived exclusively from a single study field. In order to minimize influences of areas outside the study field, and to maintain the most homogenous signal possible from the radiometer, each field was limited to areas of uniform crop type. This was done using GIS and crop type data retrieved at the beginning of the experiment. Two of the 22 fields were affected by this, one with a small area of pasture in a predominantly bean field,

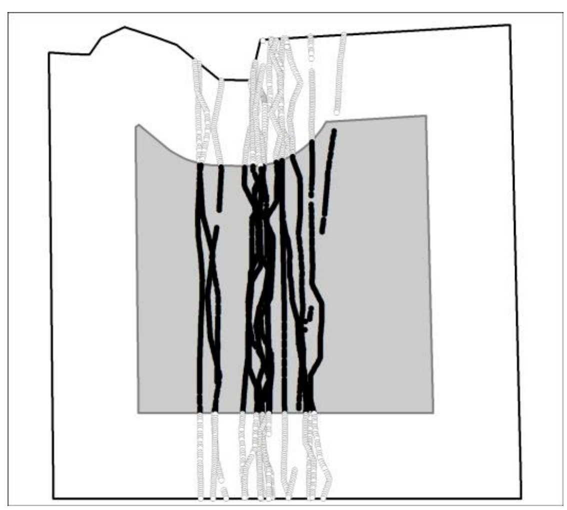

Figure 2.5- Example of the 150 m buffer applied to field 11.

Shaded area in the centre was used in the analysis. Radiometer readings (black lines) that fell within the area were used to calculate field average T_B. The figure displays flight lines for all flight days.

and another with approximately ¼ of its area planted with corn and the rest with canola. In both cases, the areas covered by the secondary crop (pasture & corn) were removed from the field and treated as external areas. Any moisture or vegetation measurements taken in these regions of the field were not used in field averages.

Since the radiometer footprint could fit entirely inside the field of interest, each of the 22 fields had a 150 m interior buffer applied using GIS. The 150m distance was chosen as it represents one half of the radiometer footprint radius. Each field then had a zone where the radiometer footprint had a majority of its area on the field of interest (shaded area in Figure 2.5). If the radiometer footprint is approximated as a circular area with radius of 300m centred on the boresight point, any point falling within the zone has at least 63% of its corresponding footprint on the field of interest. An overlay procedure (intersect) was performed with the radiometer points and the buffered field polygon layer. This operation assigned a field ID to each point over a field, and removed all points outside the field boundaries from future analysis.

All radiometer points within the buffered field layer were used to create a field average emissivity for that flight day (Appendix I). For each point, emissivity was calculated using equation (1.2). Points that fell between 0 – 150 m from each field edge were not used as part of the averages due to decreased homogeneity of vegetative cover in the footprint, and a reduced signal from the field of interest.

With all the PALS data assembled in GIS, the final table was exported and arranged into a database by the field ID and sampling date. These "field dates" were linked to the same values from the soil moisture and modelled vegetation tables to complete the field averaged values. With the three main variables collected into a single table, the correction equations were applied to field-averaged emissivity to model the vegetation and roughness-corrected emissivity values on a per field per day basis. The relationship to soil moisture was then plotted on scatterplots and the slope and R^2 of the linear relationship was determined.

2.3.6.1 Soil moisture – emissivity relationship - For every field on each date that both low-altitude radiometer data and soil moisture measurements were available, field averaged corrected emissivity was calculated using the interpolated VWC measurement and field measured roughness using the τ-ω model detailed in (1.1) - (1.7).

Plots of e versus field measured soil moisture by field were created to show the efficacy of the correction equations on a field-by-field basis for both polarizations. The relationships are described by linear equations:

$$\begin{aligned} e &= a_0 - S_0\, m_v & \text{(a)} \\ e_g &= a_g - S_g\, m_v & \text{(b)} \\ e_s &= a_s - S_s\, m_v & \text{(c)} \end{aligned} \qquad (2.1)$$

Where:

e, e_g, e_s – emissivity of surface (vegetated, rough, or smooth)

m_v – field measured volumetric moisture content (cm^3cm^{-3})

S_0, S_g, S_s – sensitivity to soil moisture (slope) for vegetated, rough, and smooth soil surface, respectively

a_0, a_g, a_s – regression constant (on vegetated, rough, or smooth surface)

Variables e, S, and a are polarization dependent.

In order to examine the effect of variable vegetation across different fields, field averaged soil moisture and emissivity were broken up into three groups by VWC value: low vegetation (<0.25 kg/m^2), moderate vegetation, (0.25 – 2.5 kg/m^2), and high vegetation (> 2.5 kg/m^2) (Njoku, et al., 2002). Each day's values were assigned to one of the three groups and the linear relationship was plotted.

2.3.6.2 Optimization of *b* - Values for the *b* parameter were taken from previously published values (Crow, et al., 2005; Jackson & Schmugge, 1991) for the respective vegetation types at 1.4 GHz. In order to account for polarization effects on *b*, values were adjusted by 10%; the values were increased for vertical, and decreased for horizontal (Crow, et al., 2005). Where no suitable specific value was available in the literature for a specific crop, an L-band average of 0.12 was used (Njoku & Entekhabi, 1996). Table 2.4 shows the b values used for each vegetation type.

Table 2.4- b values used for the low altitude data

Crop	b	b_V	b_H
Corn	0.115	0.1265	0.1035
Soybeans	0.08	0.0880	0.0720
Canola	0.12	0.1320	0.1080
Wheat	0.1	0.1100	0.0900
Winter Wheat	0.1	0.1100	0.0900
Pasture	0.3	0.3300	0.2700

Access to field specific conditions will not be available at larger scales, and heterogeneous vegetation types within a single pixel make the use of vegetation-specific *b* values impractical at resolutions coarser than a single field. An optimization was conducted to derive polarization-specific *b* values that could be considered representative of the range of agricultural vegetation across all of the SMAPVEX12 study fields.

This was done by first removing outliers and fields with extremely poor soil moisture-emissivity relationships. The three pasture fields were the only fields that exhibited relationships weak enough for the duration of the campaign to justify removal for this optimization step, with an uncorrected R^2 and slope lower than the average across all fields. Furthermore, grass fields have previously been found to require a higher *b* value than most other vegetation types (Jackson, et al., 1982). The optimization was done by iterating through each value of *b* in 0.01 increments between 0.01 and 0.50. For each value of *b*, the R^2 and slope of a linear regression relationship across all of the study fields (excluding pasture and outliers) were recorded in both polarizations. The R^2 and slope for each relationship was plotted against the values of b used to derive the relationship.

2.3.7 Tests of the moisture – emissivity relationship

Tests of the significance of the linear regressions were carried out using statistical analysis software (SAS 9.3). Using a regression analysis procedure (proc reg), each version of the relationship was tested for significance of slope (also referred to as regression coefficient (Snedecor and Cochran 1980)) both before and after correction for vegetation. The analysis provided plots of the relationship, residual analysis and t-test scores for significance of slope at 95% confidence. Regressions found significant were rated as 'strong', 'moderate' or 'weak' using the criteria of Snedecor and Cochran (1980) where an R^2 value of >0.75 was considered strong, >0.50 was moderate, and ≤0.50 was weak.

A second procedure was run to examine the distribution of the horizontally polarized vegetated (e_H) and bare (e_{gH}) emissivity values. This procedure (proc univariate) created a boxplot of emissivity by field and was used to identify possible outlier values in the emissivity.

2.4 RESULTS

Preliminary results from the SMAPVEX campaign reported in (Colliander, et al., 2012b; McNairn, et al., 2015) showed that the experiment was successful in measuring a wide range of ground conditions, and that the expected inverse relationship between daily average brightness temperature and daily volumetric soil moisture were present across the study fields (Figure 2.6). Precipitation was measured by weather stations in the towns of Carman and Elm Creek. Precipitation occurred at both locations on all dates from June 8th to June 13th, and then again on June 16th with amounts of over 25 mm recorded at Carman in the south. Following the frequent precipitation events at the beginning of the campaign, there was only sparse precipitation at both locations for the remainder of the experiment.

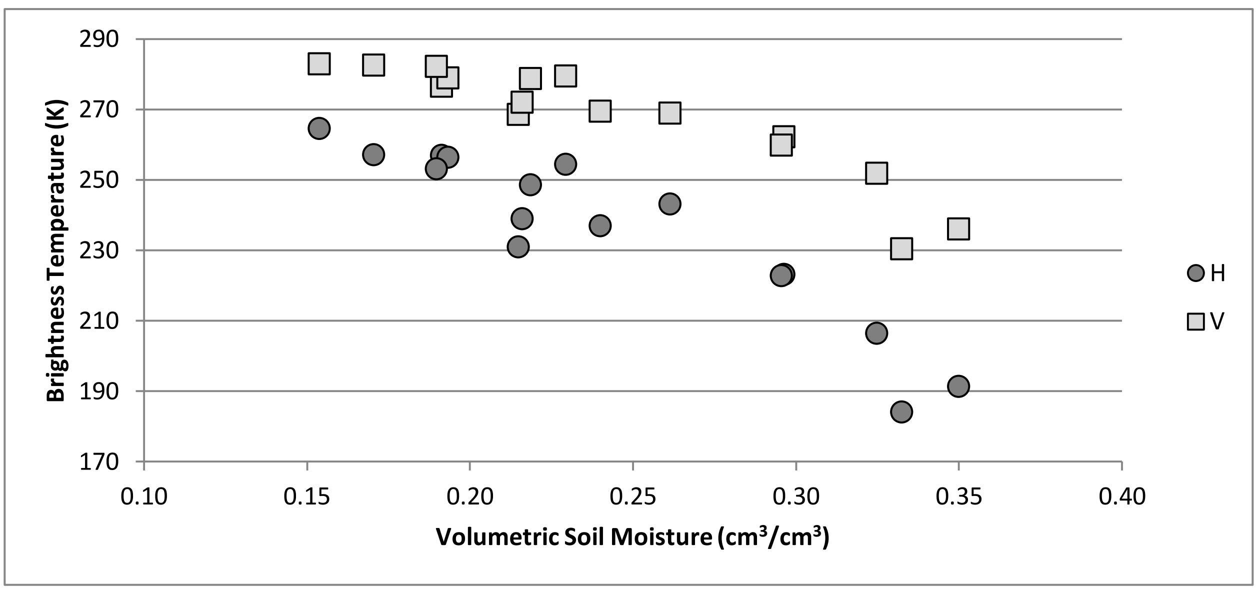

Figure 2.6 – Daily averaged soil moisture vs brightness temperature for all SMAPVEX12 dates and fields.

2.4.1 SMAPVEX12 Field Data

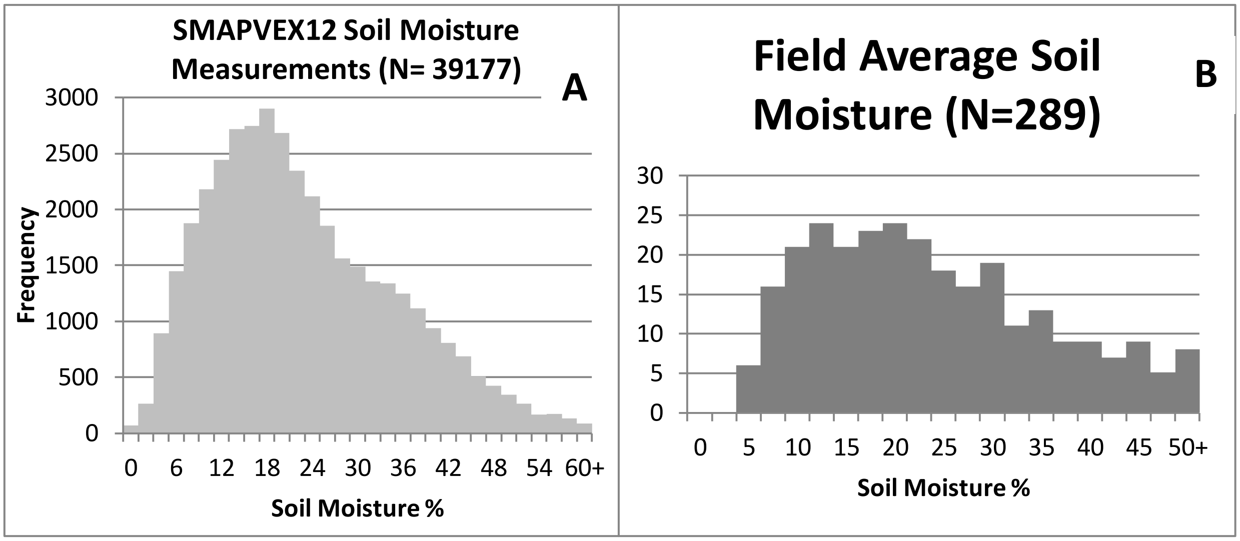

Figure 2.7- Soil moisture during SMAPVEX12

A) All measurements and B) Field averages

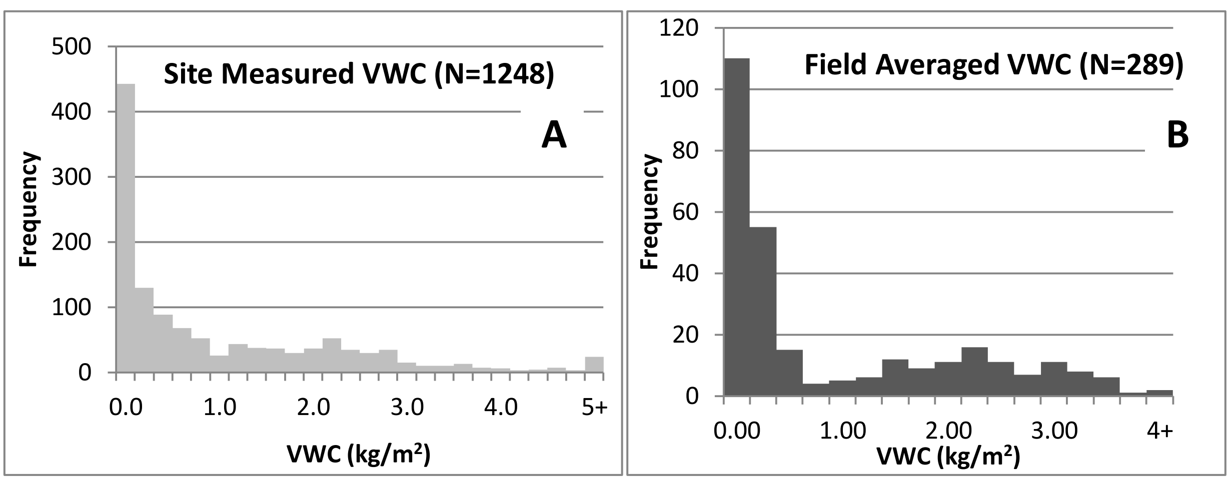

Figure 2.8- Vegetation Water Content throughout SMAPVEX 12.

A) All individual site measurements B) Field averages

2.4.1.1 Soil moisture - Over the entire duration of the field campaign, almost 40000 individual soil moisture probe measurements were taken on all 55 study fields, with an overall mean value of 23.7% volumetric soil moisture content (Figure 2.7). Even with the high values removed, the field averaged soil moisture over all low altitude fields had an overall mean of 24.9%, slightly higher than the average of all probe readings.

2.4.1.2 Vegetation - Vegetation sampled during SMAPVEX12 covered a range from early emergence to full maturity, with averaged observed VWC ranging between almost 0 to over 4 kg/m^2. The study area also included a range of soil textures from coarse sand to very fine clay, allowing for the model to be evaluated on a full range of surface conditions. Figure 2.8 shows the distribution of observed field averaged VWC over the course of the campaign, for (a) all measurements and, (b) field averages per sampling date. More than a third (35.5%) of all individual samples and nearly a third (31.6%) of field averages were between 0 and 0.2 kg/m^2. These low values were generally due to the large number of bean fields in the study that exhibited low (< 0.5 kg/m^2) VWC for the majority of the study duration (Table 2.3). Vegetation sampling carried out during SMAPVEX12 was more detailed than many previous studies. Not only was there a wider variety of crops sampled during the campaign, but also the frequency and resolution of the sampling method was greater. During the CLASIC (Cloud and Land Surface Interaction Campaign) experiment, water content values were assumed constant for senesced winter wheat and pasture fields, while values for other crops were interpolated linearly with time (Bindlish, et al., 2009). The direct sampling of vegetation parameters through the duration of the campaign allowed for field measured values to be used for vegetation parameters for all dates with soil moisture and PALS data; whereas most previous experiments have relied on satellite derived NDVI for vegetation parameters (Colliander, et al., 2012). The NDVI was calculated for the SMAPVEX12 campaign, and showed large differences from the field measured VWC on some fields (data not shown).

2.4.1.3 Roughness and Soil Texture - Figure 2.9 shows the distribution of RMS heights on the 22 low altitude fields. With 20 of those fields measured having a value between 0.4 and 1.2 cm, the effect of roughness can be considered fairly uniform across fields in the study. Detailed soil texture analysis was performed on core samples retrieved from each field during the campaign, with more general texture information taken from soil survey data (Province of Manitoba, 2014). Particle size analysis done in the lab revealed a range of soil textures from heavy clay (>60% clay) to very sandy (>85% sand), with good agreement to the soil survey data. For simplicity, fields have been categorized using the more spatially-complete soil textures from the soil survey database in this work. A list of all measured roughness values can be seen in Appendix III.

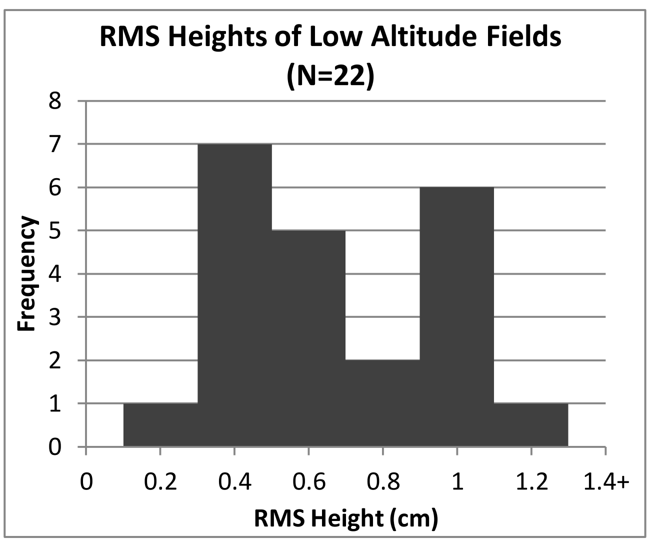

Figure 2.9- RMS Heights from 22 fields with low altitude data

2.4.1.4 Brightness and Physical Temperature - Brightness temperatures observed during the campaign had a range of ~150K for H-pol, and ~100 for V-pol. The extensive range of brightness temperatures corresponded to observed soil moisture from less than 5% to over 70%, though the highest values were removed as outliers. The range of T_B values during the SMAPVEX12 exceeded that of recent similar experiments **(Colliander, et al., 2012)**, which provided a unique opportunity to examine conditions outside the scope of previous work.
The physical temperature (T_{IR}) values used were retrieved from the aircraft simultaneous to measurements of brightness temperature. These measurements, along with their corresponding brightness temperature, were used to calculate the emissivity as in (1.2). While field measured temperature data were available, the aircraft measured field average temperature was used for the calculation because, a) aircraft temperature measurements coincided exactly with measurement of T_B and, b) an analysis of absolute difference between aircraft measured T_{IR} and ground measured T_s at 5cm found an average difference of 1.9K and a maximum of ~5K. The potential error in soil moisture estimation is low since the largest differences caused a change in emissivity of < 0.01 when placed into the model.

2.4.2 Distribution of data

Plots of the distributions of horizontally polarized emissivity (e_H) by field are shown in Figure 2.10. The outlying uncorrected emissivity values on fields 12, 51, 52 & 71 in Figure 2.10 were all recorded on the same sampling date (2012-06-12) when conditions were generally wetter across the study area. On three of those fields, the low outlying point moves into the expected range with vegetation correction, leaving the soybean field (12) as the only outlier. The point on field 12 was removed as an outlier due to its abnormally low emissivity value, and low number of contributing radiometer points (4) on that same date.

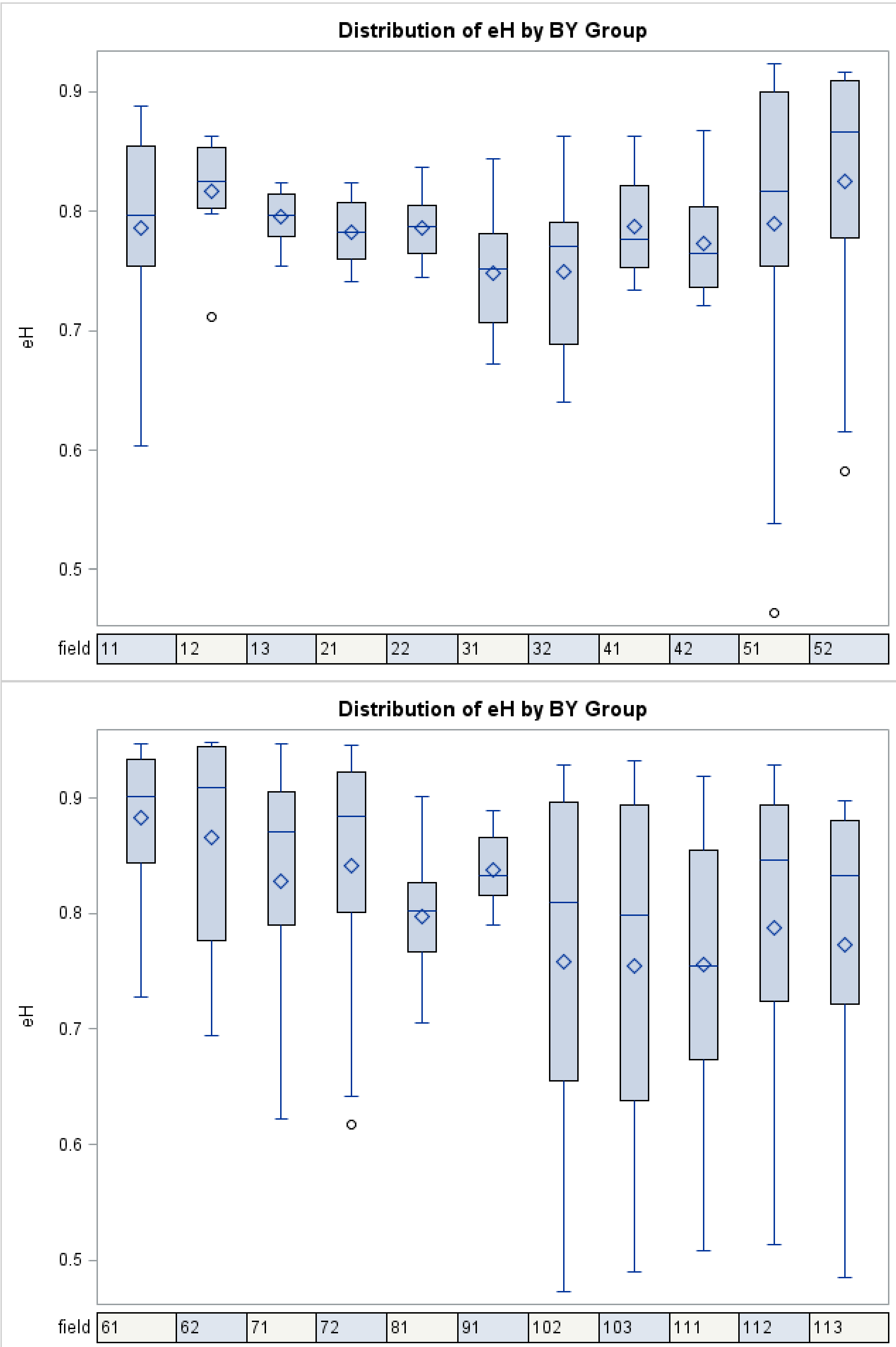

Figure 2.10 – Boxplots of the distribution of horizontally polarized uncorrected emissivity (e_H)

2.4.3 Tests of slope

Results from analysis of slope showed that most variations of the linear relationship were statistically significant at 95% confidence. Field-by-field relationships using all sampling dates with both soil moisture and horizontal emissivity data were all shown to be significant with the exception of two of the pasture fields and a soybean field. On one pasture field, the uncorrected H-pol emissivity was not significantly correlated with soil moisture; however the relationship was found significant with correction for vegetation. On the second pasture field and the soybean field, the relationships were not significant at any level of correction. Test scores and the corresponding slope can be seen in Table 2.5. Interestingly, the field-by-field relationships using vertically polarized emissivity were significant on all fields at all levels of correction with the exception of the same soybean field listed above. Due to the lack of significance on two of the pasture fields at H-pol, all three fields were removed from further regression analysis using horizontally polarized data, but were kept in the vertically polarized relationships.

With the removal of the outlying horizontal emissivity value on field 12 (soybean) as described previously in 2.4.2, the slope switched to a positive correlation in the moisture-emissivity relationship. The point, which fell at the low end of the emissivity range for that particular field, also represented the highest moisture conditions observed on that field during the campaign (~19%). Even with this outlying value included in the regression, the relationship was not significant for either polarization at 95% confidence. Due to this unrealistic relationship, a lack of significance in both polarizations, fewer sample dates than most fields and less than a full set of probe samples on most dates, this field was removed from all further regression analysis.

Linear relationships across multiple fields were found to have significant correlations. The overall regression for each emissivity value at horizontal polarization was found to have significant slope. The slope and R^2 of the overall regression at horizontal polarization improved with the removal of the measurements from the pasture fields. The slope and R^2 of relationships that included multiple rather than single fields are described in detail in section 2.4.5. Grouping measurements by VWC category showed significance for all three vegetation amounts. As with the overall regression, the horizontally polarized relationship for the low and medium VWC categories was improved with the removal of measurements from the pasture fields, with both slope and R^2 increasing for both emissivities.

Significance was also found when testing the slope of the relationship grouped by flight line. The relatively homogeneous eastern flight line also had a significant linear regression at each level of corrected emissivity. For the regression at horizontal emissivity, however, the western flight line was limited to a single field, since each of the other four fields were previously found to have a non-significant correlation and were removed from the aggregated regression.

Table 2.5- Results of tests for the significance of slope for horizontal polarization at α= 0.05.

Highlighted values are regressions with a slope not significantly different than 0 (i.e. S = 0)

Field	Crop	Line	n	Vegetated		Bare		Smooth	
				Slope	Prob	Slope	Prob	Slope	Prob
11	Beans	West	14	2.43	< 0.01	2.41	< 0.01	2.51	< 0.01
12	Beans	West	8	**0.83**	**0.23**	**0.82**	**0.23**	**1.09**	**0.24**
13	Pasture	West	15	**0.19**	**0.21**	0.59	0.21	0.63	< 0.01
21	Pasture	West	15	0.41	< 0.01	0.41	< 0.01	0.51	< 0.01
22	Pasture	West	15	**0.21**	**0.35**	**0.15**	**0.35**	**0.22**	**0.53**
31	Wheat	Central	12	0.54	< 0.01	1.19	< 0.01	1.31	< 0.01
32	Wheat	Central	11	0.53	< 0.01	0.78	< 0.01	1.23	< 0.01
41	W. Wheat	Central	11	0.31	< 0.01	1.34	< 0.01	1.88	< 0.01
42	W. Wheat	Central	13	0.32	< 0.01	0.90	< 0.01	1.17	< 0.01
51	Beans	Central	14	1.95	< 0.01	1.86	< 0.01	1.97	< 0.01
52	Beans	Central	16	1.48	< 0.01	1.38	< 0.01	1.88	< 0.01
61	Canola	Central	14	1.22	< 0.01	1.56	< 0.01	1.84	< 0.01
62	Canola	Central	7	1.75	0.01	1.58	0.01	1.72	0.01
71	Corn	Central	13	4.38	< 0.01	3.95	< 0.01	4.28	< 0.01
72	Corn	Central	15	2.36	< 0.01	2.32	< 0.01	2.45	< 0.01
81	Wheat	Central	10	1.11	< 0.01	1.53	< 0.01	1.76	< 0.01
91	Wheat	Central	14	0.60	< 0.01	1.18	< 0.01	1.58	< 0.01
102	Beans	East	16	1.01	< 0.01	0.99	< 0.01	1.11	< 0.01
103	Beans	East	16	0.90	< 0.01	0.88	< 0.01	1.00	< 0.01
111	Beans	East	13	1.47	< 0.01	1.45	< 0.01	1.62	< 0.01
112	Beans	East	15	1.60	< 0.01	1.58	< 0.01	1.71	< 0.01
113	Beans	East	15	1.28	< 0.01	1.25	< 0.01	1.55	< 0.01

2.4.4 The *b* parameter

Results from the optimization of the low altitude regression revealed that the slope of the relationship begins at a minimum at $b = 0.01$ and increases with increasing b on an approximately exponential curve. Meanwhile, the R^2 values rise to a peak before declining over the remaining values of b. Due to the steady increase in observed slope, the optimized b value was selected based on the maximum observed R^2 (Figure 2.11). As expected based on work by Crow et al (2005), the optimized value for H-pol was lower than that of V-pol, though the difference was more than that study suggested. A value of 0.06 for H-pol and 0.13 for V-pol were found to be optimal based on the criteria used. While the value for H-pol was somewhat lower than expected, the value for V-pol was very close to a previously reported mixed vegetation value for L-band of 0.12 (Njoku & Entekhabi, 1996; Mo, et al., 1982) adjusted up 10% as described in Crow et al (2005). The slope and R^2 across all b values can be seen in Table 2.6.

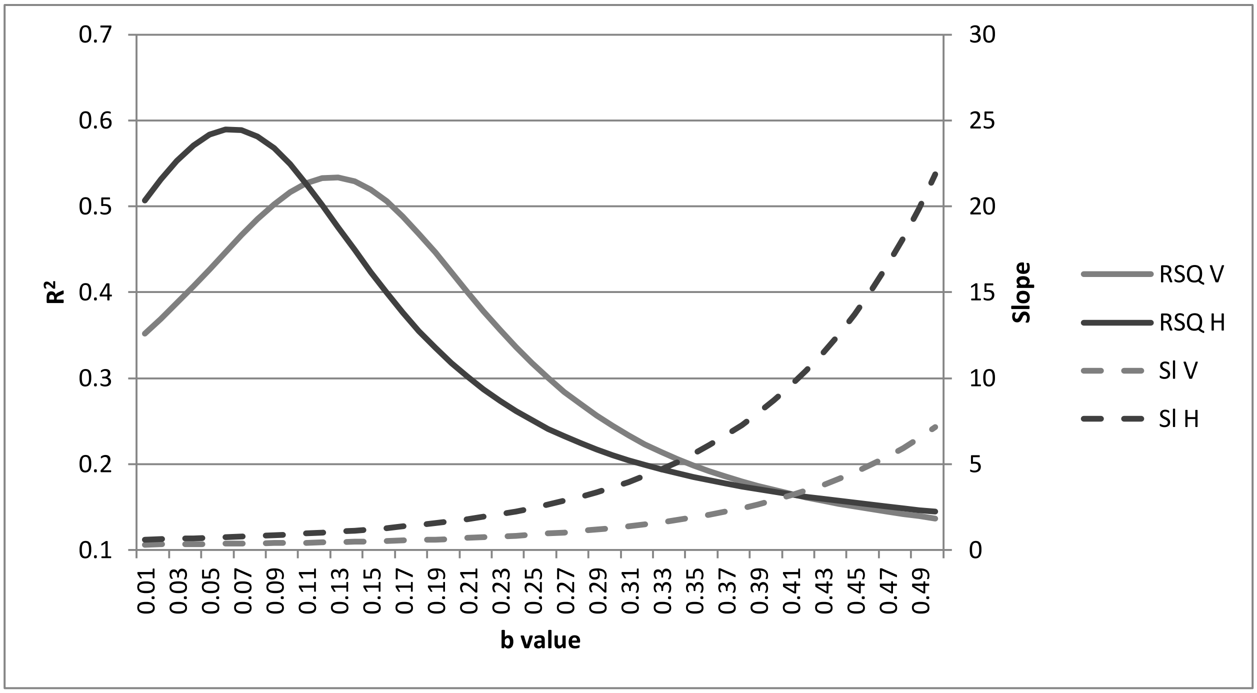

Figure 2.11 – Effect of increasing b values on the overall regressions.

Optimum value chosen based on peak of R^2 curve.

Table 2.6 – Results of the optimization of *b*

	Vertical		Horizontal			Vertical		Horizontal	
b	Slope	R^2	Slope	R^2	*b*	Slope	R^2	Slope	R^2
0.01	0.32	0.35	0.62	0.51	0.26	0.96	0.30	2.64	0.24
0.02	0.33	0.37	0.64	0.53	0.27	1.03	0.28	2.86	0.23
0.03	0.34	0.39	0.66	0.55	0.28	1.11	0.27	3.10	0.22
0.04	0.34	0.41	0.69	0.57	0.29	1.19	0.26	3.36	0.22
0.05	0.35	0.43	0.72	0.58	0.30	1.28	0.24	3.65	0.21
0.06	0.36	0.45	0.75	**0.59**	0.31	1.38	0.23	3.97	0.20
0.07	0.37	0.47	0.78	0.59	0.32	1.49	0.22	4.32	0.20
0.08	0.38	0.49	0.82	0.58	0.33	1.62	0.21	4.70	0.19
0.09	0.40	0.50	0.86	0.57	0.34	1.75	0.21	5.13	0.19
0.10	0.41	0.52	0.91	0.55	0.35	1.90	0.20	5.59	0.19
0.11	0.43	0.53	0.96	0.53	0.36	2.06	0.19	6.10	0.18
0.12	0.44	0.53	1.01	0.50	0.37	2.24	0.19	6.66	0.18
0.13	0.46	**0.53**	1.07	0.48	0.38	2.44	0.18	7.28	0.17
0.14	0.48	0.53	1.13	0.45	0.39	2.66	0.17	7.96	0.17
0.15	0.51	0.52	1.21	0.42	0.40	2.90	0.17	8.71	0.17
0.16	0.53	0.51	1.28	0.40	0.41	3.16	0.17	9.53	0.17
0.17	0.56	0.49	1.37	0.38	0.42	3.45	0.16	10.43	0.16
0.18	0.59	0.47	1.46	0.36	0.43	3.78	0.16	11.43	0.16
0.19	0.62	0.45	1.57	0.34	0.44	4.13	0.15	12.52	0.16
0.20	0.66	0.42	1.68	0.32	0.45	4.52	0.15	13.73	0.16
0.21	0.70	0.40	1.81	0.30	0.46	4.95	0.15	15.06	0.15
0.22	0.74	0.38	1.94	0.29	0.47	5.42	0.14	16.52	0.15
0.23	0.79	0.36	2.09	0.27	0.48	5.94	0.14	18.13	0.15
0.24	0.84	0.34	2.26	0.26	0.49	6.51	0.14	19.90	0.15
0.25	0.90	0.32	2.44	0.25	0.50	7.15	0.14	21.85	0.14

2.4.5 Sensitivity analysis

On about half of the fields (7 of 18 for horizontal and 11 of 21 for vertical), the sensitivity (slope) of the relationship between emissivity and observed soil moisture increased when vegetation and roughness effects were taken into account (i.e.: $S_0 < S_g < S_s$) (Table 2.7). On the remaining fields, however, bare surface sensitivity (S_g) was lower than the vegetated sensitivity (S_0). Previously, it has been shown that sensitivity to soil moisture should always be higher for a bare field than for a vegetated one (Du, et al., 2000). The reason why this was not the case for all fields in SMAPVEX12 is uncertain, however it is likely due to the generic correction parameters used for the fields that showed decreased sensitivity. By inverting the model to estimate brightness temperature from soil moisture, and in turn more accurately calculating vegetation opacity, this issue could likely be addressed; however, this step fell outside the objectives of this analysis.

On all fields, the final correction for roughness increased smooth surface sensitivity above the bare sensitivity (i.e.: $S_g < S_s$) (Figure 2.12). While the increase in sensitivity was observed on all fields, only 8 of the 18 fields exhibited a stronger relationship (greater R^2) with the application of the correction equations for roughness and vegetation at horizontal polarization. The improvement was marginally better for vertical polarization, where 9 of 21 fields showed an improved R^2.

The weakest relationships between soil moisture and observed emissivity were on the three pasture fields and the southern soybean field on the west flight line (Table 2.3– Fields 13, 21, 22 and 12). Three of these fields (12, 13 & 22) were previously found to have no significant correlation between soil moisture and horizontally polarized emissivity. The relationship was significant on the pasture fields with the vertically polarized emissivity, though the peak R^2 observed was 0.71. Weak correlation between soil moisture and emissivity on pasture fields was expected, as poor soil moisture sensitivity on bent and thatched grass fields has been found in the past (Jackson & Le Vine, 1996). Additionally, the pasture fields used in this study all contained mixed vegetation cover (patches of forest and brush) and areas of open water. The poor relationship observed on the soybean field was unexpected, given the general strength of the linear relationship on the other soybean fields in the study. However, as detailed in 2.4.3, the field included fewer than the normal number of soil moisture measurements, as well as the lowest number of sampling days of any of the fields included.

Examples of the individual field regressions can be seen in Figure 2.13 for a couple different fields at H-pol. Field 71 was a corn field that exhibited the highest sensitivity to soil moisture of any field measured. Field 41was planted with winter wheat and showed the largest improvement in sensitivity with the application of corrections for vegetation and roughness while also increasing the R^2 value.

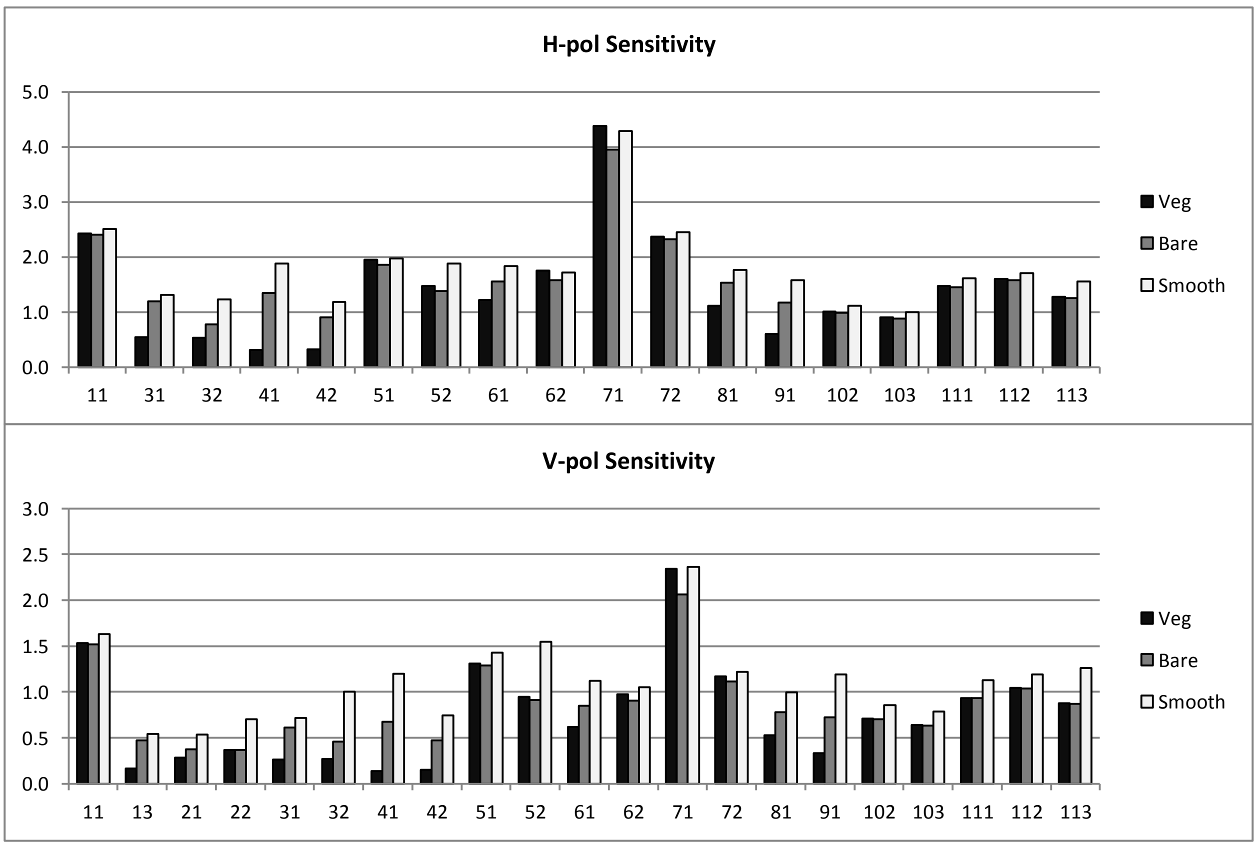

Figure 2.12- Graphs of sensitivity to soil moisture (slope) on field-by-field basis from equations in (2.1) Vegetated (a), Bare (b) and smooth (c).

Table 2.7- Summary of field sensitivities (S) and correlation coefficients (R^2) from equation (2.1)

Vegetated (Veg) from (a), rough (bare) from (b) and smooth from (c). R^2 for equations (2.1) and (2.1) are identical, shown here as "R^2 Smooth". Pasture fields 13, 21, 22 removed from H-pol due to lack of significance. Field 12 removed from both polarizations due to lack of significance.

	Vertical					**Horizontal**				
	Slope			R^2		Slope			R^2	
Field ID	Veg	Bare	Smooth	Veg	Smooth	Veg	Bare	Smooth	Veg	Smooth
11	1.53	1.52	1.63	0.84	0.84	2.43	2.41	2.51	0.82	0.81
13	0.17	0.47	0.54	0.31	0.71	[redacted]				
21	0.28	0.38	0.54	0.63	0.68					
22	0.37	0.37	0.70	0.44	0.40					
31	0.26	0.61	0.72	0.58	0.82	0.54	1.19	1.31	0.71	0.77
32	0.27	0.46	1.00	0.70	0.79	0.53	0.78	1.23	0.71	0.75
41	0.14	0.67	1.20	0.61	0.89	0.31	1.34	1.88	0.55	0.87
42	0.15	0.47	0.74	0.60	0.80	0.32	0.90	1.18	0.61	0.78
51	1.31	1.29	1.43	0.84	0.79	1.95	1.86	1.97	0.82	0.73
52	0.94	0.91	1.55	0.89	0.84	1.48	1.38	1.88	0.88	0.81
61	0.62	0.85	1.12	0.72	0.87	1.22	1.56	1.84	0.80	0.78
62	0.97	0.91	1.05	0.81	0.82	1.75	1.58	1.72	0.87	0.76
71	2.34	2.06	2.37	0.82	0.78	4.38	3.95	4.28	0.88	0.87
72	1.17	1.11	1.22	0.66	0.61	2.36	2.32	2.45	0.69	0.77
81	0.53	0.78	1.00	0.73	0.85	1.11	1.53	1.76	0.84	0.88
91	0.33	0.72	1.19	0.76	0.72	0.60	1.18	1.58	0.66	0.58
102	0.71	0.70	0.86	0.81	0.80	1.01	0.99	1.11	0.76	0.74
103	0.64	0.63	0.79	0.81	0.80	0.90	0.88	1.00	0.78	0.76
111	0.93	0.93	1.13	0.80	0.78	1.47	1.45	1.62	0.79	0.76
112	1.04	1.04	1.19	0.82	0.81	1.60	1.57	1.71	0.82	0.81
113	0.88	0.87	1.26	0.79	0.78	1.28	1.25	1.55	0.76	0.73
MEAN	0.74	0.85	1.11	0.71	0.77	1.40	1.56	1.81	0.76	0.78

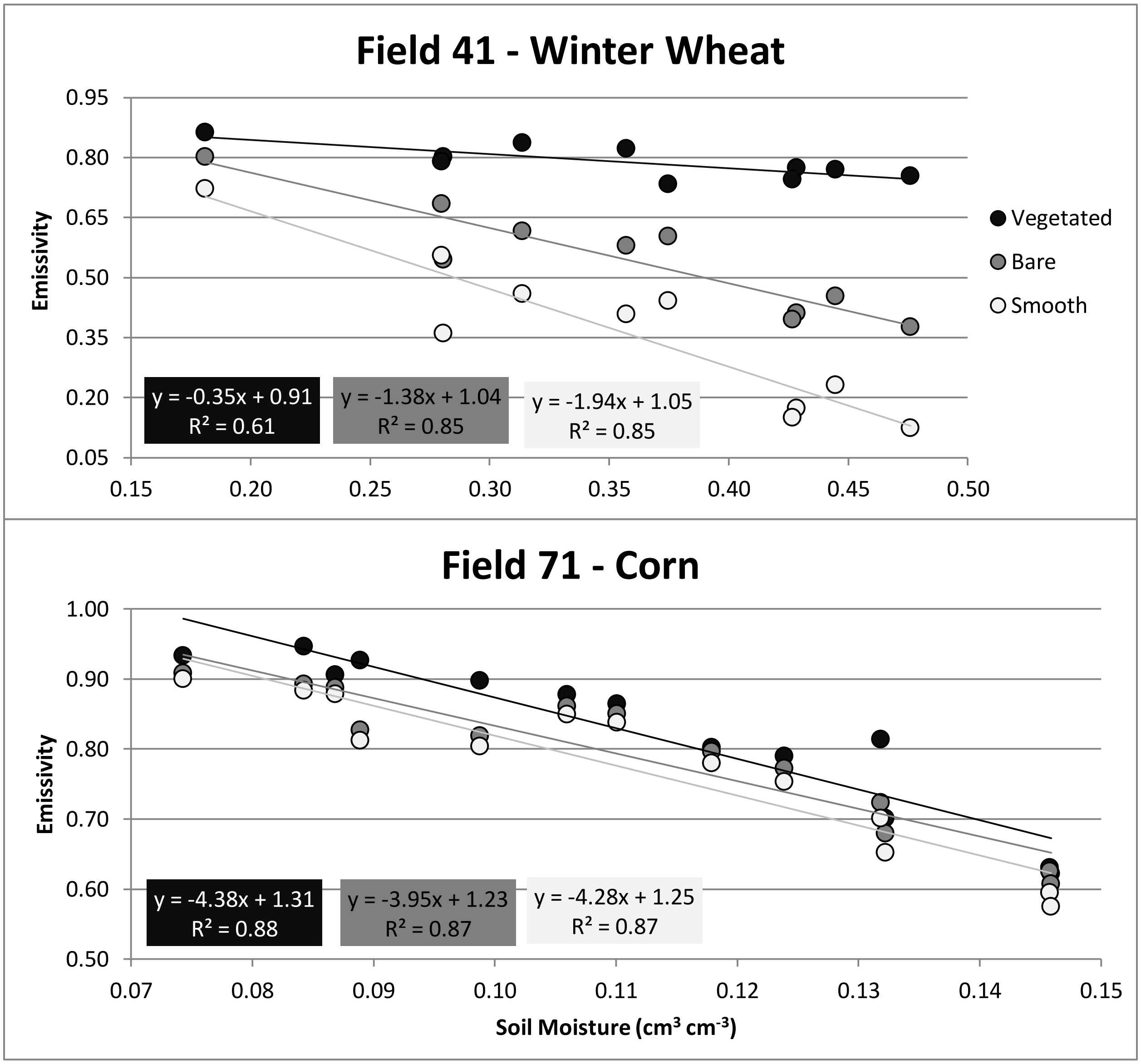

Figure 2.13 – Horizontally polarized emissivity linear relationships to volumetric soil moisture for two different fields.

Field 41 (top) showed the best improvement in slope and R^2 of any field, and field 71 (bottom) had the highest sensitivity, though had a slightly reduced R^2 with application of the correction equations.

2.4.5.1 Grouped Regression - The field-by-field analysis, summarized in Table 2.7 with examples in Figure 2.13, took the unique surface conditions on each field into account. Attempts to combine values from several fields consistently created a decreased sensitivity value and R^2 for the emissivity-soil moisture relationship. Plotting the relationship across all fields previously found to have significant correlation using equations in (2.1) gave considerably lower R^2 and sensitivity to soil moisture than was observed on any of the fields individually. Across multiple fields, the variable effects of vegetation and roughness mask the relationship between emissivity and soil moisture (Njoku, et al., 2002).

Attempts were made to group fields into more homogeneous groups in order to improve the relationship. An analysis of the eastern flight line is provided by way of example. This flight line covered five fields, all with soybean crops and all on clay soil. Thus the VWC and roughness values were very similar (Table 2.3 - Fields 102, 103, 111, 112 and 113). When the emissivity and observed soil moisture values from these five fields were combined for analysis using (2.1), the R^2 was reduced compared to the values from individual equations despite the relative homogeneity of both the soil and crops on these fields (Table 2.8). Figure 2.14 shows the linear relationship for all measurements along the eastern flight line using smooth surface emissivity.

Table 2.8- Sensitivity and correlation coefficients from (2.1) across eastern fields.

Bare field measurements <0.25 kg/m^2 VWC

	Vertical		Horizontal		
Field	S	R^2	S	R^2	n
102	0.86	0.80	1.11	0.74	16
103	0.79	0.80	1.00	0.76	16
111	1.13	0.78	1.62	0.76	13
112	1.19	0.81	1.71	0.81	15
113	1.26	0.78	1.55	0.73	15
All	0.90	0.73	1.17	0.68	75
All (Bare)	0.99	0.69	1.29	0.66	48

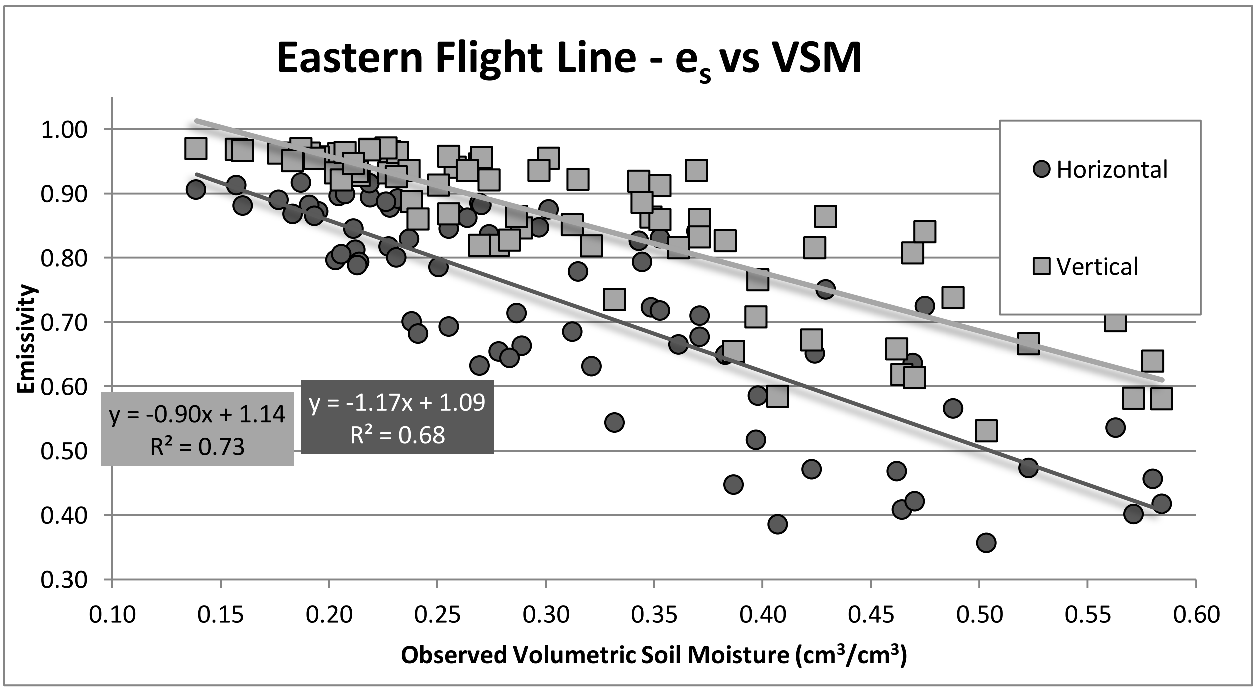

Figure 2.14 – Linear relationship between corrected horizontal and vertical emissivity and volumetric soil moisture for the eastern flight line from (2.1)

In another attempt to create more homogeneous groups for the linear regressions, all field measurements were grouped by VWC amount. Using uncorrected emissivity from (2.1) showed a decrease in sensitivity with increasing VWC in both polarizations. Table 2.9 shows the sensitivities and R^2 across all fields at varying levels of VWC. As was the case with field-by-field relationships, the horizontally polarized emissivity showed higher sensitivity than vertical, though both polarizations showed lower sensitivity than their average values from all individual field equations. Applying (2.1) for emissivity corrected for the effect of vegetation emission and attenuation improved the sensitivity to soil moisture. Interestingly, however, vegetation corrected sensitivity values increased with increasing VWC values in horizontal polarization, but peaked for the moderate VWC case for vertical polarization. Compared to the corresponding uncorrected (vegetated) values, both sensitivity and R^2 increased for both polarizations and at all VWC levels. The largest increase in sensitivity with the correction for vegetation contribution was for the high VWC case in both polarizations, as expected.

In an attempt to improve the relationship created by (2.1) on the relatively homogeneous eastern fields, the previously mentioned VWC groupings were applied, focusing solely on the low VWC measurements. When comparing the low VWC measurements to all measurements made on these fields, there were two notable differences. The slope of the relationship was higher for the measurements from the low VWC group than that calculated from all measurements along the flight line. Secondly, the R^2 actually declined when using only the low VWC measurements, meaning removing vegetation effects did not reduce the scatter in the relationship and that other ground variables have a considerable influence on the soil moisture – emissivity relationship (Table 2.8).

In general, on a field-by-field basis, linear relationships between soil moisture and emissivity were strong and improved with the use of field measured variables. However, field specific analysis is not feasible at large scales. The increased scatter observed in the relationship when combining relatively homogeneous soil and vegetation types presents a challenge to upscaling emissivity-soil moisture relationships to obtain accurate surface soil moisture measurements at the spatial resolution of the SMAP mission.

Table 2.9- Sensitivity (S) and R^2 for linear equations across all fields by VWC amounts. Vegetated uses (2.1) bare uses relationship in (2.1). Pasture fields removed from horizontal polarization due to lack of significant regression.

VWC Group	Emissivity	S	R^2	n
Low	Vegetated V-pol	0.44	0.40	102
Med		0.27	0.43	133
High		0.13	0.72	46
All		0.32	0.35	281
Low	Vegetated H-pol	0.65	0.38	79
Med		0.59	0.54	111
High		0.45	0.79	46
All		0.60	0.48	236
Low	Bare V-pol	0.44	0.39	102
Med		0.43	0.52	133
High		0.34	0.73	46
All		0.42	0.51	281
Low	Bare H-pol	0.64	0.37	79
Med		0.93	0.58	111
High		1.00	0.87	46
All		0.85	0.55	236

2.5 DISCUSSION

While the linear models in this work are simple and do not account for scattering effects of the vegetation canopy, the resulting relationships between emissivity and soil moisture were strong. The strength of the relationship was due largely to the landscape and vegetation homogeneity within each of the radiometer footprints. The uniformity of the contributing factors to each brightness temperature measurement used in this study was unique to aircraft based experiments (Colliander, et al., 2012; Njoku, et al., 2002; Jackson & Le Vine, 1996). Previous experiments involving aircraft retrieval have frequently had heterogeneous footprints, even at low altitudes. Generally, only truck based radiometer measurements have the same level of homogeneity as was available for SMAPVEX12.

The effectiveness of the corrections for vegetation and roughness were generally positive, however the extent to which they improved the relationship varied considerably. The two winter wheat fields included on the low altitude lines both showed considerable increases in both slope and R^2 with the application of the modeled emissivity values for vegetation and roughness effects. The improvement to the relationship was greater in horizontal polarization, where the slope increased from 0.31 on both fields to 1.88 and 1.17 with the modeled vegetation and roughness contributions. The R^2 also showed a marked increase, from 0.55 to 0.87 on one field and 0.59 to 0.79 on the other. An improvement was also observed in the vertically polarized relationship, though as expected, the increase was not as large. With the exception of one pasture field at vertical polarization, all individual field relationships showed a strong or moderate R^2 value.

The corrections used for vegetation were not specific to this experiment, and were taken from other studies using the same wavelength over the same crops. While empirically solving for vegetation parameters (such as vegetation opacity [τ]) might have improved the corrections, this was not a goal of this work. The objective was to examine the soil moisture – emissivity relationship, and the effect of existing methods of correction on it. Furthermore, large-scale studies often have not had access to the same highly detailed ground measured variables, and have been forced to rely on landscape averages or estimated values. The data gathered during SMAPVEX12 perhaps represents the "best case" scenario for applying these averages to such uniform footprints.

Several model parameters used in the correction of emissivity were ignored for these data, primarily in order to simplify the relationship between soil moisture and radiometer observed brightness temperature. The removal of the scattering effects from vegetation (ω) correction has precedent in several other L-band studies, with a value generally less than 0.02 (Ulaby, et al., 1983; Jackson & Schmugge, 1991); its removal should have a minimal effect on the final relationship. Roughness effects were also simplified, and while differing effects of polarization were included in the model in (1.7), no attempt was made to further investigate the angular effect on roughness through the value of the parameter N_p. Furthermore, polarization mixing effects were ignored in roughness corrections, as this has also been found negligible at L-band (Escorihuela, et al., 2007; Wigneron, et al., 2001).

Smooth soil reflectivity was calculated from radiometer observed brightness temperature, and no inversion of the tau-omega model was attempted. While it would have been possible to calculate the specular reflectivity of the soil surface using the Dobson et al (1985) mixing model from field measured parameters, the goal of this work was to compare observed brightness temperature by the radiometer to high resolution ground measured soil moisture.

With the exception of only a few fields, the use of the linear regression showed significant response in emissivity to changes of soil moisture on an individual field basis. With access to limited data on conditions in the field, these linear equations could be used to estimate soil moisture conditions from observed emissivity. These estimations would be improved with knowledge of the vegetation and roughness conditions on a field-by-field basis, but are not invalidated with the use of a more general parameterization of these conditions.

The resolution of these data leads to the accuracy of the linear relationship. Each field based regression was affected by a single vegetation type and (assumedly) uniform roughness conditions. While remaining significant, regressions that included multiple fields exhibited a considerably weaker relationship and sensitivity to soil moisture changes. The usefulness of a linear regression in relating soil moisture to emissivity across larger areas with measurements of heterogeneous vegetation, soil and contributing area to brightness temperature will be investigated in the next chapter.

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3 SOIL MOISTURE, VEGETATION AND SURFACE ROUGHNESS IMPACTS ON HIGH RESOLUTION L-BAND MICROWAVE EMISSIVITY FROM CROPPED LAND AT SECTION SCALE

3.1 ABSTRACT

High altitude overpasses by the radiometer recorded brightness temperature daily on 50 ground measured fields. The flight lines for these passes were arranged in a northwest-southeast orientation and provided coverage over the majority of the study area. Due to the spacing between flight lines, the boresight points did not consistently fall within measured fields. Using legal section boundaries, brightness temperatures were applied to each section using a 1500m diameter circle around the centre point of each section. Emissivity was calculated the same as the previous chapter and corrected for roughness using parameters averaged across the study area. Vegetation correction was carried out using an optimized *b* value from all observed fields. Much like the low altitude regressions, individual section regressions showed a good correlation between moisture and emissivity. Tests of significance of slope found most regressions had significant response to changes in soil moisture at 95% confidence. Attempts were made to predict soil moisture values from the high altitude observed emissivity values using the low altitude regression parameters for slope and intercept from various aggregated regressions. Resulting root mean square error for the moisture predictions was calculated, and showed higher than desirable values in all aggregated regression estimations.

3.2 INTRODUCTION

Passive remote sensing requires a much larger footprint than its active counterpart, potentially orders of magnitude greater from the same observation platform. The difference is due to the faint emission of microwave energy from the earth's surface being measured by passive systems, rather than the stronger output signal from active systems that "illuminate" the target and measure the backscatter. For the SMAP satellite, the active system has an observation footprint of approximately 3x3 km, whereas SMAP's passive sensor has a resolution closer to 30x30 km (Entekhabi, et al., 2012). In terms of soil moisture retrieval, this larger footprint means that there are considerably more heterogeneous ground conditions within a single pixel with passive sensors. This heterogeneity leads to an increased mix of influences from surface factors, such as soil and vegetation. Each of these factors may vary on different scales both smaller and larger than the observation scale, and each must be aggregated or averaged to the scale of the radiometer footprint. Soil properties such as soil texture and structure, for example, can vary greatly within a single field. Vegetation and roughness effects will vary at a field scale, depending on management practices. Larger scale effects such as topography and weather, will affect areas the size of watersheds or larger (Crow, et al., 2005). Each of these factors will affect the surface soil moisture content both spatially and temporally.

Due to the highly variable nature of surface soil moisture, these large footprints also include substantial differences in moisture content across the area. The mixture of soil and vegetation conditions along with high variability in soil moisture poses a problem for the accuracy of large scale and satellite based soil moisture retrievals (Merlin, et al., 2008). When possible, contributions from within the footprint can be broken down by cover type, if the fractional cover inside the pixel is known (Wigneron, et al., 2007).

Despite the previously mentioned difficulties with large-scale soil moisture retrieval, there have been numerous satellite based passive soil moisture measurement platforms. These satellites include the European Space Agency's SMOS (Soil Moisture Ocean Salinity) satellite (Crow, et al., 2012; Montzka, et al., 2013), AMSR-E (Advanced Microwave Scanning Radiometer – EOS [Earth Observational System]) on the Aqua satellite (Champagne, et al., 2010) as well as a variety of other satellites that have the capability of passive measurements in microwave wavelengths.

Generally, at observation scales typical of high altitude retrieval, the only vegetation information available is retrieved via the Normalized Difference Vegetation Index (NDVI) (Anderson, et al., 2004). NDVI is calculated remotely using the red (R, ~0.6 µm) and near-infrared (NIR, ~0.8 µm) bands as: $NDVI = (NIR - R)/(NIR + R)$. In the case of SMAPVEX12, however, vegetation was measured *in situ* by field teams at somewhat regularly spaced time intervals. The field sampling of vegetation allowed for a more direct approach in calculating vegetation water content on fields. Rather than using remotely sensed estimates, point measurements were upscaled to field level to create average vegetation water content for each field. Combined with high spatial resolution soil sampling, the available ground measured data from the SMAPVEX12 campaign was unprecedented among similar experiments (Colliander, et al., 2012; McNairn, et al., 2015; Magagi, et al., 2013).

The resolution of soil moisture sampling was also higher than has generally been available for high altitude studies. Access to daily field-scale measurements of soil moisture allowed for a much more accurate estimate of soil moisture over the study area, rather than relying on single point measurements from large in situ networks (Crow, et al., 2005).

3.2.1 Objectives

Results from the low altitude radiometer measurements presented in Chapter 2 showed good correlation to field measured soil moisture at the resolution of a single field. These relationships were based on soil moisture sampling from single fields and radiometer footprints that fit within the field of interest. The highly homogeneous conditions that contributed to the brightness temperature, soil moisture and vegetation conditions allowed for a simple linear regression to adequately describe the relationship with a good degree of accuracy. While it is expected that the relationship between soil moisture and emissivity will remain linear in nature at any scale of observation, the impact of larger areas with less homogeneous conditions on this relationship will be examined in this chapter.

Relationships for aggregations of several fields at low altitude remained linear, however an increased number of points in the relationship lead to increased spread in emissivity values at the higher end of the moisture spectrum. A similar weakening relationship is expected for aggregations with the high altitude measurements. However, it is also anticipated that on a section by section basis, the limited number of measurements and higher degree of homogeneity within a single section will keep the relationship stronger.

The objectives of this chapter are to:

1) Assess the strength of the linear relationship between soil moisture and emissivity using coarser SMAPVEX12 high altitude resolution remotely sensed data and field measured values;
2) Examine the effect of corrections on heterogeneous footprints using existing models for vegetation and roughness on the relationship; and

3) Investigate the efficacy of using low altitude regression parameters to estimate large scale soil moisture.

3.3 METHODS

3.3.1 Aircraft Data

The area used for the high altitude retrieval was the same as the area used for the low altitude retrieval discussed in chapter 2. The high altitude PALS data gathered during SMAPVEX were retrieved along eight flight lines parallel to the experiment boundary, oriented northwest-southeast. These flight lines covered 50 test fields on the ground, and were always flown after the low altitude lines, closer to noon. The aircraft flew at an altitude of ~3km, with the same beam width and look angle (20° and 40°, respectively) as the low altitude passes. This configuration created a ground footprint of approximately 1500m. Figure 3.1 shows the study area with high and low altitude flight lines, along with test fields and sections.

On each day that the radiometer was flown on the high altitude lines, there were generally between 100000 and 150000 points of radiometer data, with a maximum of 183000 on one date due to a duplicated flight line. Each point corresponded to the centre of the boresight of one radiometer measurement. As was the case for the low altitude data, each point had an associated brightness temperature value in both horizontal and vertical polarization, as well as a thermal infrared surface temperature and a time code. Due to the larger footprint of the high altitude data, the flight lines did not always pass directly over the sampled fields on the ground as they did with the low altitude lines. In order to apply observed brightness temperature measurements to the study fields, the PALS measurements had to be gridded. Rather than set up an arbitrary

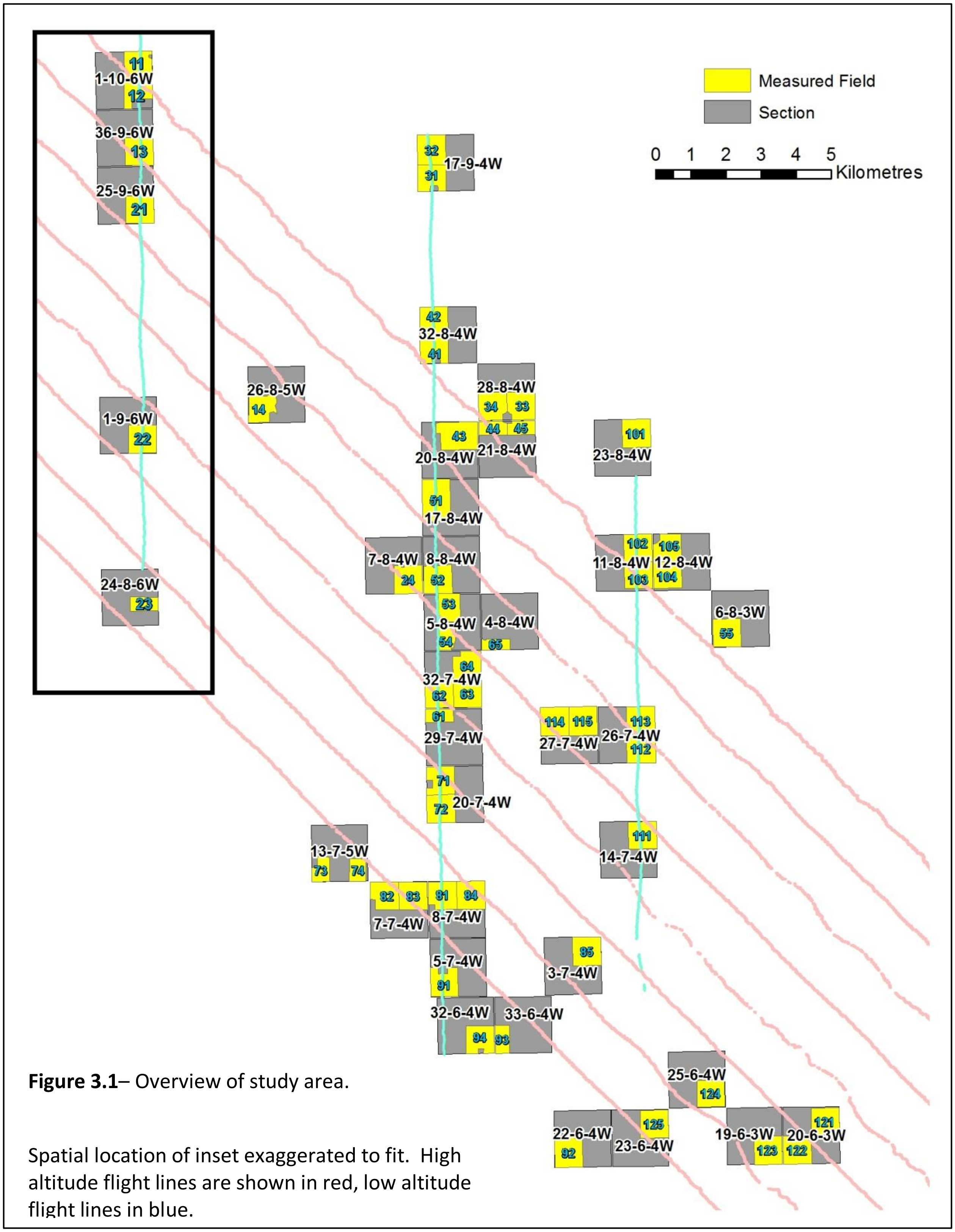


Figure 3.1– Overview of study area.

Spatial location of inset exaggerated to fit. High altitude flight lines are shown in red, low altitude flight lines in blue.

sampling grid covering the entire study area that may have left sampled fields in multiple grid cells, the boresight points were applied to the legal section grid. Sections are one square mile (~1600m on each edge), and generally contain four individual quarter sections (fields), although they can also consist of a smaller number of larger fields or a larger number of smaller fields.

Using GIS software, each section with at least one of the study fields inside it was extracted from the larger section grid. This process created 35 unique sections with ground measured soil moisture, vegetation water content and roughness representing at least 25% of its total area. The centre point of each of the 35 sections was calculated in the GIS software and then buffered to a distance of 750m, to create a 1500m diameter circle within each section. Any PALS boresight points that fell within this circle were applied to the average T_B for the respective day (Figure 3.2; Appendix II). The purpose of this step was to reduce the contribution of external areas to the average T_B values for the section, in the same way the internal buffer was applied to fields for the low altitude data. The 1500m diameter also closely approximates the actual footprint of the radiometer at the high altitude, and helps correct for the slight size difference between the radiometer footprint and section grid (1500 and 1600m, respectively). Table 3.1 summarizes the sections with both brightness temperature data and corresponding soil and vegetation measurements.

The use of the legal section grid to apply brightness temperature measurements to the fields was done for several reasons. Firstly, slight variations in the actual flightpath of the aircraft meant that the spatial location of boresight points varied from day to day and did not always cover the same fields. The slight variations in location of the points also meant that gridding the points directly would cause the resulting grid cells to shift on each sampling date, thereby introducing spatial error into the model. Secondly, the use of the section boundaries insured that the test fields on the ground would always be completely inside one grid cell when applying brightness temperature, and removed the necessity of applying ground measured soil moisture in the fields to multiple grid cells. Finally, the section grid is sufficiently comparable in size to that of the radiometer footprint at high altitude to allow a very similar method to be applied to the handling of the data at high altitude as was done with the low altitude.

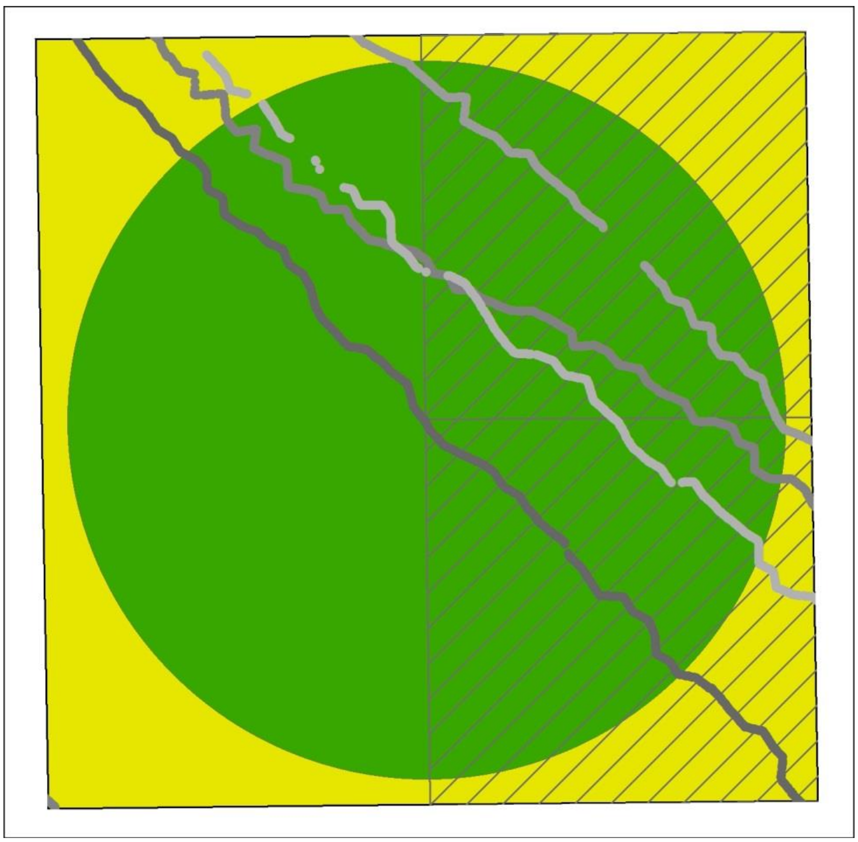


Figure 3.2 – Example of high altitude data on a section.

Grey lines represent four different flight dates.
Only points that fell within inner green circle were applied to the section on each date. Points in the outer yellow area were considered not representative of the section.
Hatched area shows position of ground measured fields within the section.

Table 3.1 – Summary of sections with high altitude data.

Highlighted test field numbers also had associated low altitude measurements

Section Name	Average Soil Moisture	Average VWC	MAX VWC	VWC Range	Test Field(s)	Crop(s)
1-10-6W	0.2198	0.017	0.225	0.208	**11, 12**	Soybean x2
11-8-4W	0.5780	0.022	0.585	0.564	**102, 103**	Soybean x2
13-7-5W	0.2436	0.835	2.613	1.777	73, 74	Wheat x2
14-7-4W	0.3972	0.045	0.900	0.855	**111**	Soybean
17-8-4W	0.2886	0.185	2.296	2.111	**51**	Soybean
19-6-3W	0.3718	0.038	0.628	0.591	123	Soybean
1-9-6W	0.3425	0.218	0.272	0.090	**22**	Pasture
20-6-3W	0.4531	1.348	3.408	2.060	121, 122	Forage, Canola
20-7-4W	0.1645	0.049	3.319	3.271	**71, 72**	Corn x2
20-8-4W	0.4336	2.158	2.771	0.742	43	Oats
21-8-4W	0.4876	1.934	2.759	0.826	44	Wheat
23-6-4W	0.3525	3.821	14.899	11.077	125	Canola
24-8-6W	0.3371	0.321	0.479	0.234	23	Pasture
25-6-4W	0.3748	2.835	8.118	5.284	124	Canola
25-9-6W	0.3666	0.431	0.526	0.172	**21**	Pasture
26-7-4W	0.4150	0.030	0.527	0.498	**112, 113**	Soybean x2
26-8-5W	0.1683	0.107	0.841	0.745	14	Soybean
27-7-4W	0.3383	0.026	2.726	2.700	114	Soybean
29-7-4W	0.2153	1.092	3.558	2.467	**61**	Canola
32-7-4W	0.2212	0.090	1.428	1.338	**62**, 63, 64	Corn/Canola, Soybean x2
33-6-4W	0.2971	0.131	3.292	3.161	93	Corn
36-9-6W	0.3580	0.266	0.370	0.313	**13**	Pasture
3-7-4W	0.3954	1.523	2.775	1.252	85	Wheat
4-8-4W	0.3871	1.358	2.474	1.117	65	Wheat
5-7-4W	0.2273	1.813	3.281	1.467	**91**	Wheat
5-8-4W	0.2677	0.090	3.861	3.771	53, 54	Corn x2
7-7-4W	0.2949	0.076	2.826	2.750	82, 83	Soybean, Corn
7-8-4W	0.1816	0.077	3.199	3.122	24	Corn
8-7-4W	0.2599	0.844	2.061	1.217	**81**, 84	Wheat, Canola
8-8-4W	0.3156	0.117	2.143	2.026	**52**	Soybean

3.3.2 Field Data

3.3.2.1 Soil and Vegetation - Soil and vegetation were sampled along two transects of eight locations each in the chosen fields around the experiment area. Soil was sampled at all 16 locations, vegetation at just three of the points, though the relative locations of the points were consistent on all fields. A detailed description of field sampling methods is given in 2.3.3. Sub section heterogeneity was ignored, and each section had the averaged ground measured values from all measured fields within the grid cell applied to it for each day that ground data were available. Each section included had between 1 and 3 measured fields within its area, and daily section averaged soil moisture was calculated from the average of all measured sites.

Vegetation measurements were handled the same way, with the average vegetation water content from all sites on the section used to calculate an average VWC for the whole section on each sampling day. In several cases this involved averaging multiple crop types, but no attempts were made to model the distribution of water content across sections with multiple measured cover types. Furthermore, the correction for vegetation effects on the high altitude brightness temperature used a single value for *b* across all sections and fields.

Values for the *b* parameter used for the vegetation correction for high altitude were taken from an optimization routine run using the low altitude data. The soil moisture to emissivity relationship was calculated using all low altitude measurements (excluding pasture fields), and the slope and R^2 of the relationship was recorded. Then the correction for vegetation was applied for all measurements using a single *b* value. The *b* value used was iterated between 0.01 and 0.50 in increments of 0.01, and the slope and R^2 for the relationship was recorded at each value. The optimum value for each polarization was chosen based on peak R^2.

3.3.2.2 Roughness - Roughness measurements were done with a pin board profiler at two sites per field. The surface profile was analyzed and the RMS of surface heights and the correlation length were calculated from the profile. Whereas individual field averages were used for the low altitude profile, corrections for roughness at high altitude were done using an average of RMS heights across all fields measured during SMAPVEX12. Since roughness measurements were done parallel to the flight line of the sensor, the measurements for high altitude were done at an orientation of ~315° which was a different angle than those for low altitude data. The roughness measurements were done along a line using three one metre long measurements with the profile board.

Roughness calculations for the high altitude flight data were done using a single surface height value across the entire region. The RMS value used was the mean observed value across all 55 agricultural fields. The average height observed was 1.07 cm, which translated to a roughness parameter value of 0.39 when calculated by equation (1.6). The use of a single value for roughness was done for simplicity, and due to the large areas contributing to the observed brightness temperature that were not measured for roughness. The assumption was that an averaged value will adequately represent contributing areas that were not measured. A list of all measured roughness values can be seen in Appendix III.

3.3.2.3 Optimized *b* - Vegetation effects on the high altitude brightness temperature were calculated through an optimization that was run on the low altitude data described in 2.3.6.2. The optimization calculated the vegetation parameter *b* based on the maximum R^2 from the low altitude relationships. A *b* value of 0.06 for horizontal and 0.13 for vertical polarization was found to create the strongest relationships based on peak R^2. Figure 2.11 shows the results of the optimization, with the corresponding slope and R^2 at each value of *b*.

3.3.3 Tests of significance

Tests of the significance of the linear regression were performed using statistical software (SAS 9.3). A regression procedure (proc reg) was run to determine the t-score of the slope of each regression on a section-by-section basis as well as for various aggregated regressions. Slopes found to be not significantly different than 0 at 95% confidence were removed from further analysis. Regressions found significant were rated as 'strong', 'moderate' or 'weak' using the criteria of Snedecor and Cochran (1980) according to the R^2 value. A value of >0.75 was considered strong, >0.50 was moderate and ≤0.50 was weak.

Distribution of the data and outliers were examined using a second procedure (proc univariate) to create boxplots of the various levels of corrected and uncorrected emissivities on each section. Data points found to remain outside the expected range of emissivities on any given section at more than one stage of correction were removed as outliers.

3.3.4 Estimates of Soil Moisture

Using the linear relationships established for the low altitude measurements described in the previous chapter, estimates of soil moisture were made for the high altitude observed emissivity. The relationships described in (2.1) were inverted, in order to solve for soil moisture using the relevant slope and intercept from the low altitude relationships with the corresponding high altitude emissivity using:

$$m_{cP}^{\mathrm{HI}} = l_{cP}^{\mathrm{LO}} * e_{cP} + b_{cP}^{\mathrm{LO}} \qquad (3.1)$$

Where:

m^{HI} is high altitude estimated soil moisture

e is high altitude observed emissivity

l^{LO} and b^{LO} are slope and intercept of low altitude regression, respectively.

Subscript c denotes correction (vegetated [0], bare [g], or smooth [s])

Subscript P is polarization (H or V)

This estimation was performed for each of the aggregations previously described (VWC groups, flight line, overall) and at each polarization. The root mean square error (RMSE) for each of these regressions was calculated, and the predicted vs. observed moisture from the high altitude retrieval was plotted.

3.4 RESULTS

3.4.1 Parameters During the Campaign

Vegetation sampled during the SMAPVEX12 campaign ranged from bare to fully mature. The corresponding range of VWC values observed from field sampling was almost 15 kg/m^2, where the highest values were recorded on fully mature canola fields. Figure 3.3A shows the distribution of individual site VWC measurements during the experiment. More than half (699) of all vegetation samples were at the extreme ends of the VWC range; below 0.50 kg/m^2 or above 10.0 kg/m^2. This distribution provided a good contrast of vegetation conditions and allowed for a thorough analysis of nearly bare fields. The large number of samples recorded under 0.50 kg/m^2 is broken down further in Figure 3.3B, which shows a significant portion of

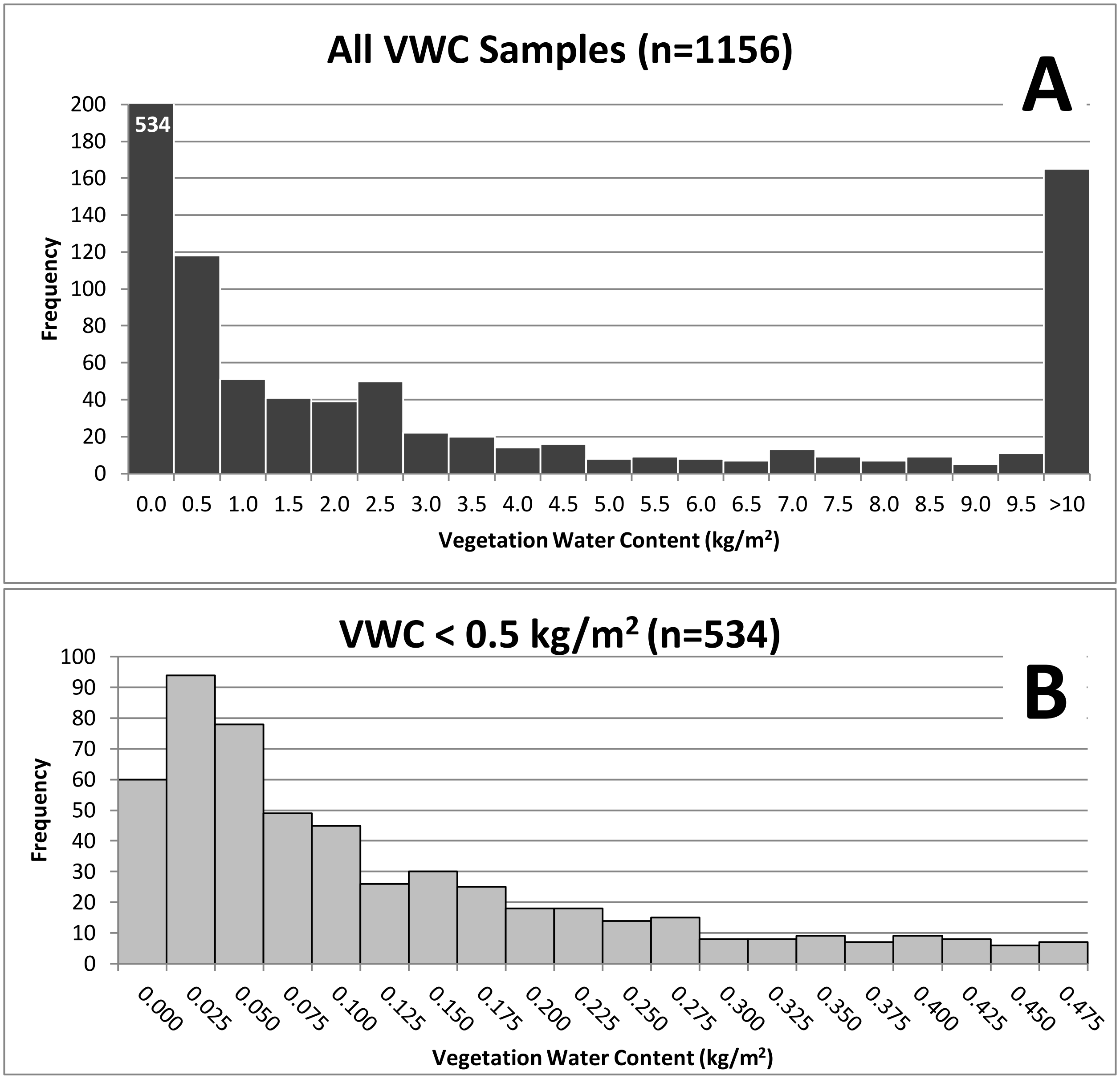


Figure 3.3 – Distribution of individual vegetation samples during SMAPVEX12

A) All samples. B) Break down of samples in 0-0.5 kg/m^2 group

those observed values that were very near bare field conditions (<0.25 kg/m^2).

Field sampling was carried out across the full spectrum of soil textures, from very fine clay (60% clay) to very coarse sand (80% sand). The distribution of the soil textures across the area changed from very coarse in the northwest to very fine in the southeast, with the transition occurring within only metres in parts of the region. This sharp transition is the result of an ancient lake bed and beaches in the region, and was one of the factors involved in choosing the region for the campaign.

Soil moisture values for each section were the averages for all measured fields within the section. Even with increased aggregation of soil moisture measurements, the distribution of observed moisture values for the high altitude data was very similar to those observed for the individual

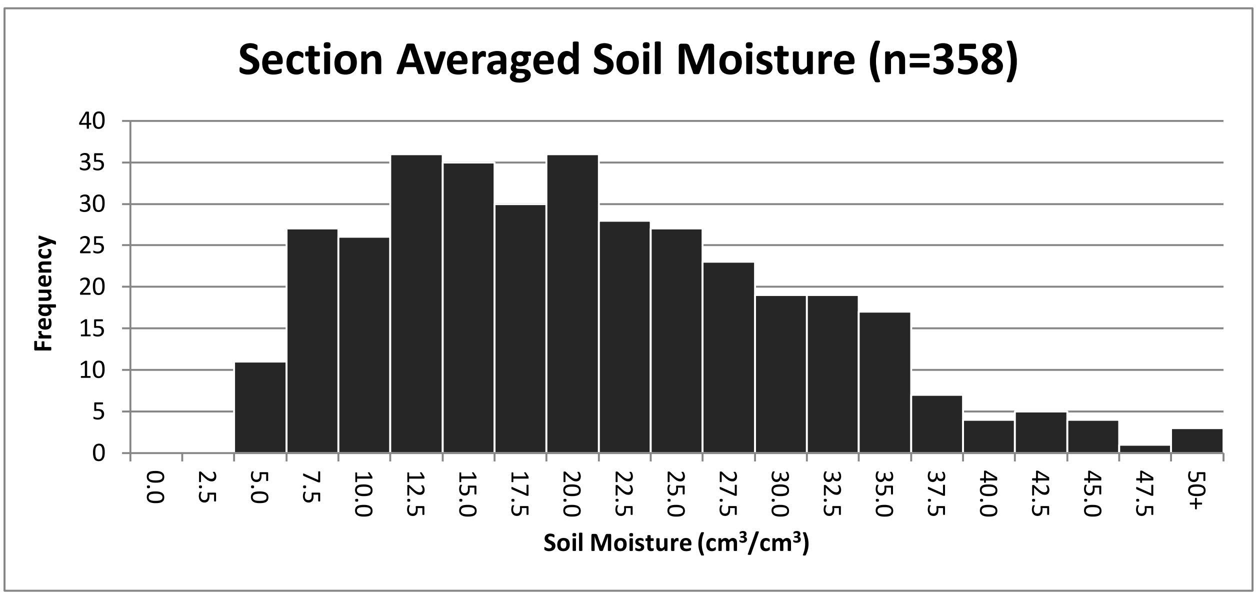


Figure 3.4 – Section averaged soil moisture from all sections with high altitude data

Sections and dates without radiometer data not included in average fields at low altitude. This is due, in part, to numerous sections containing only a single measured field. The distribution of section averaged soil moisture can be seen in Figure 3.4.

3.4.2 Radiometer Measurements

The observed range of individual brightness temperature measurements from the high altitude flight lines was ~150K for horizontal and ~100K for vertical. These ranges in brightness temperatures corresponded to observed individual soil moisture values in the ground ranging from essentially 0 to 60%. These observed ranges of brightness temperatures decreased when averaged across the section grid, however they still represented a wider range of conditions than had been observed in previous studies (Colliander, et al., 2012).

The spatial location of the flight line varied day to day, and occasionally caused a section that was sampled on one day to be completely missed on another. While the gridding system used in this work did not take into account the location of the flight line on any given sampling day, the effect of this variation cannot be ignored. The use of 1500m diameter "inside" zones within each section filtered out boresight points that fell too near the edge of the section and would not have adequately represented emission from the fields of interest. However, the contribution to brightness temperature across the footprint is not uniform, and it is possible that surface variations within the footprints could be responsible for some of the irregularities observed in the linear relationships.

3.4.3 Significance of the Relationship

The tests for significance of the linear regressions yielded some interesting results. At both polarizations, there was only one individual section regression that did not have a significant slope at $\alpha = 0.05$. The section, labeled 1-9-6W (Table 3.2), was located on the western low altitude flight line and contained a single test field with pasture vegetation. The radiometer response to soil moisture for this field was previously found to be not significant at horizontal polarization for the low altitude regression.

Contrary to the result from the tests of significance for the low altitude data, analysis of slope for the high altitude data on a section-by-section basis found a greater number of significant relationships at horizontal polarization than vertical. The only section regression to not have a significant relationship at horizontal polarization is described above. For the vertically polarized data, the same section plus an additional three sections were found to have a non-significant soil moisture-emissivity relationship. On one section, the relationship was significant for uncorrected vertical emissivity, but non-significant for vegetation and roughness corrected vertical emissivities. This section (labeled 33-6-4W in Table 3.2), contained a single sampled field which was planted with corn. The deterioration in the relationship with the application of the correction equations is likely the result of a large difference between the sampled vegetation on the test field, and the vegetation conditions on the unsampled surrounding fields, however the vegetation conditions on the rest of the section are not known. The relationship for horizontally polarized emissivity was significant on this section; however the relationship did weaken with the application of corrections for vegetation and roughness, again suggesting a large degree of heterogeneity on the section.

3.4.4 Sensitivity Analysis

On a section-by-section basis, the moisture-emissivity relationship was strong or moderate (based on R^2 values), with few exceptions. Two sections (referred to as 23-6-4W and 25-6-4W in Table 3.2), both located in the southern part of the study area and containing a single test-field planted with canola, exhibited abnormal relationships. The test-fields in these two sections recorded far higher than normal VWC amounts, with values above 14 kg/m^2 and 8 kg/m^2. These extreme VWC amounts caused the vegetation corrections to model emissivity values well below the expected range, including (erroneous) negative values. These results were not unexpected, since the VWC limit for observing soil emission through vegetation at L-band has been previously estimated at 5 kg/m^2 (Njoku & Entekhabi, 1996). While the uncorrected relationships on both sections were reasonable, the corrected relationships were not valid and the sections were removed from further analysis.

Excluding the exceptions listed previously, the remaining 28 sections showed generally strong soil moisture/emissivity relationships. Eleven of the sections showed an increase in R^2 in each polarization with the application of the correction for vegetation, with eight of those sections having the increase in both polarizations. Thirteen sections had a strong R^2 value, while another 11 showed at least a moderate relationship (Snedecor & Cochran, 1980). The slope of the relationship increased with vegetation correction (i.e. $S_0 < S_{g)}$ on 16 of 28 sections in horizontal, and 17 in vertical (Table 3.2). While an increase in sensitivity should be expected with the correction for vegetation (Du, et al., 2000), the relative number of sections (fields) that exhibited an increased sensitivity was greater for the high altitude data than with the low altitude data (Section 2.4.3). Regardless of the effect of the vegetation correction, the slope improved on all sections in both polarizations with the application of the correction for roughness ($S_s > S_g$). This general improvement was the result of the universal correction for roughness used in the model.

Table 3.2 – Summary of sensitivity (slope) and R^2 for all high altitude sections.

Crossed out sections removed from analysis due to abnormal relationships resulting from extreme VWC values

	Horizontal					**Vertical**				
	Slope			**R^2**		**Slope**			**R^2**	
Section	Veg	Bare	Smooth	Veg	Smooth	Veg	Bare	Smooth	Veg	Smooth
1-10-6W	1.010	0.998	1.255	0.677	0.684	0.366	0.353	0.522	0.206	0.198
11-8-4W	0.641	0.620	0.780	0.843	0.811	0.419	0.409	0.606	0.912	0.901
13-7-5W	1.938	2.550	3.208	0.836	0.836	0.981	1.578	2.334	0.692	0.627
14-7-4W	0.630	0.594	0.747	0.694	0.574	0.341	0.325	0.481	0.754	0.659
17-8-4W	1.070	1.033	1.299	0.646	0.573	0.759	0.773	1.143	0.704	0.709
19-6-3W	1.108	1.073	1.350	0.635	0.594	0.792	0.773	1.143	0.695	0.663
1-9-6W	0.265	0.272	0.342	0.188	0.181	0.260	0.276	0.408	0.242	0.231
20-6-3W	0.544	0.650	0.818	0.837	0.807	0.318	0.496	0.734	0.777	0.664
20-7-4W	2.165	2.293	2.885	0.583	0.726	1.095	1.219	1.804	0.463	0.623
20-8-4W	0.652	0.989	1.245	0.741	0.761	0.447	0.990	1.464	0.851	0.875
21-8-4W	0.632	0.947	1.191	0.721	0.793	0.412	0.864	1.278	0.824	0.909
~~23-6-4W~~	~~0.985~~	~~3.502~~	~~4.406~~	~~0.784~~	~~0.094~~	~~0.634~~	~~11.779~~	~~17.426~~	~~0.710~~	~~0.048~~
24-8-6W	1.563	1.722	2.167	0.633	0.670	0.959	1.133	1.676	0.718	0.765
~~25-6-4W~~	~~1.393~~	~~2.943~~	~~3.703~~	~~0.659~~	~~0.521~~	~~0.869~~	~~4.024~~	~~5.954~~	~~0.584~~	~~0.280~~
25-9-6W	0.316	0.338	0.425	0.574	0.582	0.267	0.303	0.448	0.726	0.772
26-7-4W	0.889	0.854	1.075	0.763	0.716	0.549	0.535	0.792	0.928	0.914
26-8-5W	1.486	1.493	1.879	0.866	0.818	0.669	0.665	0.984	0.857	0.796
27-7-4W	1.360	1.299	1.635	0.956	0.872	0.756	0.784	1.159	0.898	0.907
29-7-4W	1.229	1.538	1.935	0.968	0.905	0.564	0.827	1.224	0.779	0.818
32-7-4W	1.332	1.285	1.617	0.894	0.847	0.742	0.720	1.066	0.853	0.847
33-6-4W	0.828	0.577	0.727	0.670	0.266	0.517	0.312	0.462	0.715	0.185
36-9-6W	0.604	0.706	0.889	0.614	0.663	0.465	0.589	0.872	0.706	0.761
3-7-4W	1.580	2.068	2.603	0.537	0.519	0.875	1.455	2.152	0.390	0.335
4-8-4W	0.875	1.272	1.601	0.756	0.797	0.523	1.036	1.532	0.899	0.879
5-7-4W	1.281	2.026	2.550	0.557	0.610	0.780	1.796	2.657	0.510	0.584
5-8-4W	1.781	1.429	1.798	0.909	0.757	0.955	0.600	0.888	0.901	0.499
7-7-4W	1.520	1.657	2.085	0.884	0.909	0.775	0.895	1.325	0.765	0.865
7-8-4W	1.806	1.458	1.834	0.811	0.679	1.016	0.689	1.019	0.796	0.632
8-7-4W	1.128	1.249	1.572	0.655	0.656	0.619	0.732	1.082	0.492	0.455
8-8-4W	1.164	1.061	1.336	0.891	0.791	0.669	0.603	0.891	0.926	0.870

3.4.4.1 Aggregated Regressions - In an attempt to look at the soil moisture/emissivity relationship across multiple sections, the relationship was plotted based on vegetation water content amounts in the same way that was used for the low altitude data. Grouping all section averaged VWC into low (<0.25 kg/m^2), medium (0.25 ≤ VWC < 2.5 kg/m^2) and high (2.5 ≤ VWC < 5.0 kg/m^2). Unlike the groupings used for the low altitude data, however, a fourth group was included to contain VWC amounts ≥5 kg/m^2. The inclusion of the fourth group was done to contain the previously mentioned erroneous values and to remove them from the high VWC category.

The resulting relationships from the VWC groups differ from what was seen using the same groupings on the low altitude data. The relationships in both polarizations showed increased sensitivity for the medium and high VWC groups with the application of vegetation correction equations (Table 3.3). However, each group at both polarizations showed weakening R^2 with the correction for vegetation that increased with VWC amount. This reduction in strength of the linear relationship with the application of correction for vegetation is the opposite of what was observed for the low altitude data. A likely cause of the weakening relationships is the heterogeneity present within each section, where a high field measured VWC could have been included in the same footprint as a low VWC unmeasured field, or vice versa. The "extreme" VWC category is included in Table 3.3 for reference only, as the 22 measurements included in this category were not included in the overall regression or used in the soil moisture estimations. Unexpectedly, the slope and R^2 for the uncorrected (vegetated) relationship in the extremely high VWC category is better than any of the lower three categories. Part of the reason for this is likely due to the 22 measurements in that category all coming from only two different sections, both of which were sampled in canola. However, that there is any response at all to soil moisture at VWC levels over 5 kg/m^2 is contrary to what has been found in the past (Entekhabi, et al., 2012).

Table 3.3 – Slope and R^2 for the VWC grouped regressions.

Extreme category not included in overall and is shown for reference only

Polarization	VWC Group	Vegetated (e)		Bare (e_g)		n
		S	R^2	S	R^2	
Vertical	Low	0.2260	0.2400	0.2253	0.2274	91
	Med	0.2763	0.4021	0.4664	0.3962	188
	High	0.2299	0.3231	0.6373	0.2927	59
	All	0.2752	0.3536	0.3963	0.2398	338
	Extreme	0.5490	0.7036	7.4691	0.0291	22
Horizontal	Low	0.4226	0.2952	0.4211	0.2873	91
	Med	0.5023	0.4942	0.6728	0.4807	188
	High	0.4008	0.3829	0.6812	0.3605	59
	All	0.4884	0.4234	0.5750	0.3615	338
	Extreme	0.8682	0.6465	2.9867	0.0940	22

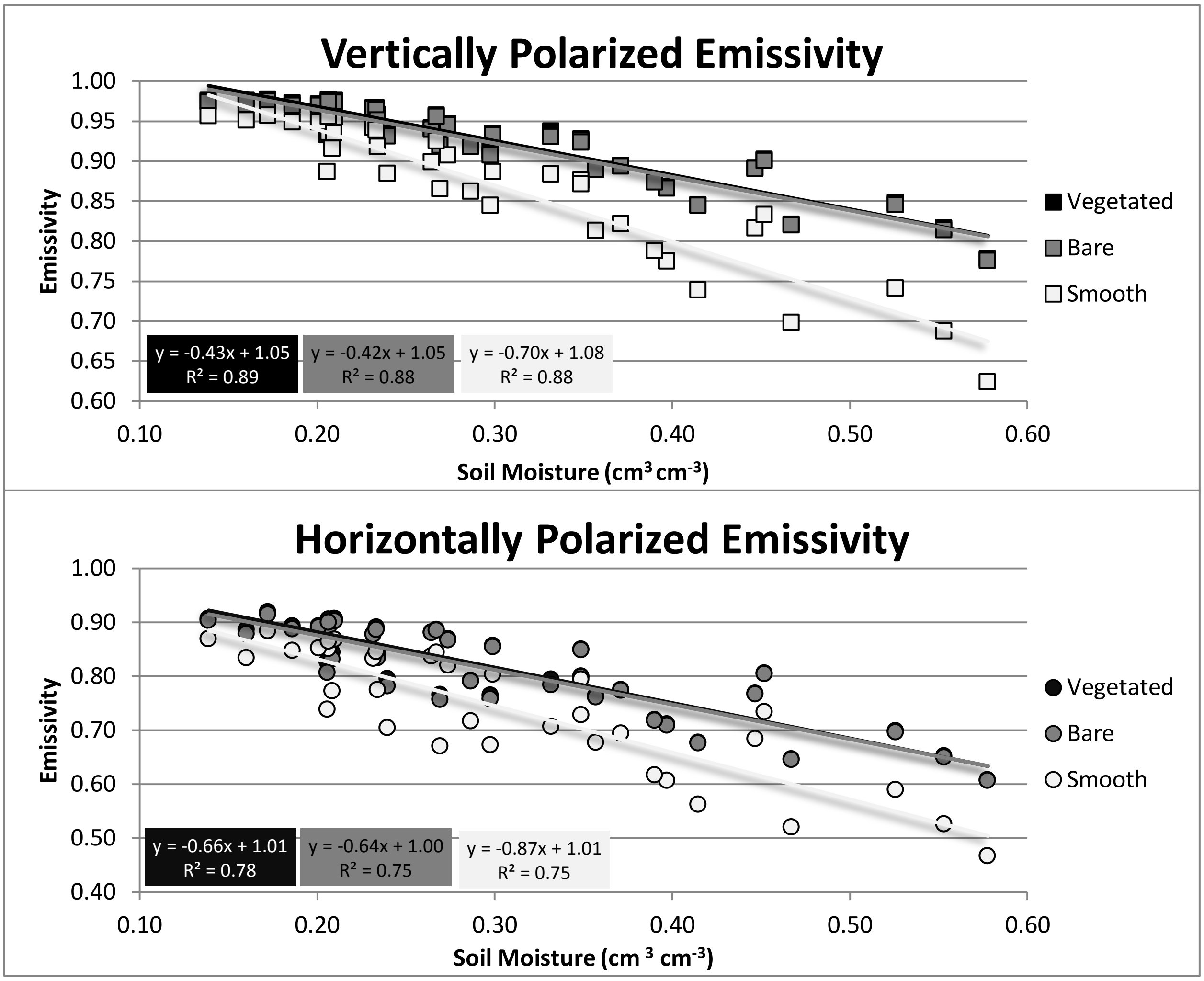


Figure 3.5- Aggregated linear relationship for sections along the low altitude eastern flight line (described in section 2.4.5.1).

The low altitude data were broken up along three flight lines (referred to as west, central and east), and as detailed in 2.4.5.1, the east line consisted of five fields with similar soil texture that were all planted with soybean crops. The similar physical characteristics of these fields made them an obvious choice for examining the linear relationship across multiple fields. Using the same approach as the low altitude data, the linear relationship between emissivity and soil moisture was plotted for the three sections that contained the five soybean fields along the east line (Figure 3.5). Before comparing the two datasets, sample dates that were not included in both (due to variations in the spatial location of flight data) were removed.

Shown in Table 3.4, the comparison of the relationship between the high and low altitude data on the east flight line yielded some interesting results. Along the flight line, the sensitivity to soil moisture was better for the low altitude data than from the larger footprint of the high altitude data. The improvement was universal across all versions of the relationship; for both the overall aggregated data for low vs high altitude, as well as comparing each section to the field(s) that fell inside it.

As expected, the degree of improvement was greater in horizontal polarization than vertical for each version of the relationship. However, the R^2 was higher for most high altitude relationships, including the aggregated relationship in horizontal polarization at both levels of correction. The stronger R^2 value at high altitude isn't totally unexpected for the vegetation adjusted relationships, since the high altitude correction was based on the optimization of the *b* parameter. What was unexpected, however, was the improvement in R^2 for the uncorrected relationships

Table 3.4 – Slope and R^2 on eastern flight line sections and corresponding low altitude fields. R^2 for the modeled bare and smooth surfaces are identical.

Section	Horizontal					Vertical				
	S Veg	S Bare	S Smooth	R^2 Veg	R^2 Smooth	S Veg	S Bare	S Smooth	R^2 Veg	R^2 Smooth
11-8-4W	0.64	0.63	0.85	0.84	0.82	0.42	0.41	0.69	0.91	0.90
102	1.06	1.04	1.17	0.83	0.81	0.73	0.73	0.89	0.86	0.85
103	0.92	0.90	1.03	0.83	0.81	0.65	0.64	0.80	0.84	0.83
14-7-4W	0.63	0.61	0.82	0.71	0.65	0.34	0.33	0.55	0.76	0.71
111	1.31	1.30	1.45	0.75	0.70	0.80	0.81	0.98	0.76	0.73
26-7-4W	0.90	0.88	1.19	0.78	0.76	0.55	0.54	0.90	0.93	0.92
112	1.50	1.47	1.60	0.75	0.73	0.93	0.93	1.06	0.76	0.74
113	1.22	1.19	1.48	0.65	0.64	0.76	0.76	1.09	0.66	0.65
All High	0.66	0.64	0.87	0.78	0.75	0.43	0.42	0.70	0.78	0.75
All Low	1.04	1.02	1.15	0.75	0.72	0.71	0.70	0.76	0.79	0.76

from the low to high altitude on two of the sections. While investigating this further was not part of this study, a possible cause of this improvement was the averaged soil moisture values (from multiple fields) more adequately representing the overall conditions in the ground.

3.4.5 Estimation of Soil Moisture from Low Altitude Regression

The linear regression parameters for the low altitude data described in the previous chapter were used to estimate soil moisture from the high altitude emissivity measurements. The linear equations were inverted in order to solve for soil moisture, and the high altitude emissivity values were substituted for the low altitude values. This created plots of measured vs. predicted soil moisture with the “ideal” low altitude equations and the observed high altitude emissivity values at each level of correction.

The results of this analysis for the overall regression (Figure 3.6) showed a consistent over-prediction at low observed moisture values, and an under-prediction at high moisture values (i.e. slope <1). There was a decrease in the R^2 of the relationship for both polarizations with corrections for vegetation and roughness effects, however, the maximum R^2 was only ~0.42 for horizontal and ~0.36 for vertical. Root mean square error (RMSE) calculated for the overall predicted values revealed an interesting trend. For the soil moisture estimates at horizontal polarization, the RMSE increased with the use of corrected emissivity values for vegetation, and then were reduced with correction for roughness, though not below the uncorrected estimate.

At vertical polarization, the RMSE rose with each correction, peaking for smooth surface emissivity at 0.09 (Table 3.5). The lowest RMSE for both polarizations was the uncorrected emissivity. While this could be viewed as positive for creating quick soil moisture estimates without ancillary ground variables, it suggests that the linear model's ability to compensate for the impact of vegetation and increase the accuracy of soil moisture estimations is poor.

Table 3.5- RMSE values for overall regression estimations

	Horizontal	Vertical
Vegetated (e)	0.077	0.084
Bare (e_g)	0.083	0.085
Smooth (e_s)	0.079	0.091

As seen in Figure 3.6, the corrections had a different effect on the two polarizations. Whereas the horizontally polarized estimations showed little change in scatter with the application of corrected emissivities, the vertically polarized estimations exhibited considerably more scatter with corrected emissivity. While not investigated, this difference is likely the result of the varying effects of vegetation on the two polarizations, and the way in which they were corrected in the linear model. The result of this analysis reduces the confidence in the use of the vertically polarized data for soil moisture estimations using a linear model.

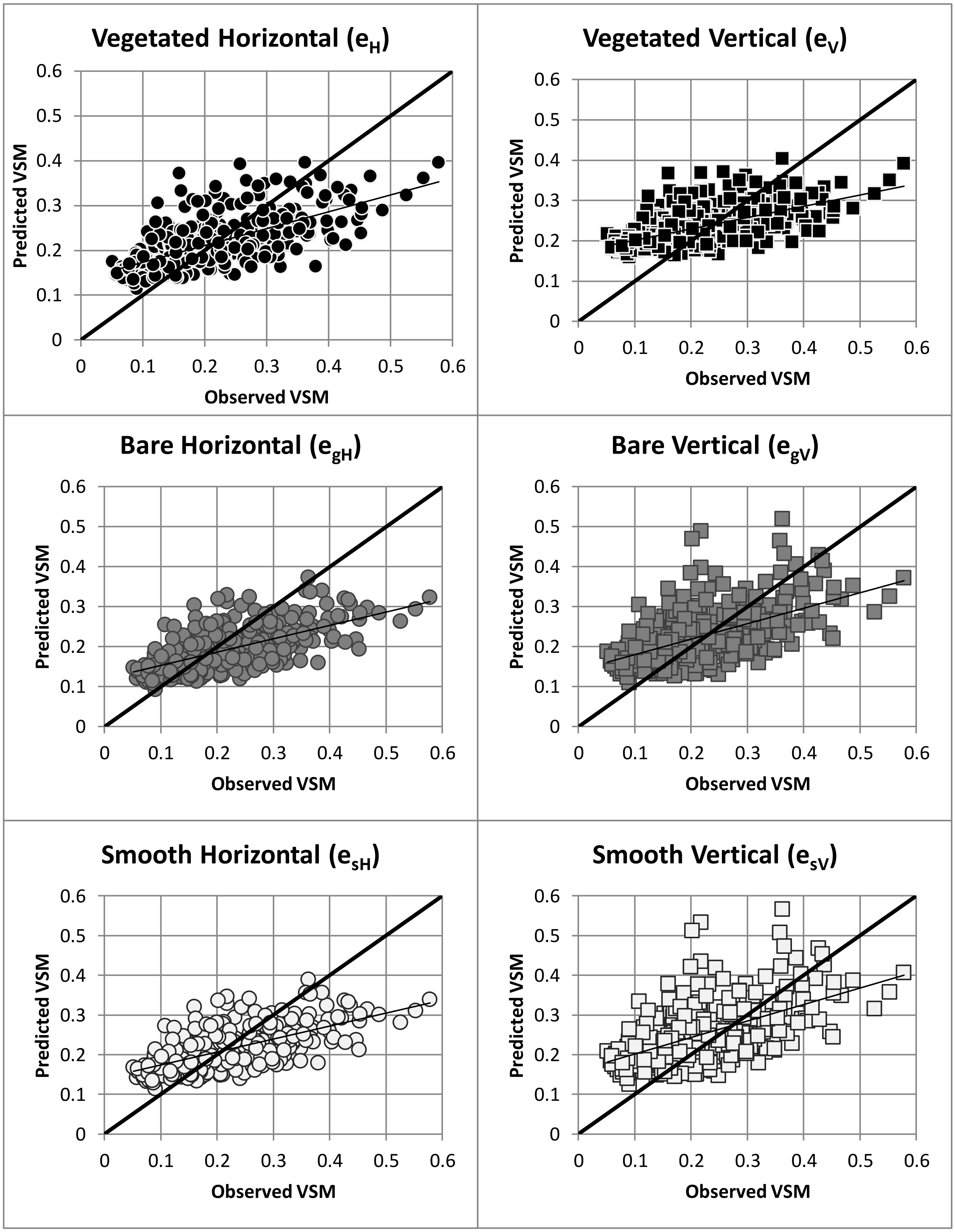


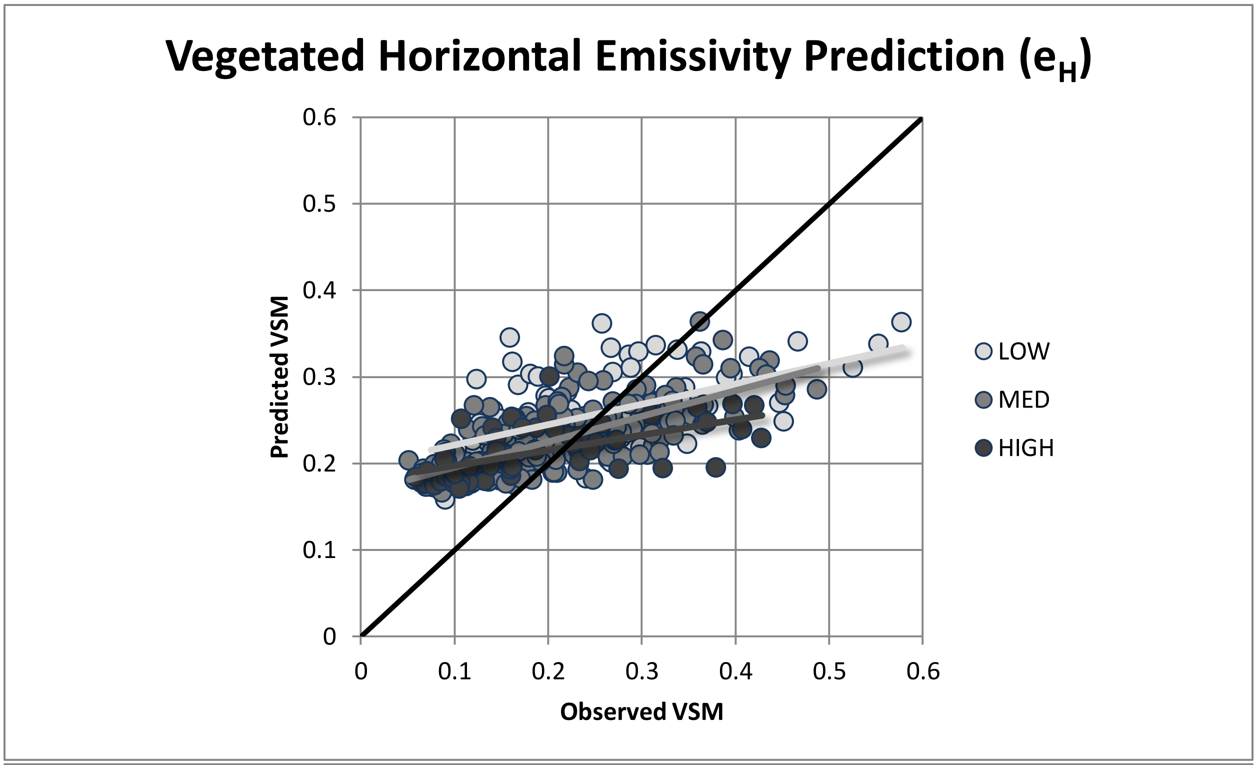
Figure 3.6 – Results of soil moisture estimation using low altitude regression parameters.

3.4.5.1 VWC Groups - The linear relationships for VWC groups were also used to estimate high altitude soil moisture using the low altitude parameters. Both the vegetated (e_P) and bare (e_{gP}) emissivities were tested when grouped into low (<0.25 kg/m^2), medium (0.25 ≤ VWC ≤ 2.5 kg/m^2) and high (>2.5 kg/m^2) VWC amounts. Two sections with VWC measurements above the L-band threshold of 5 kg/m^2 (Entekhabi, et al., 2012; Njoku & Entekhabi, 1996) were removed from the regression.

Using the intercept and slope from the same VWC groups from the low altitude regression, soil moisture was estimated using the high altitude observed emissivity from both polarizations. The low altitude regression parameters used were from the VWC groups that included all sample points found significant, as discussed in section 3.3.3. Figure 3.7 and Figure 3.8 show the observed vs predicted soil moisture values at high altitude. As discussed previously, the use of regression parameters from the vegetation corrected (bare) emissivity slightly weaken the estimations for both polarizations.

Just as was done for the overall regression estimations, RMSE was calculated for the soil moisture estimation for each VWC group and for both polarizations. The low and high VWC group estimations were found to have RMSE values higher than the error calculated from the overall regression parameters (Table 3.6). The medium VWC group had a lower RMSE than the overall error, and performed best at vertical polarization; however, the peak performance was found using the uncorrected emissivity values. The increased RMSE with the use of corrected emissivities reduces confidence in the use of a linear model to predict soil moisture using simple correction equations and high altitude data.

The three points lying on the far right of the x-axis in Figure 3.7 and Figure 3.8 were all observed on the same section (11-8-4W in Table 2.1). These soil moisture measurements were made on two soybean fields that were planted on fields with very high clay content. These values can also be seen in the chapter 2 regressions on the eastern flight line in section 2.4.5.1. The vertically polarized emissivity predictions shown in Figure 3.8 both show a point well outside the normal predicted range (>0.60 $cm^3\ cm^{-3}$) on the y-axis for the high vegetation category. While the inclusion of this point weakens the soil moisture prediction for the high VWC category, its removal only had a small effect on the overall accuracy. The reason for the extremely high predicted value for this observation is uncertain, though since the same point does not appear in overall regression estimations shown in Figure 3.6, the high vegetation, low-altitude regression parameters are likely the cause.



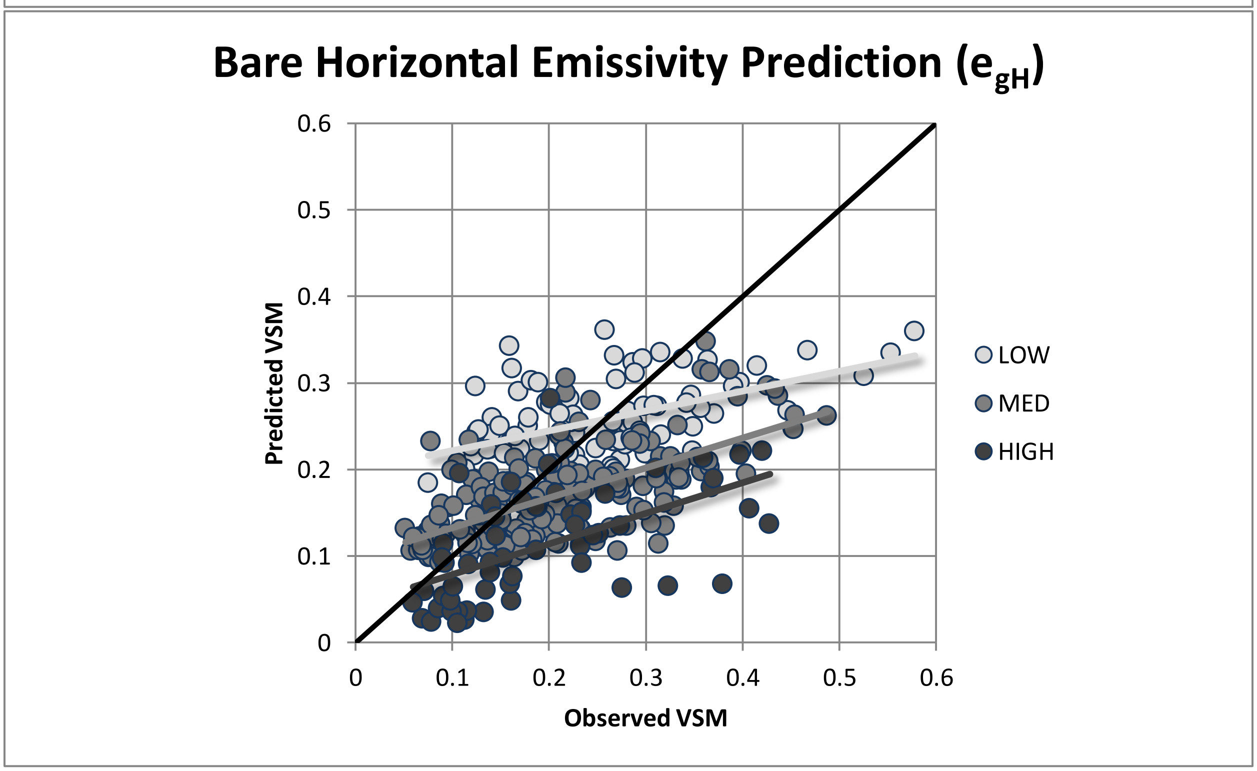
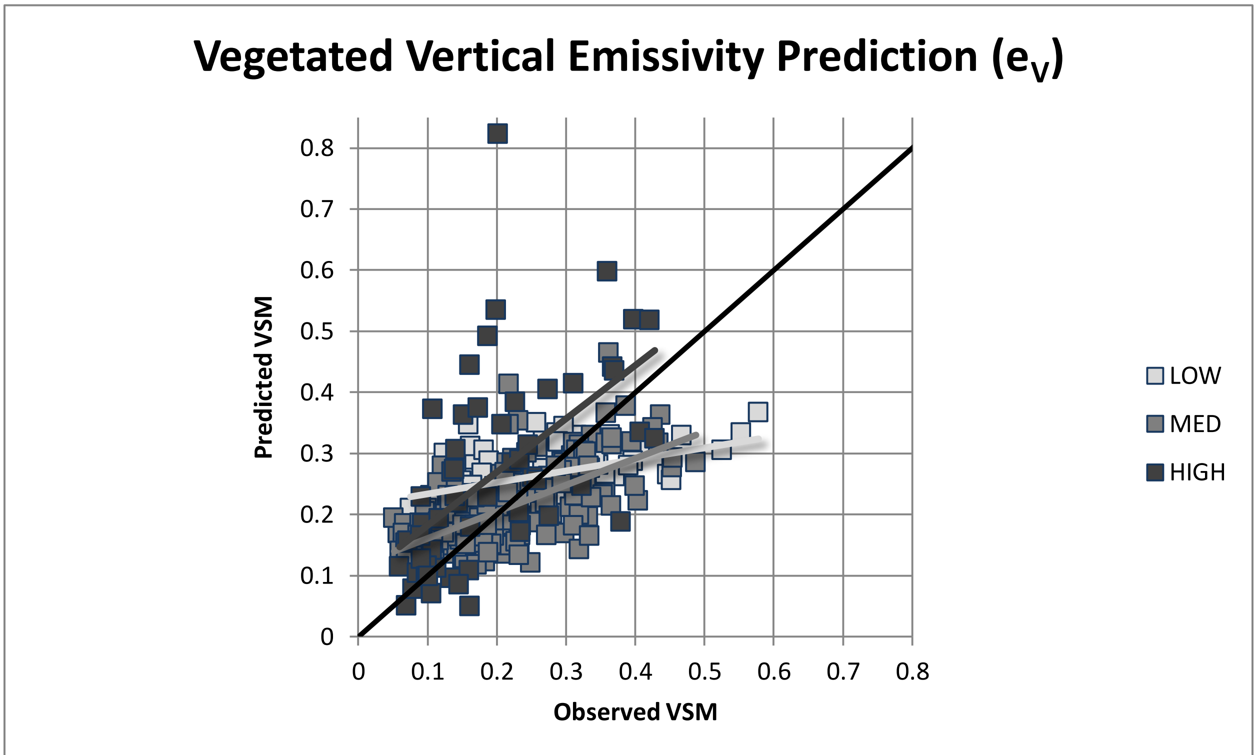


Figure 3.7- High altitude predicted vs. observed soil moisture (cm^3 cm^{-3}) using horizontal emissivity by VWC grouping.

Uncorrected (top) and vegetation corrected (bottom)
Low: < $0.25kg/m^2$, Med: $0.25 \leq VWC \leq 2.5$ kg/m^2, High: > 2.5 kg/m^2



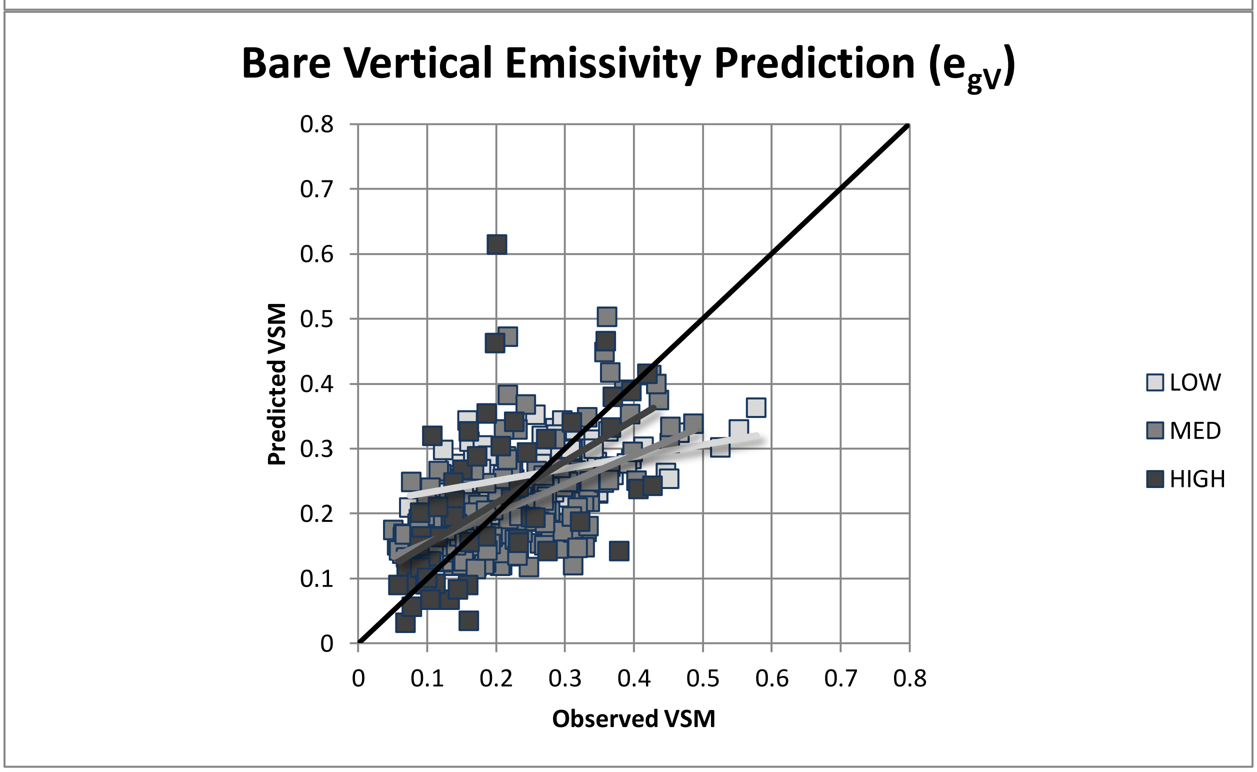


Figure 3.8 - High altitude predicted vs. observed soil moisture ($cm^3\ cm^{-3}$) using vertical emissivity by VWC grouping

Uncorrected (top) and vegetation corrected (bottom)
Low: < 0.25kg/m^2, Med: 0.25 ≤ VWC ≤ 2.5 kg/m^2, High: > 2.5 kg/m^2

Table 3.6- RMSE values for the VWC group estimations in Figure 3.7 and Figure 3.8

	Horizontal		Vertical	
	Veg	Bare	Veg	Bare
Low	0.090	0.090	0.094	0.094
Med	0.075	0.084	0.073	0.080
High	0.090	0.117	0.148	0.110
All	0.077	0.083	0.084	0.085

3.4.5.2 Flight Line Groups - The use of the low altitude linear regression equations to estimate high altitude soil moisture was severely degraded with increasing aggregation. For example, the eastern flight line was comprised of five fields observed at low altitude, each of which was planted with soybean on a similarly textured clay soil. At low altitude, each of these fields exhibited good soil moisture to emissivity relationships. Individually, each field had an R^2 of 0.7 or higher, and a slope near the mean value for all low altitude fields (summarized in Table 3.4). The aggregated relationship for these fields showed an improvement in sensitivity with application of corrections for both polarizations, but a slight decrease in R^2. If the linear regression parameters for the overall (all 22 fields) low altitude relationship are used to estimate soil moisture from the smooth surface horizontally polarized emissivity (e_{sH}), the resulting RMSE value is 0.12. However, using the same emissivity value and the regression parameters for the relationship specific to the five eastern flight line fields, the RMSE drops to 0.06, which is considerably closer to the stated SMAP goal of 0.04.

Another aggregated soil moisture estimation was attempted for the longer central flight line; which was comprised of 12 low altitude study fields on 10 sections. Of the 10 sections, seven had both low and high altitude radiometer data recorded on sampling days. Using the regression parameters from the 12 low altitude fields, soil moisture was estimated from the emissivity values from the seven sections that had both high and low altitude measurements. While the vertically polarized estimations showed an increase in error from uncorrected to smooth soil emissivity, the horizontally polarized estimation error dropped to 0.04 for the fully corrected emissivity value. The results of the different regression estimations are summarized in Table 3.7.

The results of the low altitude estimations show a strong influence from aggregation on the accuracy of the estimates. As was seen in the low altitude relationships, the efficacy of the linear model seems to degrade quickly with the inclusion of larger, more heterogeneous locations. Each regression that included a larger area has shown a decrease in R^2 and increased scatter, which has resulted in a lower accuracy when used in soil moisture estimations.

In order to further examine the impact of aggregation on the linear estimations, several sections that also contained low altitude measured fields were chosen for a section-by-section analysis. Using just one section's high altitude emissivity values and the regression parameters from the low altitude field(s) that fell inside it, soil moisture was estimated as described previously.

The eastern flight line was broken down into the three sections that comprised it, and the RMSE of each estimation was calculated. Section 26-7-4W, which contained two low altitude fields (112 and 113 in Table 3.4), was found to have a RMSE of 0.04 for the corrected smooth surface emissivity at both horizontal and vertical polarization. The northernmost section on the flight line, section 11-8-4W, which also contained two low altitude fields (Table 3.4), showed poorer RMSE when estimating soil moisture. For the corrected horizontal emissivity, the RMSE was 0.07, which was higher than was found from the estimate using the overall flight line regression parameters with the same emissivity values. On this section, the smooth surface vertically polarized emissivity gave a slightly better error value at 0.06; however, this is also higher than the error for the overall section regression estimation. The third section of the flight line, which contained a single low altitude field, had a slightly better RMSE value of 0.05 in both polarizations.

Four sections on the central line were also chosen, the first two of which were found to have RMSE values of ~0.02 using both corrected horizontal and vertical emissivity. One contained two low altitude corn fields (20-7-4W), the other a single canola field (32-7-4W). Given the better performance of the central line specific regression estimation described previously, the lower error of these two sections wasn't surprising. As a more direct comparison to the eastern flight line, the other sections both contained a single low altitude soybean field. While the error in the soil moisture estimation increased above the other two sections on the flight line, it still remained below the soybean fields on the eastern line as well as below the 0.04 objective.

All the calculated RMSE values of the soil moisture estimates can be seen in Table 3.7 for the eastern and central flights line and the sections along each. Most soil moisture estimates showed an increase in error from the use of vegetated to bare surface emissivity, with a decrease to the smooth surface emissivity. The peak error found when using vegetation corrected emissivity is partly the result of the poorer performance of the vegetation correction for low altitude on soybean crops, which dominated the eastern flight line.

Table 3.7 – Summary of RMSE values from soil moisture estimations on individual sections and flight line aggregation.

Not all central flight line sections are shown.

	Vertical			Horizontal		
	Veg	Bare	Smooth	Veg	Bare	Smooth
East Overall	**0.068**	**0.070**	**0.051**	**0.069**	**0.072**	**0.063**
11-8-4W	0.089	0.091	0.058	0.087	0.091	0.072
14-7-4W	0.066	0.067	0.052	0.058	0.061	0.053
26-7-4W	0.042	0.043	0.035	0.043	0.045	0.041
Central Overall	**0.072**	**0.069**	**0.081**	**0.054**	**0.048**	**0.040**
32-7-7W	0.028	0.039	0.023	0.024	0.036	0.023
20-7-4W	0.024	0.022	0.021	0.021	0.023	0.017
17-8-4W	0.030	0.029	0.030	0.033	0.035	0.029
8-8-4W	0.022	0.027	0.027	0.023	0.029	0.029
All Sections	***0.084***	***0.085***	***0.091***	***0.077***	***0.083***	***0.079***

3.5 DISCUSSION

3.5.1 Linear model

The tau-omega model and associated moisture-emissivity linear regression offered a reasonable description of the relationship between emissivity and soil moisture. The coarse resolution measurements of emissivity with generalized model parameters showed both reasonable accuracy and significant response to soil moisture in most cases with only few exceptions.

At both high and low altitude, the vegetation correction failed to properly account for the effect of soybean crops. This failure was evident from the decrease in sensitivity from the vegetated (e_P) to bare (e_{gP}) emissivity relationship on the majority of fields and sections planted with soybean (i.e. $S_0 > S_g$). Not only is the reduction of sensitivity with the removal of vegetation effects counter to what is expected by the model, it has previously been found to be incorrect (Du, et al., 2000). This raises concerns over the generalized vegetation parameters used for the corrections and the effect that the vegetation had on the accuracy of the regression. The high altitude regressions showed a relatively higher number of fields/sections with increased sensitivity compared to the low altitude regressions, though this is at least partially the result of an optimized *b* value for the high altitude relationship.

One possible source of the sensitivity reduction could be the temperature assumption in the tau-omega model. For the purposes of this work, it was assumed that soil temperature was equal to vegetation temperature ($T_s = T_v$). It was also assumed that the observed thermal infrared temperature (T_{IR}) was an adequate measure of the previous, which in turn serves as a reasonable proxy for a true effective temperature (T_{eff}). The effective temperature is calculated using soil temperature data at a depth of >50cm, which wasn't available for most fields in SMAPVEX12. Thus, the model assumed that remotely sensed physical temperature data from the surface was an adequate predictor of the near-surface temperature profile. While this may have been true on nearly bare fields, the influence of growing vegetation throughout the experiment would have increasingly masked the soil temperature and the measured T_{IR} would become closer to T_v than T_s.

Another potential issue with the high altitude observations could be the increased time gap between soil sampling and overpass of the radiometer. On each sampling day, teams started sampling the first field around 07:30 local time. The PALS radiometer would usually pass over the fields on the low altitude line between 08:00 and 09:00. The aircraft would often not make it back to measure the high altitude lines until after the field sampling had finished, usually sometime around 13:00. The time delay could have resulted in a considerable surface temperature difference from the time the moisture sampling was actually done, which would have affected the calculated emissivity value.

3.5.2 Efficacy of the Low Altitude Estimations

The use of the overall regression parameters from low altitude showed little promise in attempting to predict high altitude observed soil moisture over the entire study area. Using emissivity values corrected for both vegetation and roughness using high resolution ground measured values did not provide a satisfactory level of error. Based on the results presented here, it does not seem possible to be able to scale up a linear model from 600 m to 1500 m footprints over a large area to determine soil moisture.

The attempt to divide the overall area regression into slightly more homogeneous groups by vegetation amounts wasn't successful. Not only were the calculated RMSE values higher than the 0.04 goal, but the majority of the VWC category specific regression estimations had higher error than the estimation based on the regression for all fields. The best fit exhibited by the medium VWC category is surprising, given that the vegetation content is the most diverse of the three categories, and contained at least a few measurements from each of the crop types present in the study area. Furthermore, the low altitude relationships were stronger for the horizontally polarized data than the vertical, even though the predicted moisture values seem to suggest the opposite. It would have been expected that the low vegetation group would have exhibited the lowest error in predicted values due to a minimal effect from vegetation. Not only was this not the case, but the low vegetation group regression estimation yielded a higher RMSE than the overall aggregation. The failure of the linear model to adequately relate near bare field conditions at high and low altitude reduces confidence in the use of this method for soil moisture estimation.

While the area-wide parameters calculated from the low altitude linear regression did not meet the requirements for error in moisture estimation, more specific regressions showed more potential. Specifically, emissivity values from specific flight lines showed a marked improvement in RMSE. Whereas the overall regression estimation actually increased in error with the use of emissivity values corrected for vegetation and roughness, the flight line specific estimations performed better. The heavy clay soil and soybean crops of the eastern flight line reached minimum error using the smooth surface vertical emissivity (e_{sV}) at 0.05. While not ideal in terms of the goal of SMAP moisture retrieval, it represented the optimal performance of the linear model to predict soil moisture on clay soils.

The best aggregated soil moisture estimations were found on the central flight line. Despite a mix of vegetation types on the observed fields, the aggregated RMSE for e_{sH} reached the desired 0.04 goal. The vertically polarized emissivities didn't perform as well as horizontal emissivites along this flight line at any of the three levels of correction. This discrepancy between polarizations suggests a varying influence from ground variables on the different polarizations; the difference is likely the increased number of stalk-dominated vegetation types on the measured fields (corn, canola, wheat). The improvement in the soil moisture estimation on the central flight line and its sections suggests that soil type has a substantial impact on the efficacy of the linear model to estimate soil moisture. The eastern line was dominated by clay soils, whereas the central fields were much coarser textured sand and loam soils. The clay fields were found to have higher than normal error during the initial calibration of the soil moisture sensors from the field campaign (Rowlandson, et al., 2013).

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4 SYNTHESIS

The data gathered during the SMAPVEX12 campaign represented one of the most comprehensive experiments of its kind. The duration of the study and the variety of moisture, vegetation and soil conditions were nearly unprecedented in previous similar experiments (Njoku & Kong, 1977; Choudhury, et al., 1979; Ulaby, et al., 1986; Jackson, 1993; Schmugge, et al., 1986). With that in mind, the goal of this work was to examine the use of previously established models and methods on this extensive dataset, and to examine the use of simple linear regression in describing this “best case” relationship.

Using both the low and high altitude data, the soil moisture – emissivity relationship was strong when individual fields and sections were examined. While the accuracy of the relationship shows promise, it is impractical if it is only accurate at the scale of an individual agricultural field. Regular low altitude overpasses by radiometer could be used to estimate soil moisture on individual fields across a region. However, estimations of soil moisture at field scale can be carried out directly and don’t need to rely on remotely sensed values and ancillary information to complete the model. While the use of low altitude remote sensing to measure soil moisture would allow for numerous fields to be measured quickly, this method would be costly and impractical for estimating surface soil moisture.

At higher altitudes, the relationship remains essentially linear, but due to increased heterogeneity across these larger areas, the strength of the relationships are not as strong. Much like the low altitude results, the high altitude linear relationships were reliable over smaller relatively homogeneous areas. However, the correlation coefficient (R^2) declined sufficiently with increasing aggregation to preclude their use in estimating moisture values even though the sensitivity to soil moisture remained significant across most vegetation conditions present in the study area. While the response by the radiometer to changes in soil moisture was adequate, the accuracy of any prediction from the model was not. If the goal of a high altitude retrieval using the methods in this study was to be more accurate than satellite retrieval while using a simpler model, then the methods could not be considered a success.

The weakening observed in the linear relationship with increasing aggregation is somewhat counter to what might be expected. While the relationship on individual fields remained strong across most crop types, there was a considerable difference in the regression parameters. The varying slope and intercepts on different fields, a substantial difference in observed soil moisture ranges, and perhaps even the varying sample times of the fields lead to a weaker linear relationship when multiple fields were examined together.

With the soil moisture retrieval algorithm well established for satellite based retrievals such as SMAP, there would be little use in widespread aircraft based measurements. The advantage of aircraft retrieval over satellite lies in the resolution of the resulting soil moisture product. Whereas satellite retrieval is too coarse for measuring moisture content at a field scale, an aircraft based measurement has the ability to measure soil moisture quickly and at a scale that is useful for agricultural applications. In order to be practical, the retrieval must be possible without the need for detailed ground variables.

The use of low altitude regression parameters to estimate moisture from high altitude emissivity was an attempt to simply and accurately estimate soil moisture at a scale relevant to agricultural applications without the need for intensive, ongoing ground surveys. If a linear relationship between emissivity and soil moisture could be established for a soil or vegetation type using a detailed calibration survey, then larger scale measurements could be derived from that calibration without the need for further ground measurements. However the linear relationships over heterogeneous conditions began to weaken as the number of contributing fields increased. Whether the breakdown in the low altitude regression estimations was the result of the time delay between the high and low passes, increased heterogeneity in the footprints or some other factor, they were found ineffective as a tool to estimate the soil moisture.

Improvements could be made to this process by creating more specific model parameters. One weakness of the methods used in this work was a reliance on previously published values for the vegetation opacity (τ). With the quality of data available for this study, it would have been possible to invert the τ-ω model to solve for τ for the vegetation present in the study. It is possible this would have improved the vegetation modelling performed for this work, and may have helped increase the accuracy of the soil moisture estimations based on the low altitude regression parameters.

Another improvement to the modeled relationships may have resulted from concurrent soil and vegetation sampling. The vegetation sampling dates were set alternate to the soil dates, which necessitated the use of an interpolation in order to assign vegetation data to dates with soil and radiometer measurements. While there was precedence for this approach in the past (Anderson, et al., 2004), it also undoubtedly introduced error that could have been avoided if vegetation was also measured on the same dates as soil moisture. Furthermore, the roughness measurements could have been carried out a second time toward the end of the campaign, which may have improved the modeled roughness contribution.

The optimization of the *b* parameter created an estimated value that was close to values previously found for previous studies (Crow, et al., 2005; Jackson & Schmugge, 1991). The difference between the value of *b* for the two polarizations was larger than previously found, but the values closely matched what was expected. Given the empirical nature of the parameter, the use of an optimization based on retrieved low altitude data should have provided a good estimate of vegetation effects.

The low altitude relationships showed a decrease in sensitivity in both polarizations on soybean fields with the application of the emissivity correction for vegetation. These fields represented the lowest vegetation water content of the crops measured. Given the deterioration of the linear relationship with the correction for vegetation effects on the soybean fields, it was found that the best correction for soybean was essentially none at all. It is likely that the low water content of the soybean crop lead to an over-estimation of the influence of the crop on the emissivity, and that the low water content of the soybean crops had no measurable effect on soil emissivity. At high altitude, the use of the optimized parameter showed promise, with increases to the sensitivity on several of the sections that were planted with soybean.

The most positive result from this work was the performance of the linear model on individual high biomass fields, such as corn, canola and wheat. Even with the assumptions built into the model and the use of non-specific vegetation correction, the linear relationships were strong and showed a good response to soil moisture. These relationships (predominantly in the central part of the study area) also exhibited good performance in scaling the soil moisture estimations to the high altitude data. While the reason for the stronger relationships on the central fields wasn't investigated, it is likely the result of the vegetation and soil combination on those fields; this would warrant further study.

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5 APPENDICIES

I. LOW ALTITUDE FIELD DATA

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
11	2012-06-12	Soybeans	0.017	0.2158	222.4	172.0	0.7811	0.6042	0.7803	0.6029	0.7643	0.5862
11	2012-06-17	Soybeans	0.022	0.2198	232.1	186.5	0.8085	0.6497	0.8075	0.6482	0.7935	0.6334
11	2012-06-22	Soybeans	0.018	0.1758	251.6	210.2	0.8672	0.7244	0.8666	0.7234	0.8569	0.7118
11	2012-06-23	Soybeans	0.018	0.1567	259.0	224.6	0.8863	0.7687	0.8858	0.7679	0.8775	0.7581
11	2012-06-25	Soybeans	0.019	0.1441	266.9	238.4	0.9141	0.8163	0.9138	0.8156	0.9075	0.8078
11	2012-06-27	Soybeans	0.020	0.1570	262.9	226.0	0.8896	0.7649	0.8891	0.7640	0.8810	0.7541
11	2012-06-29	Soybeans	0.033	0.1372	271.8	245.4	0.9257	0.8358	0.9251	0.8348	0.9197	0.8278
11	2012-07-03	Soybeans	0.085	0.1413	278.6	253.7	0.9398	0.8557	0.9386	0.8534	0.9341	0.8472
11	2012-07-05	Soybeans	0.111	0.1345	277.1	249.8	0.9428	0.8499	0.9413	0.8467	0.9370	0.8403
11	2012-07-08	Soybeans	0.150	0.1466	278.7	252.4	0.9433	0.8543	0.9413	0.8502	0.9370	0.8439
11	2012-07-10	Soybeans	0.179	0.1313	281.9	262.7	0.9526	0.8879	0.9506	0.8840	0.9470	0.8792
11	2012-07-13	Soybeans	0.230	0.1213	267.2	231.0	0.8994	0.7777	0.8940	0.7679	0.8863	0.7581
11	2012-07-14	Soybeans	0.247	0.1242	278.0	256.1	0.9399	0.8659	0.9364	0.8595	0.9318	0.8536
11	2012-07-17	Soybeans	0.297	0.1774	256.9	221.3	0.8754	0.7542	0.8666	0.7401	0.8569	0.7292
13	2012-06-12	Pasture	0.266	0.3060	248.8	227.2	0.8703	0.7945	0.8369	0.7521	0.8131	0.7315
13	2012-06-15	Pasture	0.328	0.3148	256.1	226.4	0.8787	0.7767	0.8391	0.7186	0.8156	0.6951
13	2012-06-17	Pasture	0.370	0.3580	253.1	234.1	0.8799	0.8141	0.8348	0.7587	0.8107	0.7386
13	2012-06-22	Pasture	0.233	0.3087	250.5	221.2	0.8645	0.7634	0.8343	0.7211	0.8102	0.6979
13	2012-06-23	Pasture	0.215	0.3014	248.9	219.5	0.8548	0.7538	0.8253	0.7136	0.7998	0.6898
13	2012-06-25	Pasture	0.177	0.2942	252.8	227.0	0.8675	0.7789	0.8457	0.7496	0.8231	0.7287
13	2012-06-27	Pasture	0.139	0.2758	264.5	243.6	0.8942	0.8237	0.8808	0.8056	0.8634	0.7894
13	2012-06-29	Pasture	0.113	0.2669	258.4	230.5	0.8783	0.7836	0.8659	0.7656	0.8463	0.7461
13	2012-07-03	Pasture	0.087	0.2277	264.3	240.5	0.8918	0.8116	0.8833	0.7997	0.8663	0.7830

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
13	2012-07-05	Pasture	0.074	0.2413	263.2	235.6	0.8915	0.7981	0.8843	0.7873	0.8674	0.7696
13	2012-07-08	Pasture	0.054	0.2395	263.8	235.9	0.8906	0.7962	0.8854	0.7883	0.8687	0.7707
13	2012-07-10	Pasture	0.057	0.2209	264.7	240.9	0.8908	0.8105	0.8853	0.8027	0.8686	0.7863
13	2012-07-13	Pasture	0.085	0.2486	262.1	233.4	0.8779	0.7820	0.8686	0.7685	0.8494	0.7492
13	2012-07-14	Pasture	0.095	0.2206	262.3	243.8	0.8843	0.8220	0.8744	0.8097	0.8561	0.7939
13	2012-07-17	Pasture	0.123	0.2788	263.1	243.0	0.8919	0.8235	0.8798	0.8075	0.8623	0.7915
21	2012-06-12	Pasture	0.431	0.3666	245.1	216.9	0.8597	0.7611	0.7967	0.6763	0.7096	0.6010
21	2012-06-15	Pasture	0.425	0.3184	247.1	215.2	0.8505	0.7405	0.7843	0.6498	0.6919	0.5683
21	2012-06-17	Pasture	0.422	0.3797	245.9	223.1	0.8557	0.7762	0.7925	0.6986	0.7036	0.6285
21	2012-06-22	Pasture	0.367	0.3365	247.7	217.5	0.8577	0.7530	0.8046	0.6800	0.7209	0.6055
21	2012-06-23	Pasture	0.354	0.3153	246.5	216.0	0.8465	0.7419	0.7917	0.6687	0.7024	0.5917
21	2012-06-25	Pasture	0.354	0.3132	248.3	220.6	0.8550	0.7596	0.8034	0.6916	0.7191	0.6198
21	2012-06-27	Pasture	0.379	0.2749	263.0	238.2	0.8910	0.8069	0.8489	0.7478	0.7842	0.6891
21	2012-06-29	Pasture	0.404	0.2559	255.3	225.1	0.8741	0.7706	0.8217	0.6950	0.7453	0.6240
21	2012-07-03	Pasture	0.414	0.2381	262.6	234.7	0.8888	0.7943	0.8411	0.7246	0.7731	0.6605
21	2012-07-05	Pasture	0.412	0.2229	263.2	234.1	0.8969	0.7977	0.8529	0.7295	0.7899	0.6666
21	2012-07-08	Pasture	0.410	0.2152	262.3	232.8	0.8915	0.7911	0.8455	0.7212	0.7794	0.6564
21	2012-07-10	Pasture	0.423	0.2232	265.7	243.0	0.9006	0.8237	0.8568	0.7624	0.7955	0.7071
21	2012-07-13	Pasture	0.467	0.2911	263.7	232.6	0.8877	0.7829	0.8321	0.6982	0.7601	0.6279
21	2012-07-14	Pasture	0.482	0.2031	263.3	241.0	0.8906	0.8152	0.8343	0.7404	0.7633	0.6800
21	2012-07-17	Pasture	0.526	0.2792	264.7	242.0	0.9005	0.8231	0.8435	0.7438	0.7764	0.6842
22	2012-06-12	Pasture	0.122	0.3482	246.8	222.4	0.8651	0.7795	0.8501	0.7598	0.7150	0.6497
22	2012-06-15	Pasture	0.178	0.3200	247.8	216.6	0.8527	0.7453	0.8282	0.7112	0.6733	0.5789
22	2012-06-17	Pasture	0.216	0.3283	250.1	232.4	0.8668	0.8053	0.8395	0.7733	0.6948	0.6694
22	2012-06-22	Pasture	0.218	0.3425	249.3	222.6	0.8621	0.7698	0.8336	0.7316	0.6836	0.6087
22	2012-06-23	Pasture	0.213	0.3340	245.5	216.8	0.8427	0.7441	0.8110	0.7026	0.6405	0.5664
22	2012-06-25	Pasture	0.204	0.3163	247.2	219.3	0.8504	0.7546	0.8217	0.7167	0.6610	0.5868
22	2012-06-27	Pasture	0.193	0.3210	261.8	240.1	0.8866	0.8130	0.8660	0.7858	0.7452	0.6876
22	2012-06-29	Pasture	0.182	0.2665	254.7	223.5	0.8712	0.7645	0.8493	0.7323	0.7133	0.6097

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
22	2012-07-03	Pasture	0.199	0.2745	261.5	232.9	0.8847	0.7878	0.8632	0.7559	0.7399	0.6440
22	2012-07-05	Pasture	0.213	0.2871	260.5	233.1	0.8879	0.7944	0.8653	0.7610	0.7438	0.6515
22	2012-07-08	Pasture	0.235	0.2444	262.2	229.7	0.8912	0.7808	0.8667	0.7413	0.7466	0.6227
22	2012-07-10	Pasture	0.250	0.2454	264.9	235.7	0.8974	0.7987	0.8727	0.7598	0.7580	0.6498
22	2012-07-13	Pasture	0.272	0.2977	264.5	237.0	0.8889	0.7963	0.8595	0.7532	0.7328	0.6401
22	2012-07-14	Pasture	0.280	0.2745	263.9	243.2	0.8922	0.8223	0.8629	0.7835	0.7392	0.6843
22	2012-07-17	Pasture	0.302	0.3017	265.2	246.2	0.9020	0.8373	0.8729	0.7987	0.7583	0.7065
31	2012-06-12	Wheat	1.954	0.4337	247.7	190.7	0.8729	0.6721	0.7772	0.4810	0.7387	0.4302
31	2012-06-15	Wheat	2.359	0.4131	266.7	211.2	0.9211	0.7293	0.8446	0.5288	0.8178	0.4826
31	2012-06-17	Wheat	2.629	0.4232	258.1	198.5	0.9016	0.6935	0.7906	0.4315	0.7544	0.3757
31	2012-06-22	Wheat	3.185	0.4730	263.0	199.9	0.9123	0.6935	0.7811	0.3521	0.7433	0.2886
31	2012-06-23	Wheat	3.200	0.4527	267.2	208.9	0.9218	0.7208	0.8039	0.4078	0.7700	0.3497
31	2012-06-25	Wheat	3.231	0.3788	270.1	222.2	0.9360	0.7701	0.8382	0.5088	0.8103	0.4606
31	2012-06-27	Wheat	3.262	0.3696	281.3	232.1	0.9558	0.7885	0.8871	0.5449	0.8677	0.5003
31	2012-07-05	Wheat	2.361	0.2676	277.9	230.6	0.9537	0.7914	0.9089	0.6367	0.8931	0.6011
31	2012-07-10	Wheat	2.284	0.2030	284.3	247.8	0.9680	0.8437	0.9384	0.7327	0.9278	0.7065
31	2012-07-13	Wheat	2.469	0.4055	267.6	227.5	0.9003	0.7656	0.7973	0.5812	0.7623	0.5402
31	2012-07-14	Wheat	2.530	0.3839	270.4	228.0	0.9173	0.7737	0.8291	0.5899	0.7995	0.5497
31	2012-07-19	Wheat	2.838	0.3517	274.4	218.8	0.9246	0.7374	0.8296	0.4883	0.8002	0.4382
32	2012-06-12	Wheat	1.491	0.4445	242.5	181.5	0.8552	0.6402	0.7778	0.4892	0.5161	0.1935
32	2012-06-15	Wheat	1.846	0.4051	263.7	208.1	0.9105	0.7184	0.8479	0.5654	0.6686	0.3138
32	2012-06-17	Wheat	2.083	0.4278	252.9	191.9	0.8831	0.6701	0.7873	0.4618	0.5367	0.1502
32	2012-06-22	Wheat	2.675	0.4607	260.7	198.6	0.9046	0.6892	0.7944	0.4172	0.5521	0.0799
32	2012-06-25	Wheat	2.878	0.3876	270.7	224.5	0.9379	0.7778	0.8580	0.5629	0.6907	0.3099
32	2012-07-05	Wheat	2.545	0.1892	278.9	230.5	0.9568	0.7907	0.9102	0.6194	0.8044	0.3991
32	2012-07-10	Wheat	2.428	0.1586	285.3	253.4	0.9716	0.8629	0.9429	0.7575	0.8756	0.6171
32	2012-07-13	Wheat	2.479	0.3953	268.8	229.4	0.9048	0.7722	0.8061	0.5920	0.5776	0.3558
32	2012-07-14	Wheat	2.496	0.3180	268.5	227.1	0.9109	0.7703	0.8176	0.5871	0.6026	0.3480
32	2012-07-19	Wheat	2.580	0.3189	272.3	224.7	0.9178	0.7574	0.8274	0.5551	0.6241	0.2975

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
41	2012-06-12	Wheat	4.275	0.4927	259.6	220.2	0.9150	0.7763	0.7098	0.3892	0.4817	0.1417
41	2012-06-15	W. Wheat	4.081	0.4285	270.3	224.4	0.9327	0.7742	0.7828	0.4110	0.6122	0.1723
41	2012-06-17	W. Wheat	3.952	0.4761	261.6	215.7	0.9136	0.7534	0.7311	0.3759	0.5199	0.1230
41	2012-06-22	W. Wheat	3.682	0.4267	265.6	214.8	0.9215	0.7451	0.7740	0.3946	0.5964	0.1492
41	2012-06-23	W. Wheat	3.670	0.4447	270.0	222.8	0.9322	0.7690	0.8054	0.4528	0.6524	0.2310
41	2012-06-25	W. Wheat	3.648	0.3573	270.7	237.1	0.9380	0.8213	0.8231	0.5790	0.6841	0.4083
41	2012-06-27	W. Wheat	3.625	0.3137	280.8	246.2	0.9533	0.8359	0.8678	0.6154	0.7639	0.4596
41	2012-07-05	W. Wheat	3.535	0.2806	275.0	233.9	0.9427	0.8015	0.8419	0.5446	0.7176	0.3600
41	2012-07-10	W. Wheat	1.577	0.1810	284.3	254.0	0.9660	0.8630	0.9466	0.8016	0.9046	0.7212
41	2012-07-13	W. Wheat	1.706	0.3747	271.5	219.0	0.9094	0.7337	0.8522	0.6024	0.7360	0.4413
41	2012-07-14	W. Wheat	1.749	0.2799	274.2	233.1	0.9294	0.7900	0.8833	0.6833	0.7916	0.5550
42	2012-06-12	W. Wheat	3.397	0.5560	255.7	209.0	0.9015	0.7368	0.7387	0.4153	0.5883	0.2365
42	2012-06-17	W. Wheat	3.349	0.4929	256.0	206.4	0.8938	0.7206	0.7222	0.3862	0.5623	0.1986
42	2012-06-22	W. Wheat	3.302	0.4618	262.9	207.7	0.9121	0.7208	0.7731	0.3934	0.6425	0.2079
42	2012-06-23	W. Wheat	3.292	0.5125	266.9	218.7	0.9221	0.7558	0.7994	0.4706	0.6839	0.3088
42	2012-06-25	W. Wheat	3.217	0.4092	271.6	236.1	0.9409	0.8178	0.8512	0.6120	0.7656	0.4933
42	2012-06-27	W. Wheat	3.086	0.3460	281.9	248.3	0.9569	0.8431	0.8954	0.6759	0.8352	0.5768
42	2012-07-05	W. Wheat	2.562	0.2344	275.6	234.6	0.9448	0.8043	0.8847	0.6427	0.8184	0.5334
42	2012-07-10	W. Wheat	2.277	0.1511	284.5	255.7	0.9661	0.8684	0.9348	0.7753	0.8972	0.7066
42	2012-07-13	W. Wheat	2.210	0.4230	269.4	215.7	0.9020	0.7223	0.8151	0.5333	0.7086	0.3906
42	2012-07-14	W. Wheat	2.187	0.3321	272.5	230.5	0.9236	0.7813	0.8568	0.6343	0.7744	0.5225
42	2012-07-17	W. Wheat	2.120	0.4629	263.8	216.0	0.8994	0.7363	0.8150	0.5660	0.7085	0.4333
42	2012-07-19	W. Wheat	2.075	0.2891	273.8	231.0	0.9221	0.7782	0.8586	0.6388	0.7773	0.5284
51	2012-06-12	Soybeans	0.141	0.3517	189.5	132.6	0.6627	0.4638	0.6516	0.4494	0.6144	0.4156
51	2012-06-15	Soybeans	0.185	0.2255	262.0	220.8	0.8943	0.7536	0.8897	0.7449	0.8779	0.7292
51	2012-06-17	Soybeans	0.209	0.2886	211.7	155.0	0.7363	0.5390	0.7233	0.5206	0.6937	0.4912
51	2012-06-22	Soybeans	0.275	0.2570	252.8	207.1	0.8700	0.7129	0.8615	0.6977	0.8467	0.6791
51	2012-06-23	Soybeans	0.306	0.2326	266.9	232.6	0.9107	0.7936	0.9042	0.7814	0.8939	0.7680
51	2012-06-25	Soybeans	0.369	0.2017	278.6	259.7	0.9512	0.8867	0.9469	0.8785	0.9412	0.8711

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
51	2012-06-27	Soybeans	0.431	0.1801	287.8	268.1	0.9717	0.9054	0.9688	0.8974	0.9654	0.8911
51	2012-06-29	Soybeans	0.493	0.1434	286.0	271.2	0.9738	0.9236	0.9707	0.9161	0.9676	0.9110
51	2012-07-03	Soybeans	0.702	0.1221	288.5	272.6	0.9742	0.9204	0.9697	0.9092	0.9665	0.9036
51	2012-07-05	Soybeans	0.821	0.1579	267.3	226.2	0.9129	0.7723	0.8948	0.7342	0.8835	0.7179
51	2012-07-10	Soybeans	1.183	0.1371	287.8	266.0	0.9735	0.8997	0.9652	0.8748	0.9615	0.8671
51	2012-07-13	Soybeans	1.554	0.1726	272.7	232.3	0.9146	0.7791	0.8779	0.7042	0.8649	0.6860
51	2012-07-14	Soybeans	1.678	0.1509	278.3	253.3	0.9421	0.8572	0.9149	0.8043	0.9058	0.7923
51	2012-07-19	Soybeans	2.296	0.1865	280.1	249.2	0.9437	0.8397	0.9046	0.7532	0.8944	0.7380
52	2012-06-12	Soybeans	0.117	0.3156	215.6	166.0	0.7557	0.5819	0.7490	0.5726	0.5736	0.4167
52	2012-06-15	Soybeans	0.129	0.1979	262.9	224.2	0.8980	0.7657	0.8949	0.7600	0.8215	0.6725
52	2012-06-17	Soybeans	0.139	0.2562	222.7	177.3	0.7736	0.6157	0.7662	0.6055	0.6029	0.4617
52	2012-06-22	Soybeans	0.184	0.1894	257.1	214.3	0.8848	0.7378	0.8798	0.7286	0.7958	0.6296
52	2012-06-23	Soybeans	0.203	0.1792	267.4	237.2	0.9118	0.8088	0.9076	0.8013	0.8430	0.7288
52	2012-06-25	Soybeans	0.242	0.1543	277.5	260.7	0.9451	0.8880	0.9419	0.8828	0.9013	0.8400
52	2012-06-27	Soybeans	0.281	0.1378	287.8	268.8	0.9703	0.9063	0.9683	0.9013	0.9461	0.8652
52	2012-06-29	Soybeans	0.320	0.1175	284.1	269.2	0.9651	0.9143	0.9624	0.9090	0.9362	0.8759
52	2012-07-03	Soybeans	0.521	0.0783	288.7	271.0	0.9722	0.9128	0.9687	0.9038	0.9468	0.8687
52	2012-07-05	Soybeans	0.642	0.1659	267.2	231.9	0.9113	0.7908	0.8971	0.7640	0.8253	0.6779
52	2012-07-08	Soybeans	0.824	0.1191	282.9	256.7	0.9598	0.8709	0.9515	0.8493	0.9175	0.7943
52	2012-07-10	Soybeans	1.011	0.0854	287.8	270.1	0.9718	0.9120	0.9644	0.8936	0.9395	0.8548
52	2012-07-13	Soybeans	1.388	0.0878	284.0	258.5	0.9462	0.8614	0.9260	0.8201	0.8742	0.7545
52	2012-07-14	Soybeans	1.514	0.0787	286.8	271.1	0.9691	0.9161	0.9562	0.8885	0.9256	0.8478
52	2012-07-19	Soybeans	2.143	0.1017	284.0	261.0	0.9557	0.8781	0.9274	0.8176	0.8767	0.7511
61	2012-06-12	Canola	0.738	0.1900	245.1	207.3	0.8602	0.7276	0.8197	0.6646	0.7612	0.6045
61	2012-06-15	Canola	1.092	0.1440	274.0	249.0	0.9442	0.8578	0.9186	0.8066	0.8923	0.7719
61	2012-06-17	Canola	1.327	0.2153	256.4	228.5	0.8891	0.7923	0.8247	0.6980	0.7679	0.6439
61	2012-06-22	Canola	2.194	0.1863	267.4	242.7	0.9264	0.8407	0.8433	0.7042	0.7924	0.6511
61	2012-06-23	Canola	2.382	0.1555	274.0	258.0	0.9433	0.8881	0.8711	0.7809	0.8293	0.7417
61	2012-06-25	Canola	2.488	0.0898	277.7	270.4	0.9583	0.9330	0.9018	0.8649	0.8700	0.8406

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
61	2012-06-27	Canola	2.325	0.1101	284.6	272.1	0.9646	0.9222	0.9212	0.8502	0.8956	0.8233
61	2012-06-29	Canola	2.162	0.0702	283.3	276.2	0.9706	0.9463	0.9380	0.9012	0.9179	0.8835
61	2012-07-03	Canola	2.598	0.0697	288.6	279.3	0.9779	0.9465	0.9460	0.8886	0.9285	0.8687
61	2012-07-05	Canola	2.943	0.1689	275.7	246.6	0.9434	0.8437	0.8438	0.6416	0.7932	0.5773
61	2012-07-10	Canola	3.558	0.1009	287.6	270.8	0.9767	0.9194	0.9205	0.7800	0.8947	0.7406
61	2012-07-14	Canola	3.261	0.0859	288.5	279.9	0.9762	0.9471	0.9268	0.8673	0.9030	0.8435
61	2012-07-17	Canola	3.038	0.1449	282.3	264.0	0.9621	0.8998	0.8920	0.7641	0.8570	0.7218
61	2012-07-19	Canola	2.889	0.1012	288.1	268.1	0.9698	0.9026	0.9181	0.7801	0.8916	0.7407
62	2012-06-12	Canola	0.151	0.1799	237.2	198.0	0.8322	0.6950	0.8232	0.6817	0.7954	0.6532
62	2012-06-17	Canola	0.131	0.1952	254.5	224.5	0.8798	0.7761	0.8743	0.7677	0.8544	0.7468
62	2012-06-25	Canola	0.186	0.0851	279.8	272.6	0.9600	0.9350	0.9574	0.9315	0.9506	0.9254
62	2012-07-03	Canola	0.965	0.0633	288.1	280.0	0.9754	0.9482	0.9657	0.9320	0.9603	0.9259
62	2012-07-05	Canola	1.372	0.1443	274.6	248.5	0.9405	0.8511	0.9044	0.7807	0.8894	0.7610
62	2012-07-13	Canola	2.394	0.0836	292.1	281.1	0.9812	0.9444	0.9572	0.8908	0.9505	0.8811
62	2012-07-19	Canola	2.705	0.0941	287.1	270.0	0.9671	0.9094	0.9164	0.8057	0.9032	0.7883
71	2012-06-12	Corn	0.045	0.1458	228.2	180.1	0.7983	0.6300	0.7953	0.6255	0.7654	0.5943
71	2012-06-15	Corn	0.103	0.1179	269.4	235.3	0.9185	0.8022	0.9157	0.7966	0.9034	0.7797
71	2012-06-17	Corn	0.142	0.1459	229.8	179.8	0.7950	0.6221	0.7851	0.6073	0.7537	0.5746
71	2012-06-22	Corn	0.260	0.1322	246.7	203.1	0.8514	0.7008	0.8380	0.6790	0.8144	0.6523
71	2012-06-23	Corn	0.301	0.1239	264.2	231.4	0.9015	0.7898	0.8912	0.7719	0.8754	0.7530
71	2012-06-25	Corn	0.382	0.1101	273.7	253.5	0.9338	0.8647	0.9249	0.8500	0.9140	0.8375
71	2012-06-27	Corn	0.463	0.1060	282.1	260.7	0.9493	0.8776	0.9409	0.8613	0.9323	0.8497
71	2012-06-29	Corn	0.640	0.0869	280.8	267.0	0.9521	0.9056	0.9409	0.8878	0.9323	0.8785
71	2012-07-03	Corn	1.182	0.0743	288.4	277.2	0.9708	0.9331	0.9568	0.9079	0.9506	0.9002
71	2012-07-05	Corn	1.453	0.1319	268.4	238.5	0.9151	0.8133	0.8629	0.7235	0.8429	0.7005
71	2012-07-10	Corn	2.091	0.0988	284.0	265.4	0.9599	0.8971	0.9200	0.8189	0.9083	0.8038
71	2012-07-14	Corn	2.580	0.0843	288.2	281.3	0.9696	0.9464	0.9287	0.8924	0.9183	0.8835
71	2012-07-19	Corn	3.191	0.0889	287.4	275.7	0.9663	0.9268	0.9034	0.8265	0.8893	0.8121
72	2012-06-12	Corn	0.052	0.1731	228.5	176.1	0.8014	0.6177	0.7979	0.6123	0.7777	0.5900

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
72	2012-06-15	Corn	0.091	0.1337	269.6	235.0	0.9198	0.8019	0.9173	0.7970	0.9091	0.7853
72	2012-06-17	Corn	0.124	0.1785	237.0	185.5	0.8203	0.6421	0.8128	0.6299	0.7941	0.6086
72	2012-06-22	Corn	0.258	0.1441	259.7	215.6	0.8946	0.7425	0.8852	0.7239	0.8738	0.7080
72	2012-06-23	Corn	0.310	0.1334	269.5	237.6	0.9193	0.8107	0.9106	0.7941	0.9017	0.7823
72	2012-06-25	Corn	0.412	0.1191	277.1	259.1	0.9436	0.8824	0.9353	0.8685	0.9289	0.8610
72	2012-06-27	Corn	0.515	0.1055	286.3	268.4	0.9647	0.9042	0.9581	0.8898	0.9540	0.8835
72	2012-06-29	Corn	0.746	0.0813	284.0	271.0	0.9616	0.9176	0.9508	0.8993	0.9459	0.8935
72	2012-07-03	Corn	1.463	0.0560	288.7	277.0	0.9740	0.9345	0.9578	0.9028	0.9536	0.8972
72	2012-07-05	Corn	1.822	0.1736	266.6	234.8	0.9095	0.8011	0.8348	0.6746	0.8183	0.6559
72	2012-07-10	Corn	2.497	0.1185	282.3	261.3	0.9561	0.8850	0.8999	0.7743	0.8899	0.7613
72	2012-07-13	Corn	2.814	0.1375	287.9	275.6	0.9632	0.9222	0.9067	0.8336	0.8974	0.8241
72	2012-07-14	Corn	2.920	0.0735	287.9	280.0	0.9720	0.9453	0.9265	0.8796	0.9191	0.8727
72	2012-07-17	Corn	3.237	0.1220	276.8	259.7	0.9425	0.8844	0.8326	0.7229	0.8158	0.7069
72	2012-07-19	Corn	3.448	0.0935	286.3	277.6	0.9620	0.9329	0.8812	0.8296	0.8693	0.8198
81	2012-06-12	Wheat	1.093	0.2392	249.1	201.2	0.8740	0.7059	0.8275	0.6198	0.7793	0.5606
81	2012-06-15	Wheat	1.546	0.1632	273.7	242.0	0.9416	0.8326	0.9090	0.7593	0.8836	0.7219
81	2012-06-17	Wheat	1.847	0.2477	261.9	214.0	0.9103	0.7438	0.8474	0.6045	0.8048	0.5430
81	2012-06-22	Wheat	1.612	0.2021	268.7	221.6	0.9299	0.7668	0.8886	0.6595	0.8574	0.6065
81	2012-06-23	Wheat	1.673	0.1665	274.9	238.6	0.9455	0.8206	0.9119	0.7342	0.8872	0.6929
81	2012-06-27	Wheat	1.917	0.1163	287.0	266.2	0.9724	0.9019	0.9521	0.8461	0.9387	0.8221
81	2012-07-05	Wheat	1.817	0.1724	277.2	234.1	0.9486	0.8012	0.9134	0.6953	0.8892	0.6479
81	2012-07-08	Wheat	1.748	0.2375	273.4	228.2	0.9315	0.7777	0.8868	0.6648	0.8552	0.6126
81	2012-07-13	Wheat	1.632	0.1391	285.4	246.3	0.9583	0.8271	0.9333	0.7462	0.9146	0.7067
81	2012-07-17	Wheat	1.540	0.1827	276.4	235.6	0.9416	0.8026	0.9092	0.7165	0.8838	0.6724
91	2012-06-12	Wheat	1.813	0.2179	259.2	224.4	0.9134	0.7905	0.8543	0.6792	0.7595	0.5695
91	2012-06-15	Wheat	2.293	0.1692	274.5	245.0	0.9469	0.8450	0.8974	0.7343	0.8306	0.6435
91	2012-06-17	Wheat	2.613	0.2019	264.8	229.1	0.9219	0.7974	0.8347	0.6256	0.7272	0.4977
91	2012-06-22	Wheat	3.146	0.1994	267.0	229.4	0.9270	0.7965	0.8199	0.5739	0.7027	0.4282
91	2012-06-23	Wheat	3.239	0.2273	272.5	238.9	0.9396	0.8237	0.8468	0.6226	0.7472	0.4936
91	2012-06-25	Wheat	3.281	0.1394	275.3	252.7	0.9536	0.8753	0.8809	0.7304	0.8035	0.6383

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
91	2012-06-27	Wheat	3.177	0.1157	285.4	262.2	0.9684	0.8896	0.9214	0.7672	0.8703	0.6876
91	2012-07-05	Wheat	2.760	0.1734	275.3	238.0	0.9439	0.8160	0.8761	0.6481	0.7955	0.5278
91	2012-07-08	Wheat	2.588	0.1616	278.1	242.5	0.9492	0.8274	0.8931	0.6830	0.8236	0.5746
91	2012-07-10	Wheat	2.451	0.0888	284.7	252.9	0.9676	0.8596	0.9344	0.7502	0.8918	0.6648
91	2012-07-13	Wheat	2.246	0.1243	282.5	249.3	0.9485	0.8369	0.9018	0.7235	0.8380	0.6290
91	2012-07-14	Wheat	2.178	0.1167	284.2	257.5	0.9633	0.8730	0.9314	0.7881	0.8869	0.7156
91	2012-07-17	Wheat	1.973	0.1969	276.2	242.9	0.9417	0.8283	0.8972	0.7270	0.8304	0.6337
91	2012-07-19	Wheat	1.836	0.1332	284.3	257.4	0.9566	0.8661	0.9264	0.7938	0.8786	0.7233
102	2012-06-12	Soybeans	0.024	0.4644	197.8	136.5	0.6899	0.4762	0.6882	0.4739	0.6183	0.4076
102	2012-06-15	Soybeans	0.038	0.4245	249.8	203.4	0.8500	0.6921	0.8487	0.6899	0.8148	0.6509
102	2012-06-17	Soybeans	0.048	0.5715	191.4	136.7	0.6617	0.4725	0.6579	0.4677	0.5813	0.4007
102	2012-06-22	Soybeans	0.049	0.5229	212.9	156.5	0.7297	0.5363	0.7267	0.5320	0.6655	0.4731
102	2012-06-23	Soybeans	0.048	0.4882	232.2	181.9	0.7882	0.6174	0.7858	0.6140	0.7379	0.5654
102	2012-06-25	Soybeans	0.058	0.4294	262.5	230.2	0.8901	0.7804	0.8886	0.7780	0.8636	0.7501
102	2012-06-27	Soybeans	0.081	0.3698	282.8	256.8	0.9481	0.8607	0.9471	0.8585	0.9353	0.8407
102	2012-06-29	Soybeans	0.103	0.2698	283.7	266.9	0.9563	0.8996	0.9553	0.8976	0.9453	0.8847
102	2012-07-03	Soybeans	0.188	0.2048	289.9	272.2	0.9697	0.9106	0.9684	0.9074	0.9613	0.8957
102	2012-07-05	Soybeans	0.237	0.2893	260.1	210.7	0.8808	0.7134	0.8741	0.7004	0.8460	0.6626
102	2012-07-08	Soybeans	0.311	0.2124	282.0	250.3	0.9494	0.8426	0.9456	0.8331	0.9335	0.8121
102	2012-07-10	Soybeans	0.361	0.2284	290.0	267.9	0.9730	0.8988	0.9707	0.8917	0.9641	0.8781
102	2012-07-13	Soybeans	0.438	0.1954	291.1	269.3	0.9677	0.8951	0.9642	0.8861	0.9562	0.8717
102	2012-07-14	Soybeans	0.464	0.1575	290.4	276.0	0.9771	0.9287	0.9745	0.9222	0.9688	0.9124
102	2012-07-17	Soybeans	0.541	0.2384	270.1	223.4	0.9186	0.7598	0.9079	0.7342	0.8872	0.7007
102	2012-07-19	Soybeans	0.592	0.2034	282.8	249.2	0.9514	0.8384	0.9444	0.8194	0.9319	0.7966
103	2012-06-12	Soybeans	0.020	0.4704	197.8	141.0	0.6899	0.4919	0.6885	0.4901	0.6129	0.4207
103	2012-06-15	Soybeans	0.027	0.4696	248.2	200.0	0.8457	0.6814	0.8448	0.6798	0.8071	0.6362
103	2012-06-17	Soybeans	0.031	0.5843	190.2	140.1	0.6647	0.4894	0.6623	0.4864	0.5803	0.4165
103	2012-06-22	Soybeans	0.044	0.5802	207.5	153.0	0.7124	0.5253	0.7094	0.5213	0.6389	0.4561
103	2012-06-23	Soybeans	0.048	0.5632	224.1	174.8	0.7625	0.5948	0.7599	0.5912	0.7016	0.5355

FIELD ID	Sample Date	Crop Type	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
103	2012-06-25	Soybeans	0.055	0.4753	256.9	223.7	0.8732	0.7605	0.8715	0.7579	0.8403	0.7250
103	2012-06-27	Soybeans	0.063	0.3431	279.1	253.1	0.9357	0.8486	0.9348	0.8468	0.9189	0.8260
103	2012-06-29	Soybeans	0.083	0.2584	282.9	262.7	0.9535	0.8855	0.9526	0.8837	0.9410	0.8679
103	2012-07-03	Soybeans	0.151	0.2076	290.3	272.9	0.9713	0.9130	0.9703	0.9105	0.9631	0.8984
103	2012-07-05	Soybeans	0.185	0.2786	253.8	208.1	0.8606	0.7056	0.8546	0.6952	0.8193	0.6537
103	2012-07-08	Soybeans	0.249	0.2279	281.6	251.3	0.9485	0.8463	0.9454	0.8390	0.9322	0.8171
103	2012-07-10	Soybeans	0.309	0.1910	289.8	268.9	0.9721	0.9020	0.9701	0.8961	0.9628	0.8820
103	2012-07-13	Soybeans	0.399	0.1771	293.8	274.9	0.9727	0.9100	0.9701	0.9030	0.9628	0.8898
103	2012-07-14	Soybeans	0.429	0.1872	291.1	277.5	0.9780	0.9324	0.9757	0.9267	0.9698	0.9168
103	2012-07-17	Soybeans	0.519	0.2412	265.1	219.7	0.8998	0.7460	0.8872	0.7199	0.8598	0.6818
103	2012-07-19	Soybeans	0.579	0.2141	282.2	248.9	0.9488	0.8367	0.9415	0.8179	0.9273	0.7931
111	2012-06-12	Soybeans	0.030	0.3869	205.1	145.6	0.7154	0.5077	0.7135	0.5049	0.6544	0.4473
111	2012-06-15	Soybeans	0.045	0.3489	261.4	222.1	0.8874	0.7540	0.8863	0.7519	0.8628	0.7231
111	2012-06-17	Soybeans	0.051	0.3972	220.6	165.8	0.7603	0.5713	0.7575	0.5672	0.7075	0.5169
111	2012-06-22	Soybeans	0.062	0.3215	248.9	196.8	0.8516	0.6734	0.8495	0.6695	0.8185	0.6312
111	2012-06-23	Soybeans	0.068	0.2868	263.2	221.0	0.8892	0.7467	0.8875	0.7434	0.8643	0.7136
111	2012-06-25	Soybeans	0.081	0.2740	276.0	252.3	0.9356	0.8555	0.9344	0.8532	0.9209	0.8362
111	2012-06-27	Soybeans	0.094	0.2319	288.8	269.1	0.9708	0.9044	0.9701	0.9027	0.9640	0.8914
111	2012-07-03	Soybeans	0.256	0.1390	289.8	273.0	0.9759	0.9193	0.9744	0.9153	0.9691	0.9055
111	2012-07-05	Soybeans	0.318	0.2696	252.5	202.2	0.8610	0.6895	0.8504	0.6704	0.8196	0.6321
111	2012-07-08	Soybeans	0.411	0.3320	235.0	182.6	0.7995	0.6214	0.7797	0.5910	0.7343	0.5435
111	2012-07-10	Soybeans	0.488	0.2132	281.1	244.5	0.9509	0.8269	0.9451	0.8103	0.9338	0.7882
111	2012-07-13	Soybeans	0.625	0.1603	291.9	270.7	0.9763	0.9052	0.9726	0.8934	0.9670	0.8810
111	2012-07-19	Soybeans	0.900	0.2059	281.4	253.4	0.9465	0.8524	0.9342	0.8252	0.9206	0.8049
112	2012-06-12	Soybeans	0.035	0.4228	204.9	147.3	0.7160	0.5145	0.7136	0.5113	0.6719	0.4706
112	2012-06-15	Soybeans	0.045	0.3712	258.1	215.9	0.8782	0.7346	0.8769	0.7324	0.8590	0.7101
112	2012-06-17	Soybeans	0.052	0.4621	204.8	149.0	0.7053	0.5130	0.7017	0.5082	0.6582	0.4673
112	2012-06-22	Soybeans	0.071	0.3830	248.0	198.3	0.8507	0.6803	0.8483	0.6760	0.8262	0.6490
112	2012-06-23	Soybeans	0.075	0.3529	259.1	218.9	0.8793	0.7430	0.8772	0.7393	0.8593	0.7177

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112	2012-06-25	Soybeans	0.097	0.3530	271.7	248.7	0.9244	0.8460	0.9227	0.8431	0.9114	0.8301
112	2012-06-27	Soybeans	0.135	0.3015	285.9	263.9	0.9616	0.8875	0.9604	0.8846	0.9546	0.8750
112	2012-06-29	Soybeans	0.173	0.2707	284.3	264.3	0.9624	0.8948	0.9609	0.8913	0.9552	0.8822
112	2012-07-03	Soybeans	0.248	0.2191	288.7	268.7	0.9740	0.9064	0.9725	0.9019	0.9685	0.8938
112	2012-07-05	Soybeans	0.285	0.3126	257.4	212.2	0.8783	0.7241	0.8701	0.7089	0.8511	0.6847
112	2012-07-08	Soybeans	0.342	0.3153	275.8	238.0	0.9366	0.8083	0.9314	0.7956	0.9214	0.7786
112	2012-07-10	Soybeans	0.379	0.2556	285.9	256.7	0.9658	0.8672	0.9627	0.8574	0.9573	0.8455
112	2012-07-13	Soybeans	0.436	0.2265	292.3	270.4	0.9767	0.9037	0.9742	0.8955	0.9705	0.8868
112	2012-07-14	Soybeans	0.455	0.2189	288.7	275.1	0.9744	0.9285	0.9715	0.9221	0.9674	0.9156
112	2012-07-19	Soybeans	0.550	0.2371	282.6	254.9	0.9507	0.8575	0.9440	0.8420	0.9359	0.8289
113	2012-06-12	Soybeans	0.024	0.4073	204.6	145.4	0.7141	0.5073	0.7125	0.5051	0.5843	0.3855
113	2012-06-15	Soybeans	0.028	0.3712	260.1	217.7	0.8849	0.7409	0.8842	0.7396	0.8325	0.6767
113	2012-06-17	Soybeans	0.031	0.5035	196.7	140.8	0.6775	0.4848	0.6752	0.4818	0.5304	0.3567
113	2012-06-22	Soybeans	0.045	0.3980	245.2	195.2	0.8398	0.6686	0.8381	0.6659	0.7659	0.5851
113	2012-06-23	Soybeans	0.048	0.3615	258.5	216.6	0.8739	0.7322	0.8725	0.7298	0.8156	0.6645
113	2012-06-25	Soybeans	0.062	0.3446	272.3	246.7	0.9223	0.8357	0.9212	0.8338	0.8860	0.7937
113	2012-06-27	Soybeans	0.082	0.2971	285.5	262.3	0.9564	0.8789	0.9556	0.8770	0.9357	0.8473
113	2012-06-29	Soybeans	0.102	0.2641	283.7	264.3	0.9563	0.8909	0.9552	0.8888	0.9353	0.8619
113	2012-07-03	Soybeans	0.142	0.1835	289.4	268.3	0.9672	0.8967	0.9662	0.8939	0.9511	0.8683
113	2012-07-05	Soybeans	0.162	0.2835	261.3	213.1	0.8848	0.7216	0.8804	0.7130	0.8271	0.6437
113	2012-07-08	Soybeans	0.209	0.2507	280.8	248.3	0.9425	0.8335	0.9396	0.8268	0.9127	0.7850
113	2012-07-10	Soybeans	0.263	0.2115	288.3	263.1	0.9654	0.8810	0.9632	0.8750	0.9468	0.8448
113	2012-07-13	Soybeans	0.343	0.1936	293.4	271.3	0.9710	0.8978	0.9687	0.8910	0.9547	0.8646
113	2012-07-17	Soybeans	0.451	0.2556	270.5	227.7	0.9179	0.7726	0.9089	0.7525	0.8683	0.6927
113	2012-07-19	Soybeans	0.505	0.2313	284.1	254.3	0.9543	0.8540	0.9486	0.8395	0.9257	0.8007

II. HIGH ALTITUDE SECTION DATA

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
1-10-6W	2012-06-17	0.017	0.2198	253.4	217.6	0.8755	0.7517	0.8748	0.7510	0.7904	0.6631
1-10-6W	2012-06-22	0.017	0.1588	264.4	232.9	0.9476	0.8346	0.9473	0.8342	0.9117	0.7756
1-10-6W	2012-06-23	0.017	0.1418	265.4	237.3	0.8737	0.7812	0.8730	0.7806	0.7873	0.7031
1-10-6W	2012-06-25	0.018	0.1311	270.5	252.1	0.8944	0.8334	0.8937	0.8329	0.8220	0.7739
1-10-6W	2012-06-29	0.028	0.1288	276.4	257.2	0.9065	0.8437	0.9056	0.8430	0.8420	0.7875
1-10-6W	2012-07-03	0.062	0.1395	282.7	258.8	0.9239	0.8456	0.9223	0.8441	0.8699	0.7891
1-10-6W	2012-07-10	0.127	0.1228	281.1	263.2	0.9182	0.8596	0.9146	0.8568	0.8571	0.8063
1-10-6W	2012-07-13	0.169	0.1198	278.4	255.3	0.9182	0.8423	0.9134	0.8380	0.8550	0.7808
1-10-6W	2012-07-14	0.183	0.1137	284.8	267.1	0.9454	0.8867	0.9419	0.8835	0.9028	0.8423
1-10-6W	2012-07-17	0.225	0.1655	272.7	246.3	0.9105	0.8223	0.9034	0.8159	0.8382	0.7510
11-8-4W	2012-06-12	0.022	0.4674	241.6	190.1	0.8202	0.6454	0.8188	0.6442	0.6967	0.5186
11-8-4W	2012-06-15	0.033	0.4470	264.7	227.9	0.8909	0.7667	0.8897	0.7655	0.8153	0.6828
11-8-4W	2012-06-17	0.040	0.5780	226.2	176.7	0.7772	0.6071	0.7741	0.6047	0.6218	0.4651
11-8-4W	2012-06-22	0.047	0.5532	244.2	195.0	0.8152	0.6510	0.8123	0.6485	0.6857	0.5244
11-8-4W	2012-06-23	0.048	0.5260	254.2	209.4	0.8468	0.6974	0.8443	0.6952	0.7393	0.5875
11-8-4W	2012-06-25	0.057	0.4523	273.2	243.8	0.9015	0.8044	0.8996	0.8026	0.8319	0.7329
11-8-4W	2012-06-29	0.093	0.2647	289.6	271.1	0.9408	0.8808	0.9389	0.8790	0.8976	0.8363
11-8-4W	2012-07-03	0.170	0.2065	295.7	273.7	0.9629	0.8911	0.9607	0.8881	0.9342	0.8486
11-8-4W	2012-07-10	0.335	0.2097	293.7	275.9	0.9642	0.9058	0.9599	0.9007	0.9328	0.8656
11-8-4W	2012-07-13	0.418	0.1862	292.3	268.2	0.9723	0.8921	0.9681	0.8847	0.9465	0.8440
11-8-4W	2012-07-14	0.446	0.1724	295.0	277.3	0.9770	0.9182	0.9732	0.9123	0.9551	0.8813
11-8-4W	2012-07-17	0.530	0.2398	277.4	234.4	0.9396	0.7941	0.9277	0.7762	0.8789	0.6972
11-8-4W	2012-07-19	0.585	0.2087	284.0	250.2	0.9566	0.8427	0.9471	0.8276	0.9114	0.7667
13-7-5W	2012-06-12	0.835	0.2318	240.2	203.1	0.8372	0.7079	0.7839	0.6670	0.6381	0.5495
13-7-5W	2012-06-17	1.689	0.2176	242.8	199.5	0.8410	0.6911	0.7180	0.5975	0.5278	0.4553
13-7-5W	2012-06-22	2.393	0.2124	258.4	223.3	0.8913	0.7701	0.7551	0.6656	0.5899	0.5475
13-7-5W	2012-06-23	2.514	0.1874	266.7	241.2	0.9035	0.8173	0.7735	0.7291	0.6208	0.6334

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
13-7-5W	2012-06-25	2.613	0.1525	273.7	256.7	0.9263	0.8686	0.8211	0.8021	0.7005	0.7323
13-7-5W	2012-06-27	2.569	0.1352	279.8	266.8	0.9428	0.8992	0.8631	0.8492	0.7709	0.7960
13-7-5W	2012-07-05	2.393	0.2167	266.5	232.1	0.9122	0.7946	0.8022	0.7012	0.6689	0.5957
13-7-5W	2012-07-08	2.298	0.2436	255.6	212.6	0.8708	0.7243	0.7182	0.6048	0.5282	0.4653
13-7-5W	2012-07-10	2.197	0.1690	278.7	254.1	0.9464	0.8631	0.8870	0.8069	0.8109	0.7387
13-7-5W	2012-07-13	2.045	0.1803	280.7	258.1	0.9513	0.8747	0.9024	0.8274	0.8366	0.7664
13-7-5W	2012-07-14	1.995	0.1475	282.6	268.1	0.9616	0.9120	0.9244	0.8797	0.8734	0.8372
13-7-5W	2012-07-17	1.843	0.1629	272.5	243.7	0.9329	0.8343	0.8746	0.7788	0.7901	0.7007
14-7-4W	2012-06-15	0.045	0.3489	269.6	232.6	0.9264	0.7991	0.9253	0.7977	0.8749	0.7263
14-7-4W	2012-06-17	0.051	0.3972	248.8	203.8	0.8669	0.7102	0.8646	0.7078	0.7732	0.6047
14-7-4W	2012-06-23	0.068	0.2868	267.2	230.2	0.9187	0.7915	0.9168	0.7892	0.8606	0.7148
14-7-4W	2012-06-25	0.081	0.2740	275.0	252.4	0.9457	0.8678	0.9442	0.8662	0.9065	0.8189
14-7-4W	2012-06-27	0.094	0.2319	285.5	259.3	0.9658	0.8773	0.9647	0.8755	0.9409	0.8316
14-7-4W	2012-07-03	0.256	0.1390	288.5	267.9	0.9753	0.9055	0.9731	0.9017	0.9549	0.8670
14-7-4W	2012-07-05	0.318	0.2696	274.8	227.0	0.9257	0.7647	0.9173	0.7527	0.8615	0.6653
14-7-4W	2012-07-08	0.411	0.3320	276.7	234.2	0.9371	0.7931	0.9277	0.7793	0.8789	0.7014
14-7-4W	2012-07-13	0.625	0.1603	292.1	265.4	0.9748	0.8858	0.9688	0.8741	0.9478	0.8296
14-7-4W	2012-07-17	0.808	0.2632	276.7	236.9	0.9320	0.7981	0.9106	0.7708	0.8503	0.6899
14-7-4W	2012-07-19	0.900	0.2059	282.1	246.2	0.9461	0.8259	0.9268	0.7995	0.8775	0.7287
17-8-4W	2012-06-15	0.185	0.2255	267.1	237.0	0.8800	0.7807	0.8722	0.7742	0.7861	0.6945
17-8-4W	2012-06-17	0.209	0.2886	238.8	200.5	0.8311	0.6978	0.8187	0.6877	0.6965	0.5775
17-8-4W	2012-06-23	0.306	0.2326	269.6	241.4	0.9011	0.8066	0.8903	0.7971	0.8162	0.7254
17-8-4W	2012-06-25	0.369	0.2017	281.1	263.8	0.9374	0.8797	0.9291	0.8725	0.8812	0.8275
17-8-4W	2012-06-27	0.431	0.1801	290.0	271.4	0.9684	0.9062	0.9635	0.8997	0.9388	0.8643
17-8-4W	2012-07-03	0.702	0.1221	292.8	272.8	0.9739	0.9073	0.9668	0.8965	0.9445	0.8599
17-8-4W	2012-07-05	0.821	0.1579	277.3	242.5	0.9230	0.8070	0.8982	0.7805	0.8296	0.7030
17-8-4W	2012-07-10	1.183	0.1371	292.3	276.5	0.9760	0.9232	0.9641	0.9075	0.9399	0.8749
17-8-4W	2012-07-13	1.554	0.1726	284.5	254.9	0.9565	0.8573	0.9263	0.8179	0.8767	0.7537
17-8-4W	2012-07-14	1.678	0.1509	288.8	262.7	0.9604	0.8738	0.9300	0.8359	0.8829	0.7779
17-8-4W	2012-07-17	2.049	0.2348	278.2	248.9	0.9467	0.8469	0.8931	0.7889	0.8210	0.7144

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
17-8-4W	2012-07-19	2.296	0.1865	282.3	256.7	0.9462	0.8604	0.8826	0.8000	0.8035	0.7294
19-6-3W	2012-06-12	0.038	0.3718	209.0	164.0	0.7290	0.5719	0.7255	0.5694	0.5405	0.4173
19-6-3W	2012-06-15	0.043	0.2788	266.6	236.0	0.9062	0.8024	0.9049	0.8010	0.8407	0.7308
19-6-3W	2012-06-17	0.047	0.3642	233.6	190.1	0.8186	0.6661	0.8156	0.6636	0.6913	0.5448
19-6-3W	2012-06-22	0.063	0.3469	253.9	214.3	0.8729	0.7368	0.8701	0.7342	0.7826	0.6403
19-6-3W	2012-06-23	0.065	0.2802	265.8	234.5	0.8976	0.7922	0.8953	0.7900	0.8248	0.7159
19-6-3W	2012-06-25	0.071	0.2276	277.0	254.0	0.9362	0.8586	0.9347	0.8570	0.8906	0.8065
19-6-3W	2012-06-27	0.076	0.2409	285.9	271.2	0.9669	0.9173	0.9660	0.9163	0.9431	0.8867
19-6-3W	2012-07-03	0.155	0.2055	288.9	270.8	0.9669	0.9061	0.9652	0.9038	0.9417	0.8699
19-6-3W	2012-07-05	0.185	0.2235	270.0	234.4	0.9154	0.7944	0.9099	0.7884	0.8491	0.7136
19-6-3W	2012-07-08	0.257	0.1977	268.7	229.1	0.9057	0.7722	0.8972	0.7629	0.8278	0.6791
19-6-3W	2012-07-10	0.339	0.2043	284.8	263.0	0.9492	0.8766	0.9430	0.8699	0.9046	0.8239
19-6-3W	2012-07-13	0.463	0.1408	284.4	256.7	0.9564	0.8630	0.9489	0.8527	0.9145	0.8007
19-6-3W	2012-07-17	0.628	0.2484	267.3	230.0	0.9086	0.7817	0.8868	0.7592	0.8105	0.6741
1-9-6W	2012-06-22	0.218	0.3425	250.1	221.5	0.8552	0.7573	0.8441	0.7488	0.7390	0.6601
1-9-6W	2012-06-25	0.204	0.3163	261.4	240.4	0.8914	0.8199	0.8836	0.8141	0.8051	0.7484
1-9-6W	2012-06-29	0.182	0.2665	262.4	236.6	0.8798	0.7934	0.8722	0.7874	0.7860	0.7124
1-9-6W	2012-07-03	0.199	0.2745	273.5	246.3	0.9231	0.8311	0.9177	0.8258	0.8622	0.7643
1-9-6W	2012-07-10	0.250	0.2232	266.4	240.4	0.8911	0.8043	0.8814	0.7964	0.8015	0.7246
1-9-6W	2012-07-13	0.272	0.2977	265.4	241.3	0.8809	0.8009	0.8694	0.7922	0.7814	0.7188
20-6-3W	2012-06-12	1.348	0.4373	238.8	196.5	0.8308	0.6838	0.7326	0.6095	0.5523	0.4715
20-6-3W	2012-06-15	1.654	0.3575	268.2	232.2	0.9127	0.7903	0.8470	0.7283	0.7439	0.6323
20-6-3W	2012-06-17	1.859	0.4531	255.0	216.4	0.8859	0.7516	0.7855	0.6676	0.6409	0.5503
20-6-3W	2012-06-22	2.874	0.4209	262.3	225.6	0.8988	0.7728	0.7315	0.6436	0.5505	0.5178
20-6-3W	2012-06-23	3.173	0.3702	269.5	237.7	0.9135	0.8053	0.7460	0.6800	0.5747	0.5670
20-6-3W	2012-06-25	3.408	0.2459	276.7	254.8	0.9350	0.8608	0.7934	0.7626	0.6541	0.6788
20-6-3W	2012-06-27	3.282	0.2340	284.4	261.6	0.9602	0.8833	0.8789	0.8048	0.7972	0.7359
20-6-3W	2012-06-29	3.156	0.1627	284.2	264.9	0.9588	0.8937	0.8796	0.8257	0.7985	0.7642
20-6-3W	2012-07-03	3.046	0.1603	288.8	267.5	0.9714	0.8997	0.9196	0.8384	0.8654	0.7813
20-6-3W	2012-07-05	3.015	0.2338	277.2	245.9	0.9392	0.8329	0.8307	0.7320	0.7165	0.6373

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
20-6-3W	2012-07-08	2.966	0.3108	269.5	232.4	0.9172	0.7910	0.7734	0.6673	0.6206	0.5499
20-6-3W	2012-07-10	2.876	0.2329	281.2	254.0	0.9544	0.8620	0.8790	0.7834	0.7975	0.7070
20-6-3W	2012-07-13	2.660	0.2519	279.6	250.6	0.9442	0.8465	0.8624	0.7671	0.7696	0.6848
20-6-3W	2012-07-14	2.589	0.1869	279.3	253.1	0.9501	0.8611	0.8798	0.7917	0.7987	0.7181
20-6-3W	2012-07-17	2.373	0.3652	271.1	237.3	0.9258	0.8105	0.8339	0.7252	0.7220	0.6281
20-7-4W	2012-06-12	0.049	0.1594	230.3	183.6	0.7996	0.6374	0.7962	0.6346	0.6588	0.5056
20-7-4W	2012-06-15	0.097	0.1258	270.8	240.8	0.9140	0.8129	0.9112	0.8100	0.8512	0.7429
20-7-4W	2012-06-17	0.133	0.1622	242.2	197.7	0.8401	0.6855	0.8327	0.6789	0.7199	0.5655
20-7-4W	2012-06-22	0.259	0.1382	263.5	227.7	0.8978	0.7757	0.8884	0.7664	0.8131	0.6839
20-7-4W	2012-06-23	0.305	0.1286	272.3	245.3	0.9178	0.8267	0.9088	0.8182	0.8473	0.7541
20-7-4W	2012-06-25	0.397	0.1146	278.3	263.1	0.9348	0.8835	0.9254	0.8760	0.8750	0.8323
20-7-4W	2012-06-27	0.489	0.1057	285.3	269.6	0.9599	0.9073	0.9527	0.9000	0.9208	0.8646
20-7-4W	2012-06-29	0.693	0.0841	286.3	274.0	0.9583	0.9170	0.9472	0.9075	0.9117	0.8748
20-7-4W	2012-07-03	1.322	0.0652	289.9	276.7	0.9701	0.9260	0.9532	0.9090	0.9216	0.8769
20-7-4W	2012-07-05	1.637	0.1527	280.8	248.8	0.9494	0.8409	0.9118	0.7944	0.8523	0.7218
20-7-4W	2012-07-08	2.066	0.1645	268.9	235.0	0.9149	0.7995	0.8284	0.7229	0.7127	0.6251
20-7-4W	2012-07-10	2.294	0.1086	285.2	267.5	0.9645	0.9049	0.9227	0.8637	0.8706	0.8156
20-7-4W	2012-07-13	2.636	0.1332	289.8	274.3	0.9735	0.9216	0.9351	0.8815	0.8914	0.8396
20-7-4W	2012-07-14	2.750	0.0789	288.1	274.8	0.9767	0.9316	0.9406	0.8948	0.9006	0.8576
20-7-4W	2012-07-17	3.092	0.1398	278.0	257.5	0.9498	0.8800	0.8568	0.8052	0.7602	0.7364
20-7-4W	2012-07-19	3.319	0.0912	286.1	270.0	0.9680	0.9137	0.9013	0.8548	0.8348	0.8035
20-8-4W	2012-06-12	2.158	0.4261	246.0	203.4	0.8444	0.6982	0.6762	0.5768	0.4579	0.4273
20-8-4W	2012-06-15	2.309	0.3995	268.7	236.1	0.9050	0.7952	0.7920	0.7059	0.6517	0.6020
20-8-4W	2012-06-17	2.411	0.4336	248.6	205.5	0.8605	0.7113	0.6838	0.5788	0.4706	0.4301
20-8-4W	2012-06-22	2.643	0.3977	261.8	224.3	0.8987	0.7700	0.7515	0.6520	0.5840	0.5291
20-8-4W	2012-06-23	2.672	0.3676	269.1	236.6	0.9124	0.8020	0.7830	0.6990	0.6368	0.5928
20-8-4W	2012-06-25	2.732	0.3232	280.0	265.4	0.9468	0.8973	0.8655	0.8424	0.7749	0.7867
20-8-4W	2012-07-10	2.771	0.1613	291.5	270.7	0.9817	0.9120	0.9532	0.8641	0.9216	0.8161
20-8-4W	2012-07-13	2.453	0.2720	283.6	249.8	0.9566	0.8426	0.9002	0.7688	0.8329	0.6872

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
20-8-4W	2012-07-14	2.347	0.1884	289.8	259.9	0.9747	0.8743	0.9439	0.8185	0.9060	0.7544
20-8-4W	2012-07-17	2.029	0.3113	278.3	243.4	0.9468	0.8280	0.8941	0.7637	0.8227	0.6802
21-8-4W	2012-06-12	1.934	0.4542	252.3	211.3	0.8756	0.7335	0.7603	0.6392	0.5986	0.5118
21-8-4W	2012-06-15	2.066	0.4043	270.0	241.2	0.9204	0.8224	0.8396	0.7545	0.7314	0.6679
21-8-4W	2012-06-17	2.154	0.4876	253.8	213.6	0.8804	0.7407	0.7514	0.6367	0.5838	0.5084
21-8-4W	2012-06-22	2.501	0.4076	267.9	235.5	0.9313	0.8189	0.8395	0.7320	0.7313	0.6374
21-8-4W	2012-06-23	2.671	0.4282	272.8	244.7	0.9332	0.8370	0.8345	0.7523	0.7229	0.6649
21-8-4W	2012-06-25	2.759	0.3798	281.2	263.2	0.9573	0.8958	0.8910	0.8395	0.8174	0.7828
21-8-4W	2012-07-10	2.065	0.2488	293.0	273.4	0.9854	0.9194	0.9706	0.8885	0.9509	0.8492
21-8-4W	2012-07-13	2.161	0.3196	288.3	256.8	0.9715	0.8655	0.9407	0.8113	0.9007	0.7446
21-8-4W	2012-07-14	2.193	0.2323	290.8	268.0	0.9775	0.9010	0.9526	0.8604	0.9206	0.8111
21-8-4W	2012-07-17	2.290	0.3347	281.9	245.2	0.9572	0.8325	0.9069	0.7603	0.8441	0.6756
23-6-4W	2012-06-12	3.821	0.3525	229.5	189.5	0.8067	0.6659	0.2930	0.3921	-0.1837	0.1774
23-6-4W	2012-06-15	6.179	0.2546	265.1	228.8	0.9167	0.7912	0.3217	0.4504	-0.1357	0.2563
23-6-4W	2012-06-17	7.750	0.3467	243.8	201.1	0.8517	0.7026	-1.0590	-0.0015	-2.4473	-0.3551
23-6-4W	2012-06-23	14.364	0.3092	264.9	230.4	0.9148	0.7957	-10.159	-0.9389	-17.684	-1.6235
23-6-4W	2012-06-25	14.899	0.2443	272.5	246.4	0.9419	0.8519	-8.1217	-0.5286	-14.272	-1.0684
23-6-4W	2012-06-27	13.447	0.2404	283.2	264.2	0.9671	0.9022	-2.1539	0.1961	-4.2806	-0.0877
23-6-4W	2012-06-29	11.994	0.1351	282.5	262.3	0.9723	0.9027	-0.6268	0.3633	-1.7237	0.1384
23-6-4W	2012-07-03	9.090	0.1855	288.0	266.6	0.9804	0.9074	0.5710	0.6154	0.2818	0.4796
23-6-4W	2012-07-08	6.090	0.2542	277.8	239.7	0.9510	0.8206	0.6125	0.5342	0.3512	0.3697
23-6-4W	2012-07-10	5.896	0.1828	284.2	256.2	0.9701	0.8747	0.7785	0.6844	0.6292	0.5729
23-6-4W	2012-07-14	5.508	0.1943	279.4	251.6	0.9540	0.8591	0.7014	0.6660	0.5001	0.5480
23-6-4W	2012-07-17	5.218	0.3204	271.0	231.1	0.9277	0.7912	0.5753	0.5271	0.2890	0.3601
23-6-4W	2012-07-19	5.024	0.2292	279.5	247.2	0.9485	0.8389	0.7165	0.6461	0.5254	0.5211
24-8-6W	2012-06-12	0.321	0.3371	243.7	210.8	0.8522	0.7372	0.8352	0.7237	0.7241	0.6261
24-8-6W	2012-06-15	0.364	0.3289	261.9	230.4	0.9007	0.7922	0.8876	0.7800	0.8118	0.7024
24-8-6W	2012-06-17	0.393	0.3258	249.4	215.9	0.8690	0.7521	0.8503	0.7364	0.7493	0.6433
24-8-6W	2012-06-22	0.465	0.3354	255.6	226.0	0.8867	0.7840	0.8673	0.7677	0.7779	0.6857
24-8-6W	2012-06-23	0.479	0.3295	262.3	235.0	0.8990	0.8054	0.8812	0.7902	0.8011	0.7161

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
24-8-6W	2012-06-25	0.470	0.3130	267.9	249.4	0.9155	0.8521	0.9010	0.8408	0.8342	0.7846
24-8-6W	2012-06-27	0.422	0.3065	274.0	257.3	0.9273	0.8705	0.9161	0.8617	0.8595	0.8129
24-8-6W	2012-06-29	0.375	0.2807	274.4	256.7	0.9343	0.8737	0.9253	0.8660	0.8750	0.8187
24-8-6W	2012-07-03	0.309	0.2641	280.2	260.8	0.9397	0.8744	0.9330	0.8682	0.8878	0.8217
24-8-6W	2012-07-08	0.245	0.2848	273.4	243.7	0.9280	0.8272	0.9217	0.8204	0.8690	0.7570
25-6-4W	2012-06-12	2.835	0.3748	208.5	161.8	0.7247	0.5623	0.2796	0.3176	-0.2062	0.0766
25-6-4W	2012-06-15	5.148	0.3292	261.1	227.7	0.8823	0.7692	0.3248	0.4831	-0.1306	0.3006
25-6-4W	2012-06-17	6.690	0.3720	231.2	186.5	0.8118	0.6548	-0.8232	0.0154	-2.0526	-0.3323
25-6-4W	2012-06-23	8.118	0.3450	263.9	233.6	0.8961	0.7931	-0.6337	0.2618	-1.7352	0.0012
25-6-4W	2012-06-25	8.061	0.2880	273.8	252.4	0.9270	0.8543	-0.1261	0.4848	-0.8854	0.3029
25-6-4W	2012-06-27	8.004	0.2878	283.5	269.0	0.9579	0.9087	0.3624	0.6802	-0.0675	0.5672
25-6-4W	2012-06-29	7.866	0.1935	282.9	268.5	0.9538	0.9053	0.3334	0.6754	-0.1161	0.5608
25-6-4W	2012-07-03	7.429	0.1837	287.1	270.2	0.9687	0.9118	0.6105	0.7174	0.3478	0.6176
25-6-4W	2012-07-05	7.210	0.2551	278.3	253.4	0.9417	0.8577	0.3260	0.5596	-0.1285	0.4040
25-6-4W	2012-07-08	6.883	0.3248	264.2	227.4	0.9015	0.7759	-0.0186	0.3411	-0.7054	0.1085
25-6-4W	2012-07-10	6.499	0.2670	282.9	261.2	0.9600	0.8862	0.6369	0.6850	0.3920	0.5738
25-6-4W	2012-07-17	4.579	0.3326	270.3	241.2	0.9236	0.8239	0.6383	0.6391	0.3944	0.5116
25-9-6W	2012-06-12	0.431	0.3666	253.6	227.1	0.8617	0.7715	0.8400	0.7556	0.7321	0.6693
25-9-6W	2012-06-15	0.425	0.3298	259.9	232.8	0.8696	0.7788	0.8493	0.7636	0.7478	0.6801
25-9-6W	2012-06-23	0.354	0.3153	257.4	234.7	0.8682	0.7918	0.8513	0.7800	0.7511	0.7023
25-9-6W	2012-06-25	0.354	0.3132	263.6	242.3	0.8783	0.8074	0.8628	0.7964	0.7703	0.7245
25-9-6W	2012-06-27	0.379	0.2749	270.0	247.4	0.8951	0.8201	0.8807	0.8091	0.8002	0.7417
25-9-6W	2012-07-03	0.414	0.2381	272.0	245.7	0.8961	0.8094	0.8804	0.7967	0.7997	0.7249
25-9-6W	2012-07-05	0.412	0.2229	271.5	245.4	0.8922	0.8064	0.8760	0.7935	0.7924	0.7206
25-9-6W	2012-07-10	0.423	0.2232	275.1	254.0	0.9024	0.8331	0.8873	0.8217	0.8113	0.7587
25-9-6W	2012-07-13	0.467	0.2911	270.1	246.6	0.8958	0.8181	0.8778	0.8043	0.7955	0.7351
25-9-6W	2012-07-17	0.526	0.2792	268.4	245.9	0.8996	0.8243	0.8800	0.8092	0.7991	0.7419
26-7-4W	2012-06-12	0.030	0.4150	246.9	197.7	0.8448	0.6766	0.8433	0.6751	0.7376	0.5603
26-7-4W	2012-06-15	0.037	0.3712	266.5	230.6	0.8941	0.7738	0.8928	0.7725	0.8204	0.6922
26-7-4W	2012-06-22	0.058	0.3905	257.5	211.5	0.8748	0.7184	0.8723	0.7159	0.7863	0.6155

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
26-7-4W	2012-06-23	0.061	0.3572	265.4	227.4	0.8900	0.7624	0.8877	0.7601	0.8120	0.6754
26-7-4W	2012-06-25	0.080	0.3488	277.4	254.7	0.9244	0.8488	0.9223	0.8469	0.8699	0.7928
26-7-4W	2012-06-27	0.108	0.2993	286.2	262.2	0.9339	0.8555	0.9314	0.8530	0.8852	0.8012
26-7-4W	2012-06-29	0.137	0.2674	288.2	267.0	0.9564	0.8857	0.9543	0.8832	0.9235	0.8420
26-7-4W	2012-07-03	0.195	0.2013	292.6	269.0	0.9705	0.8923	0.9684	0.8889	0.9471	0.8497
26-7-4W	2012-07-05	0.224	0.2980	276.1	231.1	0.9123	0.7636	0.9054	0.7552	0.8416	0.6687
26-7-4W	2012-07-10	0.321	0.2335	289.7	266.7	0.9663	0.8896	0.9624	0.8839	0.9370	0.8430
26-7-4W	2012-07-13	0.390	0.2101	293.5	272.7	0.9752	0.9059	0.9717	0.9000	0.9525	0.8647
26-7-4W	2012-07-14	0.413	0.2068	295.4	273.6	0.9761	0.9041	0.9725	0.8977	0.9540	0.8616
26-7-4W	2012-07-17	0.481	0.2712	279.1	237.7	0.9435	0.8037	0.9335	0.7883	0.8887	0.7136
26-7-4W	2012-07-19	0.527	0.2342	285.3	251.4	0.9571	0.8435	0.9487	0.8300	0.9141	0.7700
26-8-5W	2012-06-12	0.107	0.1683	253.1	214.1	0.8646	0.7312	0.8596	0.7267	0.7650	0.6302
26-8-5W	2012-06-15	0.096	0.1402	271.8	242.2	0.9166	0.8166	0.9139	0.8139	0.8558	0.7481
26-8-5W	2012-06-22	0.123	0.1494	263.8	233.6	0.9030	0.7996	0.8989	0.7957	0.8307	0.7236
26-8-5W	2012-06-23	0.138	0.1371	271.4	250.4	0.9183	0.8473	0.9144	0.8440	0.8567	0.7889
26-8-5W	2012-06-25	0.169	0.1046	278.7	265.7	0.9295	0.8861	0.9253	0.8831	0.8750	0.8418
26-8-5W	2012-06-29	0.231	0.0751	284.7	273.2	0.9533	0.9150	0.9495	0.9119	0.9154	0.8808
26-8-5W	2012-07-03	0.351	0.0763	289.1	274.0	0.9473	0.8977	0.9406	0.8919	0.9006	0.8537
26-8-5W	2012-07-10	0.596	0.0577	289.2	278.7	0.9546	0.9200	0.9444	0.9122	0.9069	0.8812
26-8-5W	2012-07-13	0.701	0.1304	274.1	243.7	0.9156	0.8138	0.8929	0.7921	0.8207	0.7187
26-8-5W	2012-07-14	0.736	0.0967	280.3	255.1	0.9318	0.8482	0.9124	0.8296	0.8534	0.7695
26-8-5W	2012-07-17	0.841	0.1331	274.5	247.9	0.9219	0.8326	0.8960	0.8090	0.8259	0.7416
27-7-4W	2012-06-12	0.026	0.3383	241.5	192.0	0.8326	0.6620	0.8311	0.6606	0.7172	0.5408
27-7-4W	2012-06-15	0.062	0.2814	264.7	225.8	0.9014	0.7689	0.8993	0.7667	0.8314	0.6843
27-7-4W	2012-06-22	0.641	0.3052	258.9	214.2	0.8861	0.7332	0.8584	0.7050	0.7629	0.6009
27-7-4W	2012-06-23	0.724	0.2699	267.0	231.6	0.9082	0.7879	0.8827	0.7625	0.8036	0.6786
27-7-4W	2012-06-25	0.896	0.2339	276.2	252.1	0.9373	0.8555	0.9150	0.8337	0.8577	0.7750
27-7-4W	2012-06-27	1.074	0.2087	287.0	261.3	0.9673	0.8806	0.9530	0.8587	0.9212	0.8088
27-7-4W	2012-06-29	1.253	0.1761	286.9	265.6	0.9705	0.8983	0.9549	0.8763	0.9244	0.8326
27-7-4W	2012-07-03	1.451	0.1510	292.8	272.5	0.9812	0.9132	0.9692	0.8911	0.9484	0.8526

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
27-7-4W	2012-07-05	1.523	0.2569	279.6	241.6	0.9434	0.8151	0.9050	0.7652	0.8410	0.6823
27-7-4W	2012-07-10	1.811	0.1928	286.9	262.6	0.9660	0.8844	0.9371	0.8465	0.8946	0.7923
27-7-4W	2012-07-13	2.203	0.1832	293.0	273.6	0.9840	0.9189	0.9663	0.8855	0.9435	0.8451
27-7-4W	2012-07-14	2.334	0.1714	294.9	273.7	0.9876	0.9168	0.9726	0.8800	0.9541	0.8377
27-7-4W	2012-07-17	2.726	0.2583	278.1	238.2	0.9452	0.8094	0.8618	0.7079	0.7686	0.6047
29-7-4W	2012-06-15	1.092	0.1440	272.9	243.1	0.9338	0.8316	0.9041	0.8002	0.8395	0.7297
29-7-4W	2012-06-17	1.327	0.2153	253.2	217.2	0.8813	0.7561	0.8138	0.6997	0.6882	0.5937
29-7-4W	2012-06-22	2.194	0.1863	268.2	232.9	0.9249	0.8032	0.8418	0.7225	0.7352	0.6245
29-7-4W	2012-06-25	2.488	0.0898	278.7	267.4	0.9593	0.9204	0.9052	0.8824	0.8414	0.8409
29-7-4W	2012-06-29	2.162	0.0702	287.3	273.8	0.9789	0.9330	0.9561	0.9059	0.9265	0.8727
29-7-4W	2012-07-03	2.598	0.0695	290.0	274.0	0.9815	0.9274	0.9552	0.8910	0.9251	0.8525
29-7-4W	2012-07-08	3.460	0.1455	283.7	250.8	0.9755	0.8624	0.9207	0.7634	0.8673	0.6798
29-7-4W	2012-07-10	3.558	0.1009	286.9	267.7	0.9729	0.9077	0.9094	0.8389	0.8484	0.7820
29-7-4W	2012-07-13	3.335	0.0985	290.3	273.6	0.9732	0.9175	0.9170	0.8609	0.8610	0.8118
29-7-4W	2012-07-14	3.261	0.0859	292.6	278.0	0.9721	0.9236	0.9157	0.8727	0.8588	0.8278
29-7-4W	2012-07-17	3.038	0.1450	281.1	247.4	0.9517	0.8376	0.8645	0.7387	0.7731	0.6464
32-7-4W	2012-06-15	0.090	0.1783	272.5	237.6	0.9167	0.7993	0.9141	0.7964	0.8562	0.7245
32-7-4W	2012-06-17	0.098	0.2212	248.8	215.2	0.8616	0.7451	0.8569	0.7412	0.7604	0.6498
32-7-4W	2012-06-23	0.124	0.1704	272.0	249.3	0.9228	0.8459	0.9195	0.8429	0.8653	0.7874
32-7-4W	2012-06-25	0.152	0.1210	277.5	266.8	0.9414	0.9050	0.9383	0.9027	0.8967	0.8683
32-7-4W	2012-06-27	0.194	0.1278	286.4	271.2	0.9631	0.9119	0.9606	0.9092	0.9340	0.8771
32-7-4W	2012-06-29	0.237	0.0905	287.2	277.6	0.9923	0.9593	0.9916	0.9577	0.9859	0.9428
32-7-4W	2012-07-03	0.512	0.0754	289.0	276.3	0.9771	0.9338	0.9727	0.9283	0.9543	0.9030
32-7-4W	2012-07-05	0.681	0.1472	280.3	249.5	0.9422	0.8387	0.9272	0.8205	0.8780	0.7572
32-7-4W	2012-07-10	1.058	0.0894	287.8	276.0	0.9775	0.9373	0.9678	0.9260	0.9461	0.8999
32-7-4W	2012-07-13	1.181	0.0793	291.0	278.7	0.9765	0.9354	0.9649	0.9222	0.9413	0.8947
32-7-4W	2012-07-14	1.222	0.0872	292.5	280.2	0.9857	0.9444	0.9783	0.9326	0.9636	0.9088
32-7-4W	2012-07-17	1.346	0.1461	284.6	261.6	0.9691	0.8909	0.9512	0.8653	0.9184	0.8178
32-7-4W	2012-07-19	1.428	0.0941	289.1	268.6	0.9705	0.9018	0.9520	0.8772	0.9197	0.8339
33-6-4W	2012-06-12	0.131	0.2971	229.3	190.0	0.8036	0.6657	0.7946	0.6587	0.6562	0.5382

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
33-6-4W	2012-06-15	0.270	0.1775	264.4	230.2	0.9125	0.7943	0.9041	0.7854	0.8394	0.7096
33-6-4W	2012-06-17	0.362	0.2594	247.7	207.0	0.8645	0.7224	0.8467	0.7062	0.7434	0.6025
33-6-4W	2012-06-22	0.619	0.2118	256.4	221.3	0.8917	0.7696	0.8663	0.7461	0.7762	0.6564
33-6-4W	2012-06-23	0.672	0.2739	266.9	236.8	0.9187	0.8154	0.8979	0.7949	0.8290	0.7225
33-6-4W	2012-06-25	0.868	0.1436	273.0	253.4	0.9398	0.8723	0.9192	0.8537	0.8647	0.8020
33-6-4W	2012-06-27	1.156	0.1544	282.0	266.1	0.9624	0.9082	0.9443	0.8900	0.9067	0.8511
33-6-4W	2012-06-29	1.444	0.0831	281.0	264.0	0.9636	0.9056	0.9406	0.8816	0.9005	0.8398
33-6-4W	2012-07-03	2.161	0.0601	286.8	269.5	0.9734	0.9149	0.9445	0.8806	0.9071	0.8385
33-6-4W	2012-07-05	2.544	0.1410	274.2	239.0	0.9362	0.8161	0.8488	0.7261	0.7468	0.6294
33-6-4W	2012-07-08	3.117	0.1080	270.2	233.7	0.9246	0.7996	0.7829	0.6734	0.6366	0.5581
33-6-4W	2012-07-10	3.292	0.0901	281.9	257.7	0.9613	0.8788	0.8818	0.7971	0.8021	0.7254
33-6-4W	2012-07-13	3.244	0.0929	283.4	261.2	0.9579	0.8830	0.8733	0.8055	0.7879	0.7368
33-6-4W	2012-07-14	3.228	0.1068	282.8	271.4	0.9654	0.9264	0.8965	0.8779	0.8267	0.8348
33-6-4W	2012-07-17	3.180	0.2076	271.2	239.0	0.9290	0.8188	0.7909	0.7018	0.6500	0.5965
36-9-6W	2012-06-12	0.266	0.3114	252.4	225.1	0.8601	0.7670	0.8469	0.7571	0.7436	0.6714
36-9-6W	2012-06-15	0.328	0.3198	256.7	230.7	0.8627	0.7752	0.8465	0.7634	0.7429	0.6798
36-9-6W	2012-06-17	0.370	0.3580	250.4	226.5	0.8603	0.7781	0.8416	0.7649	0.7348	0.6819
36-9-6W	2012-06-22	0.233	0.3087	254.0	225.8	0.8575	0.7621	0.8458	0.7533	0.7418	0.6662
36-9-6W	2012-06-23	0.215	0.3120	255.7	227.6	0.8573	0.7631	0.8465	0.7550	0.7430	0.6685
36-9-6W	2012-06-25	0.177	0.2942	259.9	242.9	0.8681	0.8113	0.8599	0.8060	0.7655	0.7375
36-9-6W	2012-06-29	0.113	0.2669	265.7	241.1	0.9159	0.8309	0.9126	0.8278	0.8537	0.7671
36-9-6W	2012-07-03	0.087	0.2277	271.9	245.3	0.9025	0.8140	0.8995	0.8114	0.8318	0.7449
36-9-6W	2012-07-10	0.057	0.2209	271.9	248.1	0.9012	0.8225	0.8993	0.8209	0.8314	0.7576
36-9-6W	2012-07-13	0.085	0.2486	272.1	252.9	0.9087	0.8447	0.9061	0.8426	0.8427	0.7870
36-9-6W	2012-07-14	0.095	0.2206	274.2	257.5	0.9104	0.8550	0.9075	0.8529	0.8451	0.8009
36-9-6W	2012-07-17	0.123	0.2788	269.3	249.2	0.9044	0.8368	0.9003	0.8337	0.8331	0.7749
3-7-4W	2012-06-12	1.523	0.3623	219.7	174.0	0.7660	0.6065	0.6076	0.5004	0.3430	0.3240
3-7-4W	2012-06-15	1.922	0.2866	260.0	226.3	0.8846	0.7700	0.7784	0.6893	0.6290	0.5795
3-7-4W	2012-06-17	2.187	0.3584	236.8	193.2	0.8289	0.6762	0.6404	0.5438	0.3980	0.3827

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
3-7-4W	2012-06-23	2.772	0.3601	260.5	228.7	0.8847	0.7765	0.7047	0.6549	0.5055	0.5331
3-7-4W	2012-06-25	2.775	0.2740	271.3	248.3	0.9188	0.8410	0.7916	0.7543	0.6510	0.6676
3-7-4W	2012-06-27	2.602	0.2758	282.7	265.6	0.9555	0.8980	0.8924	0.8466	0.8199	0.7924
3-7-4W	2012-07-05	1.910	0.3368	270.2	236.3	0.9176	0.8025	0.8424	0.7337	0.7362	0.6396
3-7-4W	2012-07-08	1.744	0.3954	252.1	205.3	0.8589	0.6993	0.7449	0.6049	0.5729	0.4653
3-7-4W	2012-07-10	1.759	0.3192	275.2	247.6	0.9356	0.8419	0.8830	0.7918	0.8041	0.7183
3-7-4W	2012-07-13	1.781	0.2981	284.2	259.0	0.9550	0.8703	0.9177	0.8286	0.8622	0.7681
3-7-4W	2012-07-17	1.811	0.3536	267.5	231.7	0.9145	0.7923	0.8418	0.7242	0.7352	0.6267
4-8-4W	2012-06-12	1.358	0.3871	241.8	189.1	0.8218	0.6426	0.7174	0.5578	0.5269	0.4017
4-8-4W	2012-06-15	1.743	0.2943	269.2	229.6	0.9030	0.7699	0.8247	0.6977	0.7065	0.5910
4-8-4W	2012-06-22	2.474	0.3663	254.5	205.7	0.8551	0.6913	0.6643	0.5451	0.4380	0.3845
4-8-4W	2012-06-23	2.436	0.3333	265.9	229.4	0.8844	0.7629	0.7357	0.6527	0.5575	0.5301
4-8-4W	2012-06-25	2.360	0.2702	280.0	257.4	0.9226	0.8482	0.8275	0.7803	0.7111	0.7027
4-8-4W	2012-07-05	1.979	0.2109	278.6	232.2	0.9172	0.7644	0.8380	0.6787	0.7287	0.5653
4-8-4W	2012-07-10	1.788	0.1371	292.9	277.2	0.9678	0.9159	0.9409	0.8888	0.9010	0.8495
4-8-4W	2012-07-17	1.521	0.2194	277.4	239.4	0.9413	0.8121	0.9017	0.7616	0.8354	0.6774
5-7-4W	2012-06-12	1.813	0.2179	228.4	192.8	0.7987	0.6741	0.6275	0.5671	0.3764	0.4142
5-7-4W	2012-06-15	2.293	0.1692	268.1	239.6	0.9174	0.8202	0.8201	0.7424	0.6989	0.6515
5-7-4W	2012-06-17	2.613	0.2019	242.9	205.5	0.8448	0.7149	0.6233	0.5707	0.3693	0.4191
5-7-4W	2012-06-22	3.146	0.1994	258.4	228.4	0.8959	0.7919	0.6971	0.6594	0.4929	0.5391
5-7-4W	2012-06-23	3.239	0.2273	269.2	247.7	0.9226	0.8488	0.7676	0.7489	0.6109	0.6603
5-7-4W	2012-06-25	3.281	0.1394	275.4	260.8	0.9420	0.8922	0.8234	0.8198	0.7043	0.7562
5-7-4W	2012-06-27	3.177	0.1157	281.4	272.0	0.9572	0.9252	0.8743	0.8770	0.7895	0.8336
5-7-4W	2012-07-05	2.760	0.1734	271.6	240.1	0.9243	0.8172	0.8068	0.7183	0.6765	0.6188
5-7-4W	2012-07-08	2.588	0.1616	266.6	232.5	0.9118	0.7950	0.7877	0.6926	0.6445	0.5840
5-7-4W	2012-07-10	2.451	0.0868	280.5	260.1	0.9570	0.8874	0.9012	0.8347	0.8345	0.7763
5-7-4W	2012-07-13	2.246	0.1243	281.7	261.1	0.9543	0.8844	0.9021	0.8357	0.8361	0.7776
5-7-4W	2012-07-14	2.178	0.1167	281.9	270.3	0.9621	0.9227	0.9207	0.8913	0.8672	0.8529
5-7-4W	2012-07-17	1.973	0.1969	274.9	246.8	0.9413	0.8448	0.8852	0.7887	0.8079	0.7140
5-7-4W	2012-07-19	1.836	0.1332	282.0	261.6	0.9583	0.8890	0.9222	0.8520	0.8698	0.7997

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
5-8-4W	2012-06-12	0.090	0.2677	241.9	192.1	0.8287	0.6579	0.8233	0.6530	0.7042	0.5305
5-8-4W	2012-06-15	0.136	0.2016	263.5	225.6	0.8857	0.7581	0.8803	0.7529	0.7996	0.6656
5-8-4W	2012-06-17	0.169	0.2577	230.1	176.4	0.7964	0.6105	0.7844	0.6000	0.6390	0.4588
5-8-4W	2012-06-22	0.323	0.2231	259.8	218.3	0.8765	0.7364	0.8622	0.7227	0.7693	0.6248
5-8-4W	2012-06-23	0.409	0.2063	268.0	236.4	0.8930	0.7875	0.8770	0.7735	0.7941	0.6935
5-8-4W	2012-06-25	0.580	0.1770	277.7	260.4	0.9266	0.8687	0.9106	0.8562	0.8503	0.8054
5-8-4W	2012-06-27	0.751	0.1669	288.7	267.6	0.9546	0.8848	0.9414	0.8704	0.9019	0.8247
5-8-4W	2012-06-29	0.923	0.1450	287.1	270.5	0.9540	0.8989	0.9371	0.8831	0.8947	0.8419
5-8-4W	2012-07-03	1.640	0.1143	293.3	275.6	0.9645	0.9062	0.9380	0.8787	0.8962	0.8358
5-8-4W	2012-07-05	2.061	0.1756	279.4	249.5	0.9387	0.8382	0.8765	0.7765	0.7933	0.6976
5-8-4W	2012-07-10	2.999	0.1129	291.3	279.8	0.9705	0.9322	0.9184	0.8916	0.8634	0.8533
5-8-4W	2012-07-13	3.287	0.0999	291.2	278.3	0.9701	0.9272	0.9086	0.8782	0.8470	0.8352
5-8-4W	2012-07-14	3.382	0.1059	294.8	282.7	0.9780	0.9379	0.9308	0.8946	0.8841	0.8573
5-8-4W	2012-07-19	3.861	0.1168	285.7	266.6	0.9564	0.8924	0.8384	0.8030	0.7294	0.7335
7-7-4W	2012-06-12	0.076	0.2867	233.6	192.6	0.8151	0.6721	0.8102	0.6682	0.6822	0.5510
7-7-4W	2012-06-15	0.100	0.2123	271.2	240.9	0.9237	0.8206	0.9210	0.8178	0.8678	0.7534
7-7-4W	2012-06-17	0.118	0.2695	247.3	203.6	0.8575	0.7061	0.8517	0.7006	0.7517	0.5949
7-7-4W	2012-06-22	0.194	0.2117	260.3	225.1	0.8986	0.7774	0.8917	0.7705	0.8186	0.6894
7-7-4W	2012-06-23	0.233	0.1904	271.5	244.8	0.9232	0.8322	0.9169	0.8259	0.8609	0.7645
7-7-4W	2012-06-25	0.310	0.1712	276.7	261.0	0.9399	0.8865	0.9332	0.8809	0.8881	0.8388
7-7-4W	2012-06-27	0.387	0.1644	285.0	274.5	0.9648	0.9295	0.9599	0.9251	0.9329	0.8986
7-7-4W	2012-06-29	0.474	0.1487	285.8	271.6	0.9690	0.9210	0.9636	0.9149	0.9391	0.8849
7-7-4W	2012-07-03	0.805	0.1185	288.4	274.5	0.9742	0.9272	0.9661	0.9174	0.9433	0.8882
7-7-4W	2012-07-05	0.993	0.2316	269.6	233.7	0.9210	0.7982	0.8893	0.7643	0.8146	0.6811
7-7-4W	2012-07-08	1.274	0.2949	260.2	216.6	0.8895	0.7406	0.8298	0.6832	0.7150	0.5714
7-7-4W	2012-07-10	1.550	0.1962	280.7	255.9	0.9572	0.8725	0.9276	0.8375	0.8787	0.7801
7-7-4W	2012-07-13	2.097	0.1805	282.9	258.5	0.9584	0.8758	0.9153	0.8275	0.8582	0.7665
7-7-4W	2012-07-14	2.279	0.1555	283.6	272.2	0.9663	0.9275	0.9270	0.8964	0.8779	0.8599
7-7-4W	2012-07-17	2.826	0.2227	274.4	242.7	0.9401	0.8315	0.8438	0.7377	0.7384	0.6450

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
7-8-4W	2012-06-12	0.077	0.1244	248.5	209.8	0.8524	0.7197	0.8485	0.7163	0.7464	0.6161
7-8-4W	2012-06-15	0.114	0.1276	269.5	241.0	0.9037	0.8079	0.8999	0.8044	0.8324	0.7353
7-8-4W	2012-06-17	0.143	0.1816	244.2	204.6	0.8470	0.7096	0.8394	0.7031	0.7312	0.5982
7-8-4W	2012-06-22	0.318	0.1214	263.4	229.9	0.8846	0.7721	0.8715	0.7604	0.7848	0.6759
7-8-4W	2012-06-23	0.385	0.1153	272.1	247.4	0.9020	0.8201	0.8884	0.8089	0.8131	0.7415
7-8-4W	2012-06-25	0.520	0.0997	279.0	265.8	0.9287	0.8849	0.9150	0.8752	0.8577	0.8311
7-8-4W	2012-06-27	0.654	0.0518	287.5	270.1	0.9389	0.8821	0.9237	0.8694	0.8723	0.8233
7-8-4W	2012-06-29	0.788	0.0671	285.9	271.9	0.9446	0.8984	0.9276	0.8850	0.8787	0.8444
7-8-4W	2012-07-03	1.361	0.0655	291.2	276.6	0.9551	0.9072	0.9287	0.8851	0.8806	0.8446
7-8-4W	2012-07-05	1.699	0.0894	282.8	257.5	0.9444	0.8597	0.9010	0.8170	0.8342	0.7523
7-8-4W	2012-07-10	2.477	0.0687	290.7	279.8	0.9650	0.9290	0.9188	0.8953	0.8640	0.8584
7-8-4W	2012-07-13	2.787	0.0717	288.3	270.5	0.9629	0.9033	0.9044	0.8503	0.8399	0.7975
7-8-4W	2012-07-14	2.890	0.0595	292.1	275.4	0.9702	0.9149	0.9205	0.8662	0.8669	0.8190
7-8-4W	2012-07-17	3.199	0.0910	279.8	254.7	0.9501	0.8648	0.8521	0.7769	0.7523	0.6981
8-7-4W	2012-06-12	0.844	0.2599	240.1	204.7	0.8407	0.7168	0.7878	0.6768	0.6447	0.5627
8-7-4W	2012-06-15	1.213	0.1598	268.0	241.1	0.9249	0.8321	0.8866	0.7970	0.8102	0.7253
8-7-4W	2012-06-25	2.013	0.1515	276.3	259.3	0.9459	0.8878	0.8929	0.8461	0.8206	0.7918
8-7-4W	2012-06-27	1.956	0.1211	283.8	272.4	0.9615	0.9228	0.9252	0.8951	0.8747	0.8580
8-7-4W	2012-07-05	1.859	0.2034	271.6	235.4	0.9269	0.8031	0.8626	0.7365	0.7699	0.6435
8-7-4W	2012-07-10	1.931	0.2280	282.5	255.3	0.9636	0.8706	0.9298	0.8249	0.8825	0.7631
8-7-4W	2012-07-13	1.975	0.1540	289.5	272.2	0.9806	0.9220	0.9621	0.8938	0.9366	0.8563
8-7-4W	2012-07-14	1.989	0.1424	284.4	263.8	0.9686	0.8985	0.9382	0.8614	0.8966	0.8125
8-7-4W	2012-07-19	2.061	0.1282	282.5	260.2	0.9579	0.8825	0.9154	0.8377	0.8583	0.7804
8-8-4W	2012-06-12	0.117	0.3156	240.3	191.3	0.8196	0.6526	0.8123	0.6461	0.6858	0.5212
8-8-4W	2012-06-15	0.129	0.1979	268.2	228.1	0.8860	0.7537	0.8809	0.7486	0.8005	0.6599
8-8-4W	2012-06-22	0.184	0.1894	255.7	211.2	0.8659	0.7150	0.8572	0.7067	0.7610	0.6031
8-8-4W	2012-06-23	0.203	0.1792	265.0	234.3	0.8885	0.7857	0.8806	0.7788	0.8000	0.7007
8-8-4W	2012-06-25	0.242	0.1543	279.5	258.8	0.9263	0.8577	0.9200	0.8522	0.8661	0.8000
8-8-4W	2012-06-29	0.320	0.1175	289.4	272.0	0.9494	0.8923	0.9436	0.8868	0.9056	0.8468

SURVEYDESC	Sample Date	VWC	Moisture	VTEMP	HTEMP	e_V	e_H	e_{gV}	e_{gH}	e_{sV}	e_{sH}
8-8-4W	2012-07-03	0.521	0.0783	294.0	274.2	0.9674	0.9023	0.9611	0.8940	0.9350	0.8566
8-8-4W	2012-07-05	0.642	0.1659	279.0	242.4	0.9179	0.7975	0.8979	0.7760	0.8291	0.6969
8-8-4W	2012-07-10	1.011	0.0854	292.6	280.9	0.9717	0.9328	0.9601	0.9213	0.9333	0.8935
8-8-4W	2012-07-13	1.388	0.0878	287.4	265.1	0.9592	0.8850	0.9347	0.8571	0.8907	0.8066
8-8-4W	2012-07-14	1.514	0.0787	289.7	266.7	0.9663	0.8894	0.9437	0.8598	0.9057	0.8103
8-8-4W	2012-07-17	1.892	0.1536	278.5	245.0	0.9434	0.8297	0.8925	0.7709	0.8199	0.6900
8-8-4W	2012-07-19	2.143	0.1017	284.3	259.2	0.9534	0.8692	0.9034	0.8171	0.8383	0.7525

III. ROUGHNESS MEASUREMENTS

Site_ID	FIELD	Hi-Alt RMS	Lo-Alt RMS		Site_ID	FIELD	Hi-Alt RMS	Lo-Alt RMS
11-1	11	1.110	0.560		72-1	72	1.210	0.640
11-2	11	1.150	0.230		72-2	72	0.930	0.280
12-1	12	1.620	1.190		73-1	73	1.710	0.690
12-2	12	0.880	0.890		73-2	73	1.450	0.940
13-1	13	0.650	0.460		74-1	74	1.490	1.430
13-2	13	0.350	0.640		74-2	74	2.260	0.970
14-1	14	0.760	1.040		81-1	81	0.440	0.800
14-2	14	0.620	0.720		81-2	81	0.910	0.680
21-1	21	0.970	1.340		82-1	82	0.820	0.910
21-2	21	1.420	0.440		82-2	82	0.980	0.650
22-1	22	1.350	1.360		83-1	83	1.010	0.810
22-2	22	0.740	1.030		83-2	83	1.240	1.330
23-1	23	0.970	0.810		84-1	84	0.740	0.770
23-2	23	1.760	1.560		84-2	84	0.750	0.880
24-1	24	1.800	0.310		85-1	85	0.700	0.850
24-2	24	1.780	0.740		85-2	85	1.010	1.070
31-1	31	0.680	0.490		91-1	91	1.130	0.870
31-2	31	0.940	0.700		91-2	91	0.700	1.240
32-1	32	1.670	1.630		92-1	92	0.620	1.030
32-2	32	1.080	1.000		92-2	92	0.900	0.680
33-1	33	0.670	0.870		93-1	93	1.710	0.770
33-2	33	0.700	1.090		93-2	93	1.750	1.430
34-1	34	1.320	0.660		94-1	94	1.780	1.620
34-2	34	N/A	0.550		94-2	94	0.780	0.360
41-1	41	1.410	0.860		101-1	101	0.510	0.360
41-2	41	0.880	1.410		101-2	101	0.570	0.740
42-1	42	1.610	1.020		102-1	102	1.280	0.760
42-2	42	1.610	0.990		102-2	102	1.080	0.580
43-1	43	1.230	1.420		103-1	103	0.750	0.760
43-2	43	0.760	2.540		103-2	103	0.600	0.630
44-1	44	0.970	1.100		104-1	104	0.950	0.970
44-2	44	1.040	0.900		104-2	104	1.350	0.930
45-1	45	0.940	0.890		105-1	105	1.010	1.060
45-2	45	1.600	0.820		105-2	105	1.100	0.900
51-1	51	0.710	0.470		111-1	111	0.780	0.600
51-2	51	0.550	0.480		111-2	111	0.830	0.690
52-1	52	1.450	1.650		112-1	112	0.930	0.620

Site_ID	FIELD	Hi-Alt RMS	Lo-Alt RMS		Site_ID	FIELD	Hi-Alt RMS	Lo-Alt RMS
52-2	52	0.730	0.520		112-2	112	1.030	0.480
53-1	53	1.000	0.450		113-1	113	0.970	0.820
53-2	53	0.600	0.650		113-2	113	0.540	0.990
54-1	54	0.810	0.590		114-1	114	0.440	0.430
54-2	54	0.840	0.490		114-2	114	0.340	0.370
61-1	61	1.000	0.700		115-1	115	1.150	0.630
61-2	61	1.230	0.880		115-2	115	0.690	0.900
62-1	62	1.700	0.550		121-1	121	1.230	0.940
62-2	62	1.310	0.590		121-2	121	1.260	1.050
63-1	63	0.730	0.600		122-1	122	1.590	1.190
63-2	63	0.920	0.730		122-2	122	1.050	1.850
64-1	64	1.890	1.600		123-1	123	1.140	1.980
64-2	64	0.980	0.690		123-2	123	1.300	1.730
65-1	65	0.750	0.870		124-1	124	1.460	1.300
65-2	65	0.880	1.250		124-2	124	1.710	1.330
71-1	71	1.240	0.460		125-1	125	1.340	1.440
71-2	71	1.890	0.640		125-2	125	1.400	1.240