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Understanding yield effects of controlled drainage through soil moisture excess and deficit metrics

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UNDERSTANDING YIELD EFFECTS OF CONTROLLED DRAINAGE THROUGH SOIL MOISTURE EXCESS AND DEFICIT METRICS

For the degree of Master of Science in Engineering

Is approved by the final examining committee:

Jane R. Frankenberger
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Approved by Major Professor(s): Jane R. Frankenberger

Approved by: Bernard Engel 12/7/2015

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UNDERSTANDING YIELD EFFECTS OF CONTROLLED DRAINAGE THROUGH SOIL MOISTURE EXCESS AND DEFICIT METRICS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Caroline Hughes

In Partial Fulfilment of the

Requirements for the degree

of

Master of Science in Engineering

December 2015

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West Lafayette, Indiana

Dedicated to the students of Purdue University and students around the world who are still fighting for racial justice and gender equality

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TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Table Page

Appendix Table

LIST OF FIGURES

ABSTRACT

Hughes, Caroline E. MSE, Purdue University, December 2015. Understanding Yield Effects of Controlled Drainage through Soil Moisture Excess and Deficit Metrics. Major Professor: Jane R. Frankenberger.

Understanding the risks or benefits to crop yields is an important factor in implementing a water management practice such as controlled drainage. Soil moisture from monitoring sites in Minnesota, Iowa, Indiana, and Ohio were used to compare deficit and excess moisture conditions in free-draining and controlled drainage sites and understand those inconsistent impacts. Time and magnitude of soil moisture deficit and excess stress were determined using metrics based on thresholds, depths in the soil profile, and corn growth stages. Seventeen metrics were found to show statistically significant correlation with yields as well as a difference in the quantity of stress between controlled and free-draining fields. Based on one metric of soil moisture deficit stress, free-draining plots experienced 77 additional cm-days of moisture deficit stress from the R3 stage until maturity compared to controlled plots and an additional 118 cm-days over the entire season. Meanwhile, controlled drainage plots were found to experience between 0.5 and 3.19 additional cm-days of excess stress during the period from seedling emergence to V6 compared to free-draining plots. In general at the sites studied, moisture deficits occurred during the latter half of the growing season while moisture excesses occurred during the earlier half; both types of stress were shown, when quantified with several different metrics, to correlate negatively with yield. While moisture excess was greater with controlled drainage, the differences were small and often not statistically significant; meanwhile greater differences were found in moisture deficit between free and controlled drainage. Due to a reduction in soil moisture deficit, controlled drainage has the potential to provide yield benefits in years when deficit stress occurs.

CHAPTER 1 INTRODUCTION

The availability of inexpensive soil moisture sensors has made soil moisture data more widely available and provided opportunities to study and characterize an important hydrologic variable. The field of drainage, and the study of drainage strategies such as controlled drainage, can benefit from soil moisture monitoring which contributes to more complete monitoring and understanding of controlled drainage impacts. Many controlled drainage studies have focused primarily on water quality impacts, especially nitrate-N reductions via decreased drainflow (Lalonde, et al. 1996, Skaggs et al. 2010, Evans et al. 1995, Adeuya et al. 2012). While these impacts are fairly consistent, effects on crop yield remain difficult to understand and predict. For example, Cook and Verma (2012) found a nitrate load reduction averaging 61% over two years but no “consistent pattern” in yield effects Additional insights can be gained from monitoring additional environmental variables.

Measuring soil moisture means knowing the “temporal condition of water available to plants” (Legates, et al. 2011) and for this reason is useful in understanding the inconsistent yield effects of controlled drainage. For example, Madramootoo et al. (2001) monitored soil moisture over a 2-year study of a water table management experiment and found that in a year when soil moisture exceeded field capacity during June, corn yields in the managed field were 25% lower than that of a freely-draining field. When some aspect of a field’s hydrologic response is altered by a particular drainage practice, it is important to not only characterize the change but determine what the end effect will be on other processes or properties, such as the field's agricultural productivity. Though pollution generation or contribution to flooding are also areas important to study, this work focuses on the use of soil moisture data to evaluate the performance of controlled drainage in terms of crop yield.

When used for decision support, soil moisture data can be directly useful to farmers. Boyd (2015) reported that monitoring soil moisture at the field scale with capacitance probes is especially useful for scheduling irrigation. In rain-fed agriculture, the information can be used to optimize N and other inputs to maximize yield and reduce losses. Phillips et al. (2014) called for on-site soil moisture monitoring to be integrated with remotely sensed soil moisture as well as measurements of other environmental variables and used in predictive models for the purpose of comparing different cropping systems, including ones that introduce new or alternative crops to existing rotations.

Researchers often call for measurements of soil moisture for the purpose of calibrating and validating hydrologic models that then predict soil moisture based on surrogate information (Vereecken, et al. 2008). In turn, this simulated soil moisture can be used to answer questions about agricultural management. For example, Narsimhand and Srinivasan (2005) developed the Soil Moisture Deficit Index for the SWAT model and found it to be highly correlated with wheat and sorghum yields. Soil moisture was chosen as the best hydrologic variable for the index (as opposed to some other measure like water table) because crops can extract water from different depths in the soil profile depending on their growth stage. Though their deficit index applied to a spatial scale larger than a field, analyzing soil moisture deficits can also be effective at the scale of an individual field, without additional datasets or modeling software. When soil moisture and yield information is incorporated with information about controlled drainage, such as when or how much the soil moisture will be most affected by the drainage system, a better understanding of potential costs and benefits of a controlled drainage system can result. Though controlled drainage can offer important water quality benefits such as N load reductions, its widespread adoption will be more likely if questions about its yield impacts are more definitively answered.

1.1 Objectives

This work explores the yield impacts of controlled drainage through analysis of soil moisture across four controlled drainage study sites in the Midwest. Monitoring soil moisture at high temporal resolution and analyzing it based on soil properties at different locations requires the coordination of data from several sources and an efficient and consistent method for handling data gaps. The objectives for the work are:

1. Create consistent and complete soil moisture datasets for four drainage sites by collecting, processing, and filling soil moisture monitoring data and assessing the quality of the resulting data.
2. Quantify relationships between soil moisture excess and deficit stresses and corn crop yield under controlled and free drainage, by developing soil moisture stress metrics.
3. Identify metrics that successfully correlate with yield and show differences between controlled and free drainage, and use the results to explain yield variation across years and sites.

1.2 Organization

Objective 1 is addressed by Chapter 2, which describes data collection and handling and the effect of filling on data quality. Chapter 3 covers Objectives 2 and 3, including the analysis of soil moisture data from the four drainage sites; the determination of soil moisture excess and deficit; the relationship between excess or deficit to yield reductions; and a comparison of the soil moisture stresses in free-draining and controlled plots. Conclusions and suggestions for future research are presented in Chapter 4.

CHAPTER 2 SOIL MOISTURE DATA COLLECTION AND HANDLING

This chapter describes each controlled drainage site analyzed for yield impact in Chapter 3, focusing on the methods of preparing soil moisture data for that analysis. The desired outcome of the data handling was to create a complete soil moisture time series during the growing seasons when corn was grown.

2.1 Sites

Volumetric soil moisture was monitored continuously at four sites in the Midwest. The sites, located in Minnesota, Iowa, Indiana, and Ohio, had plots with both free drainage and controlled drainage, with two replicates each in Iowa and Indiana (Figure 2.1). Three sites, in Indiana, Ohio, and Iowa, used probes manufactured by Decagon Devices (5TM, www.decagon.com) to measure soil moisture and recorded data on a Decagon Em50 data logger, while in Minnesota soil moisture was monitored with TDR probes also manufactured by Decagon and recorded data using a Campbell Scientific CR1000. Probes were buried at depths of 10 cm, 20 cm, 40 cm, 60 cm, and 100 cm. Temporal resolution was 5 minutes. Porosity, determined from bulk density measurements at several depths, was computed from a simple average of three to four sampling locations within each plot and a weighted average over the soil profile (Table 2.1).

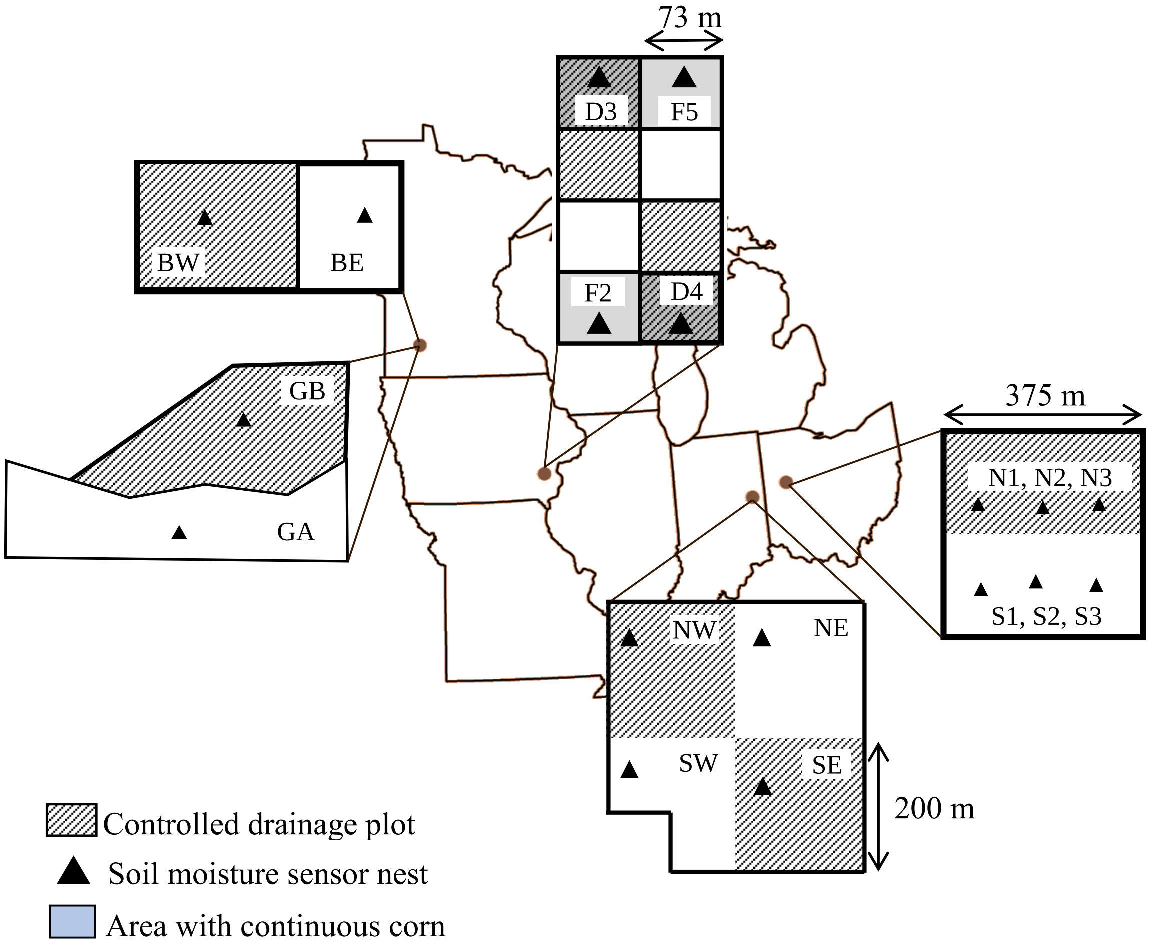

Figure 2.1 Indiana (DPAC), Iowa (SERF), Ohio (St. Johns), and Minnesota (SWROC) field site layouts.

The Indiana site was located at the Davis Purdue Agricultural Center (DPAC), in Randolph County (40.26 N, 85.16 W). The field was divided into four plots about 4 ha in area. Two plots were conventionally drained and two had controlled drainage. During the years that corn was grown (2012 and 2014), the outlet depth was 0.4 m during the growing season and varied from 0.1 to the depth of the drain during the non-growing season (Figure 2.2). Soil moisture was monitored at one location in each plot; in the controlled plots, nests were located within the zone of influence of the outlet control structure.

The Iowa site was located at the Southeast Research and Demonstration Farm (SERF) in Crawfordsville, IA (41.2 N, 91.5 W). Two plots at this site had controlled drainage and two had conventional drainage. Only the continuous corn, planted on half of each plot in an area measuring 73.1 m wide by 24 rows of corn, was used in this analysis. One nest of soil moisture sensors was located in the continuous corn portion of each plot. Boards were kept at a depth of 0.4 m during early 2012, replaced at 0.76 m after planting in 2012, and maintained at this depth for 2013 and 2014 (Figure 2.2).

The Ohio site, St. Johns, was on a private farm in Clay Township, Auglaize County, in northwestern Ohio (40.5 N, 84.1 W). One field was divided into two plots, approximately 6.9 ha in area each, one having controlled drainage and one having free drainage. The depth of the boards at St. Johns varied from 1.0 to 0.2 m during the growing season and were 0.4 m during the winter. Soil moisture was monitored at three locations in each plot.

The Minnesota site was located at the Southwest Research and Outreach Center in Lamberton, MN (44.3 N, 95.5 W). Field B was divided into two plots, one with controlled drainage and one with free drainage. Field G had four plots: controlled drainage, free drainage, no drainage, and drainage with subirrigation. Only the controlled and free-draining plots, GB and GA, were analyzed. The exact depths of the boards in the control structure not recorded. Soil moisture was monitored at a single location in each plot.

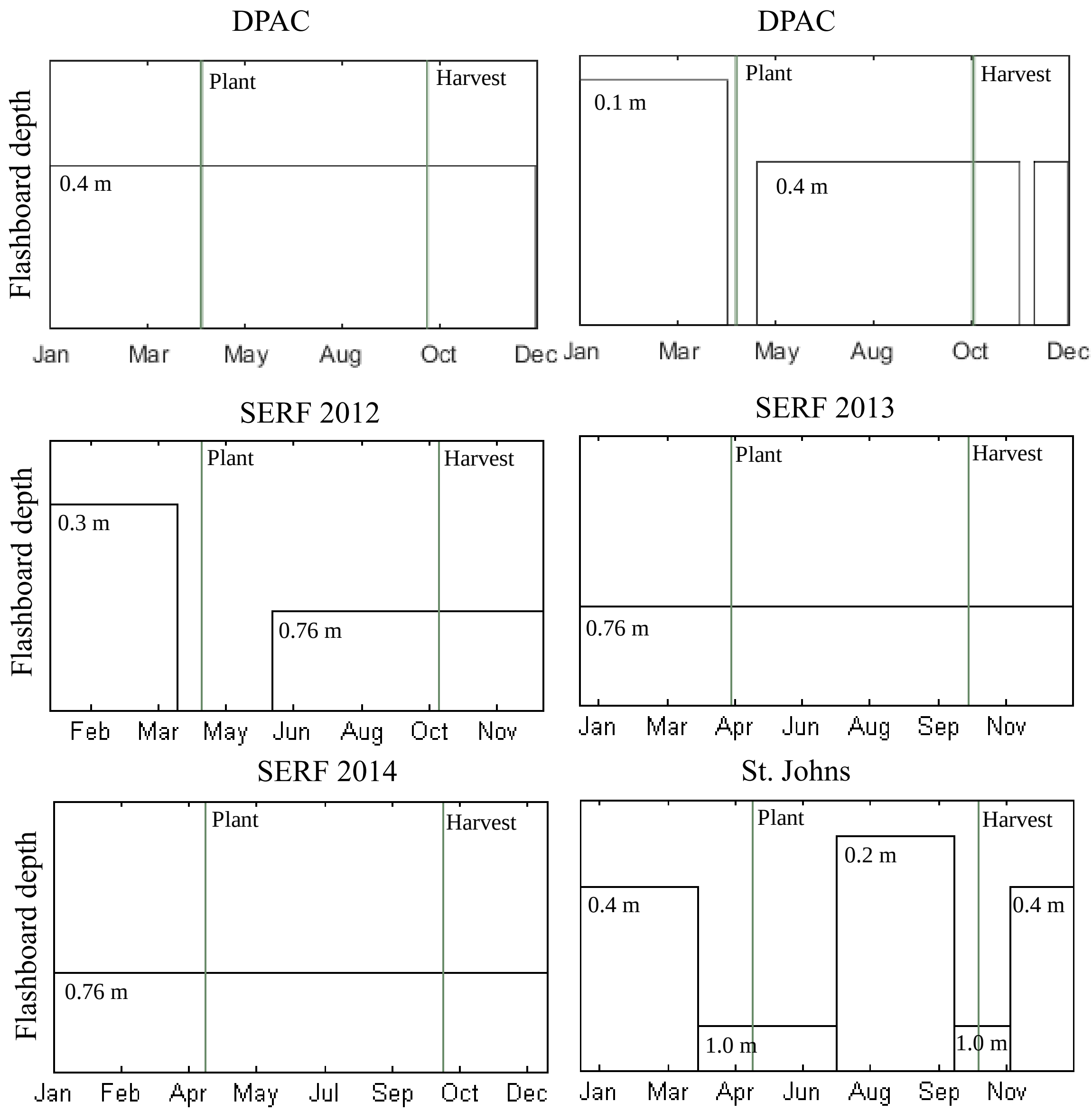

Figure 2.2 Key board and field management dates for each year and field site.

Table 2.1. Average porosity and soil series at DPAC, SERF, St. Johns, and SWROC

Plot	Porosity range	Average Porosity	Soil series
DPACE NE	0.36 - .51	0.44	Blount silt loam
DPAC NW	0.36 - 0.44	0.44	Condit silt loam
DPAC SE	0.41 - 0.51	0.46	Pewamo silty clay loam/Condit silt loam
DPAC SW	0.42 - 0.50	0.45	Pewamo silty clay loam
SERF 2	0.41 - 0.62	0.48	Taintor silty clay loam
SERF 3	0.46 - 0.59	0.50	Kalona silty clay loam
SERF 4	0.44 - 0.54	0.48	Taintor silty clay loam
SERF 5	0.43 - 0.61	0.49	Kalona silty clay loam
SJ N1	0.43 - 0.47	0.45	Montgomery silty clay loam/ Blount silt loam
SJ N2	0.40 - 0.48	0.43	Montgomery silty clay loam/ Blount silt loam
SJ N3	0.39 - 0.49	0.43	Montgomery silty clay loam/ Blount silt loam
SJ S1	0.41 - 0.46	0.43	Montgomery silty clay loam/ Blount silt loam
SJ S2	0.39 - 0.47	0.43	Montgomery silty clay loam/ Blount silt loam
SJ S3	0.42 - 0.59	0.44	Montgomery silty clay loam/ Blount silt loam
SWROC BE	0.44 - 0.56	0.52	Havelock clay loam
SWROC BW	0.46 - 0.64	0.53	Havelock clay loam
SWROC GA	0.44 - 0.59	0.52	Nishna silty clay
SWROC GB	0.43 - 0.60	0.51	Nishna silty clay

2.2 Missing data

Sensor breakage, battery failure on the data logger, or sensor removal for farm operations such as tillage can result in missing time-stamps, time-stamps without data, or erroneous data. Data was processed to fill in time-stamp gaps, remove data known to be erroneous (e.g., sensors were moved to a different location during tillage and planting in 2012 at DPAC). In addition, an hourly time series was created by selecting the 5 minute observation closest to the top of the hour. This processing was done using a MATLAB

(MathWorks, 2015) script developed by Lahdou (2014). An additional script was developed to identify and remove values that were less than zero or in excess of the soil porosity. The result is a complete set of time stamps with some missing observations. Missing data at DPAC was dominated by many short gaps of under six hours and a few very long gaps of several weeks. Out of 170 total gaps across all sensors, 84 were 6 hours or shorter and 44 were two weeks or longer. At SERF, 58 out of 355 total gaps lasted longer than two weeks and 157 lasted less than six hours. At St. Johns, 8 out of 75 total gaps were two weeks or longer and 57 were six hours or shorter. At SWROC, 76 out of 479 total gaps were greater than two weeks in duration and 205 lasted six hours or less. The distribution of data availability and gaps is illustrated in Figures 2.3-2.6.

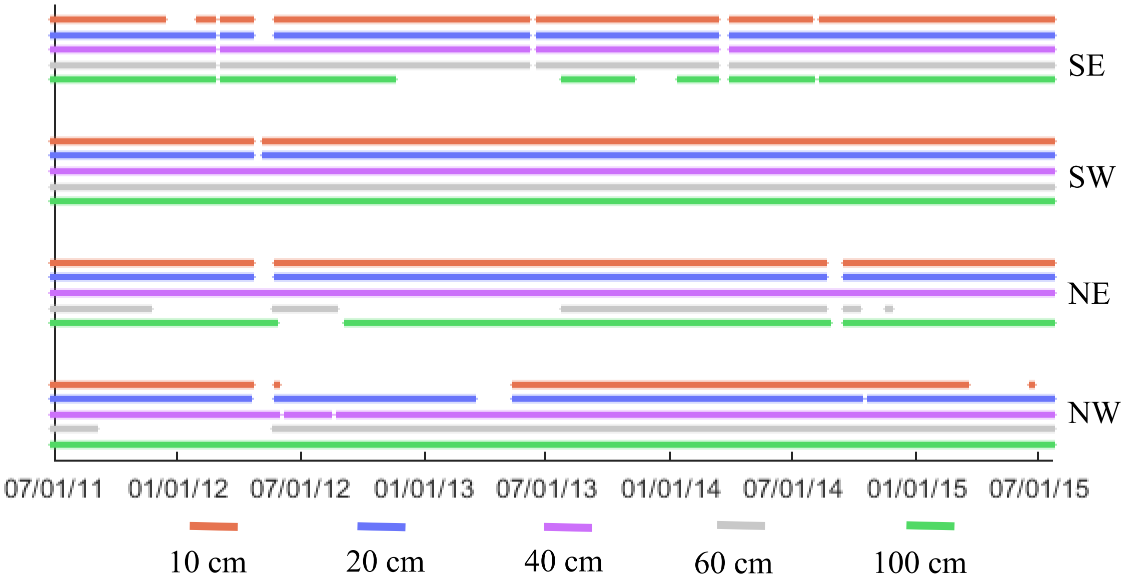

Figure 2.3 Data availability at DPAC in each plot at the 10, 20, 40, and 100 cm sensor depths (2011 – 2015)

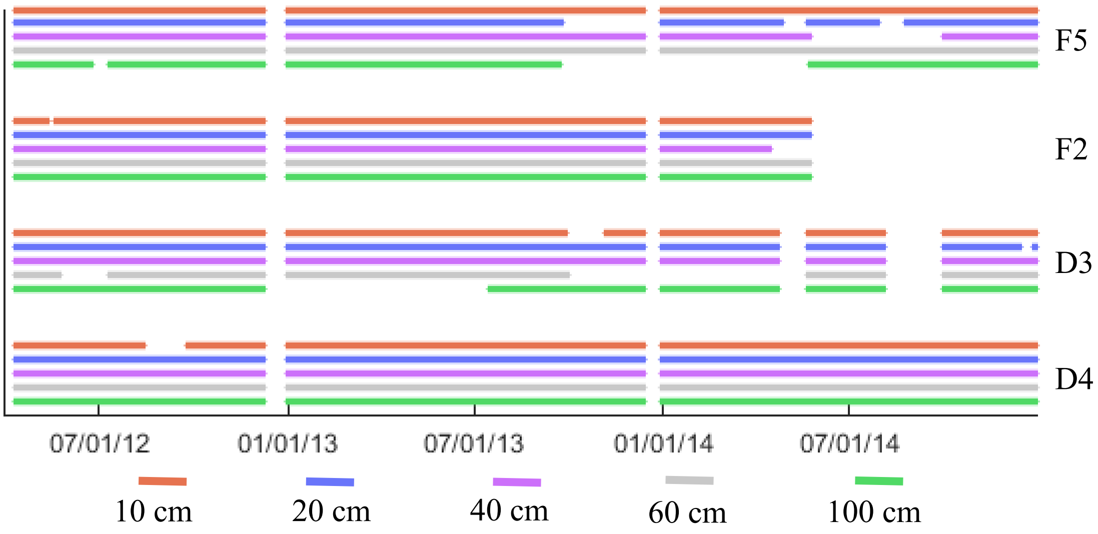

Figure 2.4 Data availability at SERF in each plot at the 10, 20, 40, and 100 cm sensor depths (2012 – 2014)

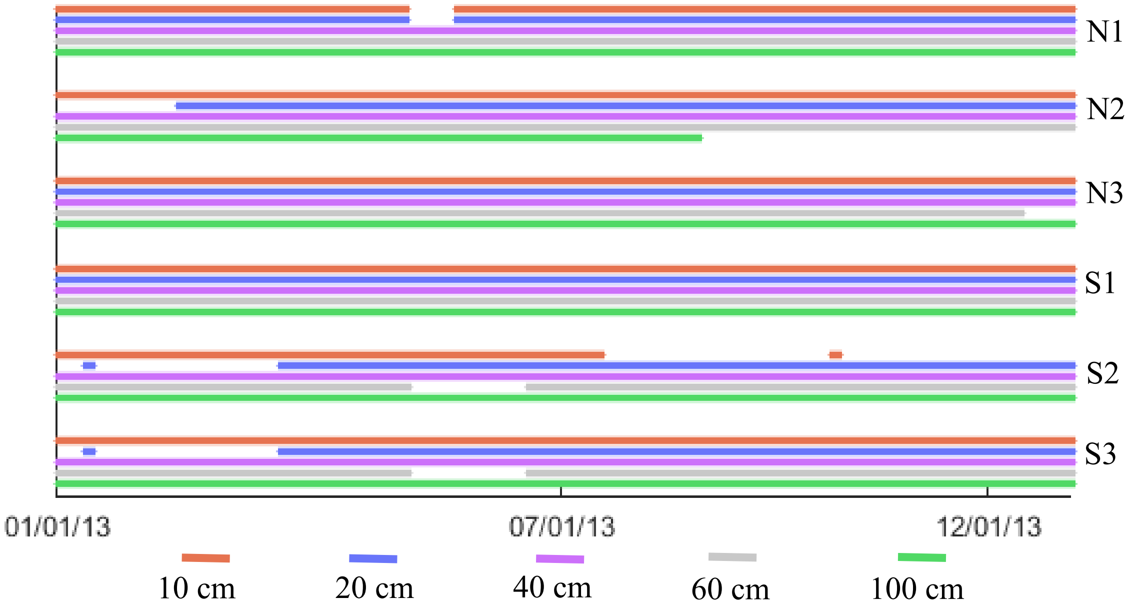

Figure 2.5 Data availability at St. Johns in each plot at the 10, 20, 40, and 100 cm sensor depths (2013)

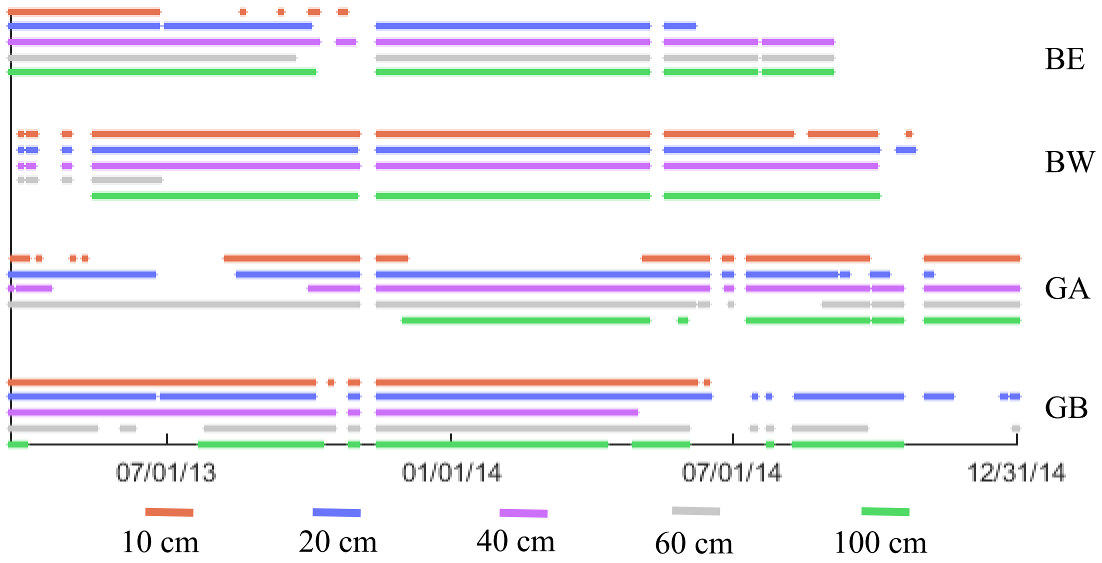

Figure 2.6 Data availability at SWROC in each plot at the 10, 20, 40, and 100 cm sensor depths (2013-2014)

2.3 Data filling procedure

A data filling method based on correlated sensor pairs was adapted from Lahdou (2014). The method was semi-automated to work at all sites with the goal of finding more data gaps than could be identified manually and determining how much data was missing both before and after filling, which had not been done previously. Filling was done on hourly-resolution data. For gaps of three hours in length or less, estimated values were determined by an average of the two values before and after the outage. For gaps longer than three hours, missing data was first filled in a semi-automated process using correlated sensors, when possible. Finally, data was filled via linear interpolation, as described below.

When gaps were longer than three hours, a nearby sensor was chosen as a replacement from which values were estimated. Replacement 1 was the best-correlated neighboring sensor in the same nest as the one with missing data. For example, if 40 cm sensor data was missing, either the 20 cm or 60 cm may have been used as the replacement. A Pearson correlation coefficient was calculated between the sensor records, and the sensor with the highest correlation coefficient was selected as the replacement.

Pearson correlation coefficients to select replacements were calculated over the entire soil moisture record. Because all raw data sets had some gaps, data were deleted from both data sets whenever either of them was missing data. As a result, the timestep between observations when calculating correlation was not always the same, so correlation was only possible with zero time lag.

For DPAC only, a second replacement sensor, Replacement 2, was identified from among sensors at the same depth in another plot to be used in case Replacement 1 would not work. Each quadrant at DPAC was matched with another quadrant based on which had the highest average correlation coefficient across all depths. This was the method used by Brooks (2013) and Lahdou (2014). This method was sometimes altered when the matching approach resulted in sensors being paired together despite being poorly correlated with each other, such that all sensor pairs were correlated with a coefficient of at least 0.5. For example, the SE and NE plots were paired because of their high average correlation, but because correlation coefficients between sensors in these plots at the 60 and 100 cm depth were below 0.5, Replacement 2 for the 60 and 100 cm sensors in the SE plot were from the NW plot instead (Table 2.2). With every sensor assigned two potential replacements, the choice between Replacement 1 and Replacement 2 was made independently for each outage. The records of both replacements were checked for gaps and the one with fewer gaps was selected as the replacement for that outage. When the data logger's batteries were dead, all the sensors in a single nest would contain gaps at the same time; this is an example of when Replacement 2 would be selected for filling.

Table 2.2 Sensor pairs and correlation coefficients at DPAC for estimating missing data

Outage	Replacement 1	R	Replacement 2	R
SE 10	SE 20	0.94	NE 10	0.94
SE 20	SE 10	0.94	NE 20	0.87
SE 40	SE 60	0.94	NE 40	0.90
SE 60	SE 40	0.94	NW 60	0.85
SE 100	SE 60	0.84	NW 100	0.88
NE 10	NE 20	0.99	SE 10	0.94
NE 20	NE 10	0.99	SE 20	0.87
NE 40	NE 20	0.82	SE 40	0.90
NE 60	NW 60*	0.76	NE 40	0.48
NE 100	NW 100	0.64	NW 100	0.64
SW 10	SW 20	0.57	NW 10	0.85
SW 20	SW 40	0.86	NW 20	0.95
SW 40	SW 60	0.90	NE 40	0.91
SW 60	SW 40	0.90	SE 60	0.86
SW 100	SW 10	0.61	SE 100	0.88
NW 10	NW 20	0.98	SW 10	0.94
NW 20	NW 10	0.98	SW 20	0.95
NW 40	NW 20	0.86	SW 40	0.84
NW 60	NW 40	0.72	SE 60	0.85
NW 100	NW 100	0.56	SE 100	0.88

*In this case, because the best-correlated sensor in the same quadrant had a correlation of less than 0.5, Replacement 2 was used as Replacement 1.

At SERF, St. Johns, and SWROC, sensors were generally not as well-correlated with each other as at DPAC, and selecting two replacement sensors with Pearson correlation coefficients greater than 0.5 was often not possible. Based on the best correlation coefficients, one replacement sensor was chosen for each sensor. The replacement sensors at SERF and St. Johns were selected from among any adjacent sensor in the same quadrant or any sensor at the same depth in another quadrant within the same treatment. At SWROC, each field had only one sensor nest in each treatment, so the replacement sensor always came from the same nest. Correlation coefficients between sensors ranged from 0.5 to 0.92 (Tables 2.3, 2.4, and 2.5). If no correlation coefficient was found higher than 0.5 and missing data occurred in the record, these gaps were not filled by the correlated pair method but instead filled with linear interpolation.

Table 2.3 Sensor pairs and correlation coefficients at SERF for estimating missing data

Outage	Replacement	R	Outage	Replacement	R
F5 10	F5 20	0.80	D3 10	D3 20	0.83
F5 20	F5 40	0.92	D3 20	D3 40	0.85
F5 40	F5 20	0.92	D3 40	D3 20	0.85
F5 60	F5 40	0.81	D3 60	D3 100	0.71
F5 100	F5 60	0.64	D3 100	D3 60	0.71
F2 10	F5 10	0.79	D4 10	D4 20	0.50
F2 20	F2 40	0.58	D4 20	D4 40	0.81
F2 40	F2 60	0.84	D4 40	D4 20	0.81
F2 60	F2 40	0.84	D4 60	D4 40	0.80
F2 100	None	[<.5]	D4 100	D4 60	0.66

Table 2.4 Sensor pairs and correlation coefficients at St. Johns for estimating missing data

Outage	Replacement	R	Outage	Replacement	R
N1 10	N2 10	0.71	S1 10	S3 10	0.82
N1 20	N1 10	0.57	S1 20	S2 20	0.77
N1 40	N1 60	0.61	S1 40	S1 60	0.69
N1 60	N1 40	0.61	S1 60	S1 40	0.69
N1 100	None	[<.5]	S1 100	S3 100	0.71
N2 10	WN2 20	0.80	S2 10	S2 20	0.52
N2 20	WN2 10	0.80	S2 20	S1 20	0.77
N2 40	WN2 20	0.59	S2 40	S2 20	0.71
N2 60	None	[<.5]	S2 60*	S2 20	0.71
N2 100	None	[<.5]	S2 100	S3 100	0.57
N310	WN2 10	0.74	S310	S1 10	0.82
N320	WN3 40	0.86	S320	S3 10	0.67
N340	WN3 20	0.86	S340	None	[<.5]
N360	None	[<.5]	S360	None	[<.5]
N3100	None	[<.5]	S3100	S1 100	0.71

* Sensor S2 20 was found to be correlated with S2 60 with an R-value of .71 during the season of the outage, so it was used as a working sensor despite not being adjacent to the 60cm sensor.

Table 2.5 Replacement sensors and correlation coefficients assigned to each sensor for estimating missing data at SWROC

Outage	Replacement	R	Outage	Replacement	R
BW 10	20	0.97	GA 10	20	0.81
BW 20	10	0.97	GA 20	40	0.86
BW 40	20	0.89	GA 40	20	0.86
BW 60	40	0.81	GA 60	100	0.90
BW 100	60	0.69	GA 100	60	0.90
BE 10	20	0.7	GB 10	20	0.54
BE 20	10	0.7	GB 20	40	0.78
BE 40	60	0.96	GB 40	20	0.78
BE 60	40	0.96	GB 60	100	0.72
BE 100	60	0.82	GB 100	60	0.82

Once a replacement sensor was selected and a period of missing data identified, a scaling ratio, S, was calculated based on the twelve-hour mean of soil moisture prior to the outage. Soil moisture immediately after the end of the outage were not used to calculate the scaling ratio because sensors may return erroneous data during the first few hours after they begin working again (Lahdou 2014). Filled values were calculated by multiplying the soil moisture in the replacement sensor by the scaling ratio for each hour of the outage:

$$S = \frac{\sum_{i=\,t_0-12}^{t_0} Outage_i}{\sum_{i=\,t_0-12}^{t_0} Replacement_i}$$

$$Filled_i = Replacement \times S$$

During time periods where the Replacement sensor was also not functioning (or Replacements 1 and 2 in the case of DPAC), the remaining gaps were filled using linear interpolation from the average of the 12 values before the outage started to the average of the 12 values after the outage ended.

2.4 Filling Results

The filling method based on correlated pairs worked to remove gaps unless both a sensor and its replacement had missing data at the same time (Table 2.6). At DPAC, partly because of the use of secondary replacements, this filling process removed almost all gaps except during the 2012 tillage and planting period during which the 10 cm and 20 cm sensors were removed from all quadrants. The remaining gaps at the 10 cm depth in the SE and NE quadrants were filled using linear interpolation.

Table 2.6 Data gaps as percent of total observations before and after filling with correlated pairs

	10 cm		20 cm		40 cm		60 cm		100 cm	
	before	after	before	after	before	after	before	after	before	after
DPAC										
SE	26.4	2.4	21.2	0.0	18.8	0.0	18.8	0.9	34.3	0.0
NE	5.3	2.4	5.1	0.0	0.5	0.0	57.6	0.0	9.6	0.0
NW	34.8	0.01	8	0.0	1.8	0.0	18	8	0.1	0.0
SW	1.4	0.0	1.4	0.0	0.01	0.0	0.0	0.0	0.0	0.0
SERF										
F2	9.8	8.8	7.4	7.4	13.4	7.4	7.4	7.4	8.0	7.9
F5	5.4	5.4	22.3	10.3	18.2	10.3	5.4	5.4	30.0	5.4
D3	31.2	24.7	28.7	24.8	23.3	22.6	60.2	22.2	53.1	22.2
D4	9.4	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
St. Johns										
N1	5.1	4.8	4.8	4.8	0.0	0.0	0.0	0.0	0.0	0.0
N2	0.0	0.0	11.7	<0.01	<.01	<.01	0.1	<.01	36.6	36.6
N3	0.0	0.0	0.0	0.0	0.0	0.0	7.3	7.2	0.0	0.0
S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S2	0.5	<.01	0.2	<0.01	0.1	<.01	0.0	0.0	0.0	0.0
S3	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0
SWROC										
GA	58.4	58.4	42.3	42.3	40.7	40.7	21.4	21.4	53.9	53.9
GB	40.1	27.8	28.7	26.5	44.0	27.0	41.4	38.5	50.0	38.0
BE	84.8	71.1	43.5	43.5	27.5	27.5	33.6	27.7	29.6	29.2
BW	29.1	25.0	25.2	25.0	26.2	25.0	93.1	26.2	26.7	26.1

Despite only having one replacement sensor, the method of correlated pairs identified and removed most gaps in the data at SERF and St. Johns. At SERF, gaps during December of 2013 and 2014 remained because all sensors in every plot experienced an outage simultaneously. At St. Johns, large gaps were left behind in the records of sensors N1 10, N1 20, N2 100, and N3 60. For N1 10 and 20, the gap was left because these two sensors were paired for filling with each other but had gaps at the same time. In the other three cases, the gap was left because no replacement sensor could be found with a Pearson correlation coefficient greater than 0.5. These five sensor records were filled using linear interpolation. At SWROC, Many of the data gaps occurred at the same time in all sensors, so many data gaps remained after the automated filling process. Where gaps remained in the period needing to be analyzed, they were filled with linear interpolation. As will be discussed in section 3.1 and 3.2, due to the large overlaps in missing data at SWROC, some plots and years were not used in analysis after the filling process.

After the three-step filling process, each plot had a complete volumetric water content time series from every sensor (Figures 2.7 to 2.15). The rapid changes in soil moisture from the 100 cm sensors at St. Johns S3, St. Johns N3, SERF F5, and SERF F2 raised questions about whether these measurements at the 100 cm depth were reliable enough for analysis. At St. Johns N3, the data from the 100 cm sensor create a pattern unlike any of the other sensor measurements, suggesting a problem with the sensor caused by poor soil contact or an issue with the data logger. Though the rapid fluctuations in soil water content may represent preferential flow, there is also the possibility that the measurements were dissimilar to the others because of a change in the soil properties between the 60 and 100 cm sensors. Finally, additional soil properties that were central to the analysis of excess and deficit stress, including water retention, were only measured to the depth of 60 cm, with no measurements available to represent the 80 – 100 cm soil layer associated with the 100 cm sensor. For these reasons, only the 10, 20, 40 and 60 cm volumetric water retention measurements were used in the analysis of excess and deficit soil moisture.

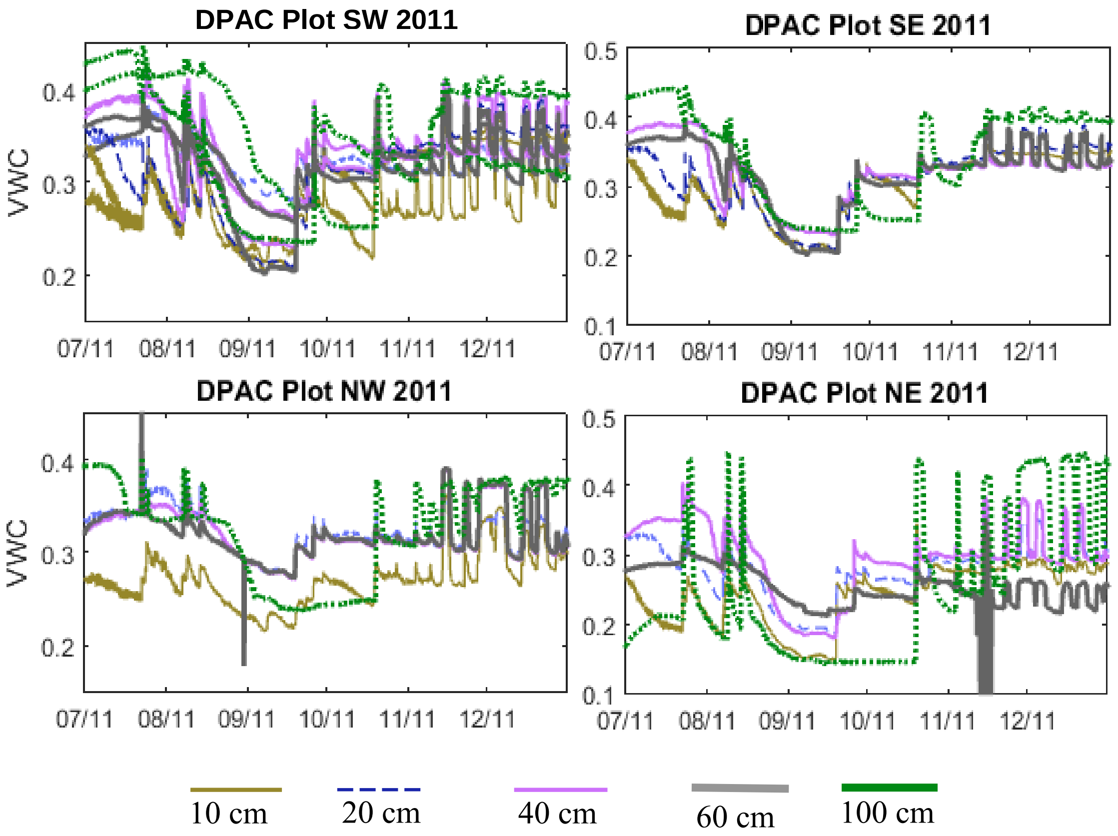

Figure 2.7 Filled volumetric soil moisture data from DPAC from July 1, 2011, to December 31, 2011 at the 10, 20, 40, 60, and 100 cm depths

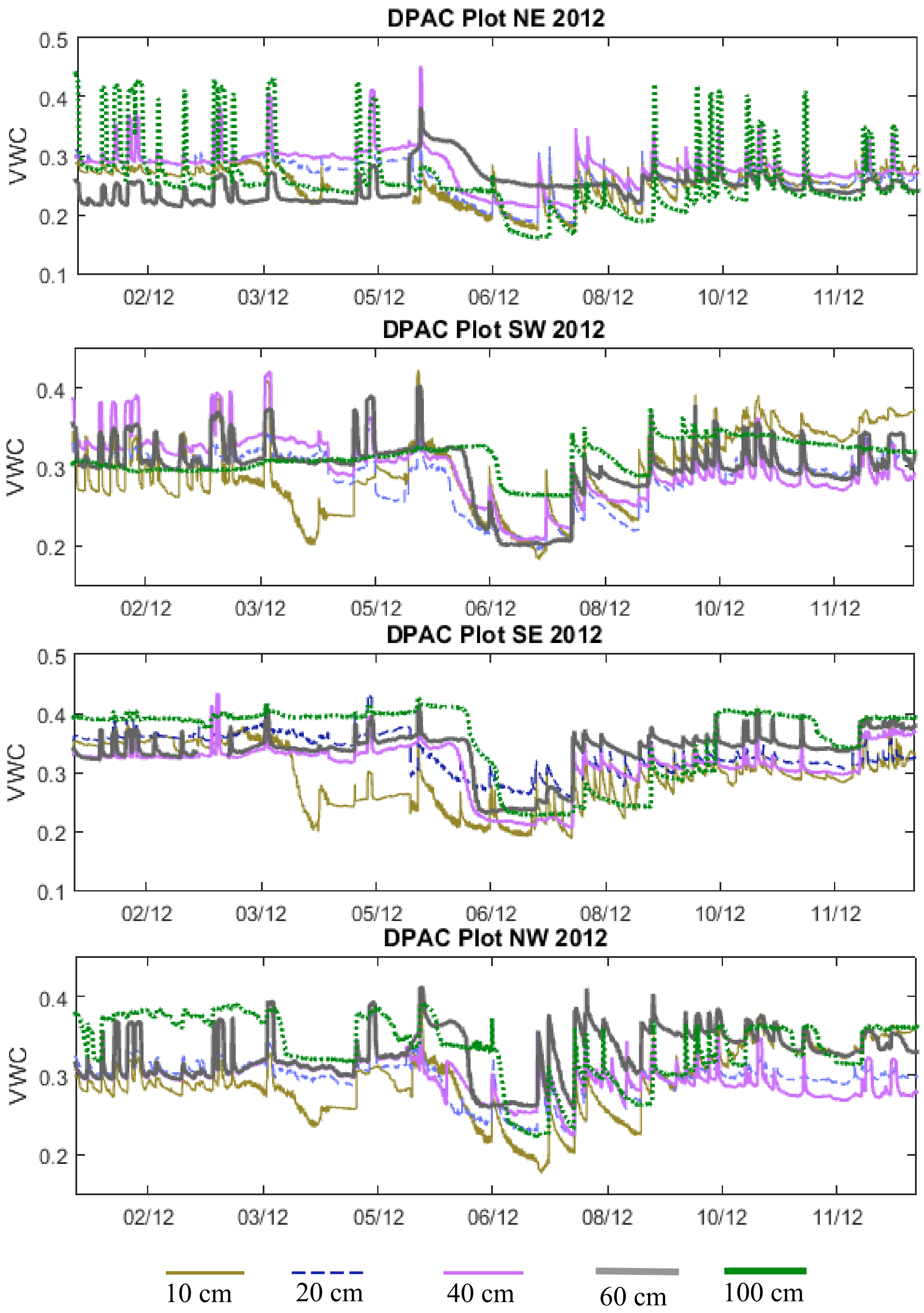

Figure 2.8 Filled volumetric soil moisture data from DPAC for 2012 at the 10, 20, 40, 60, and 100 cm depths

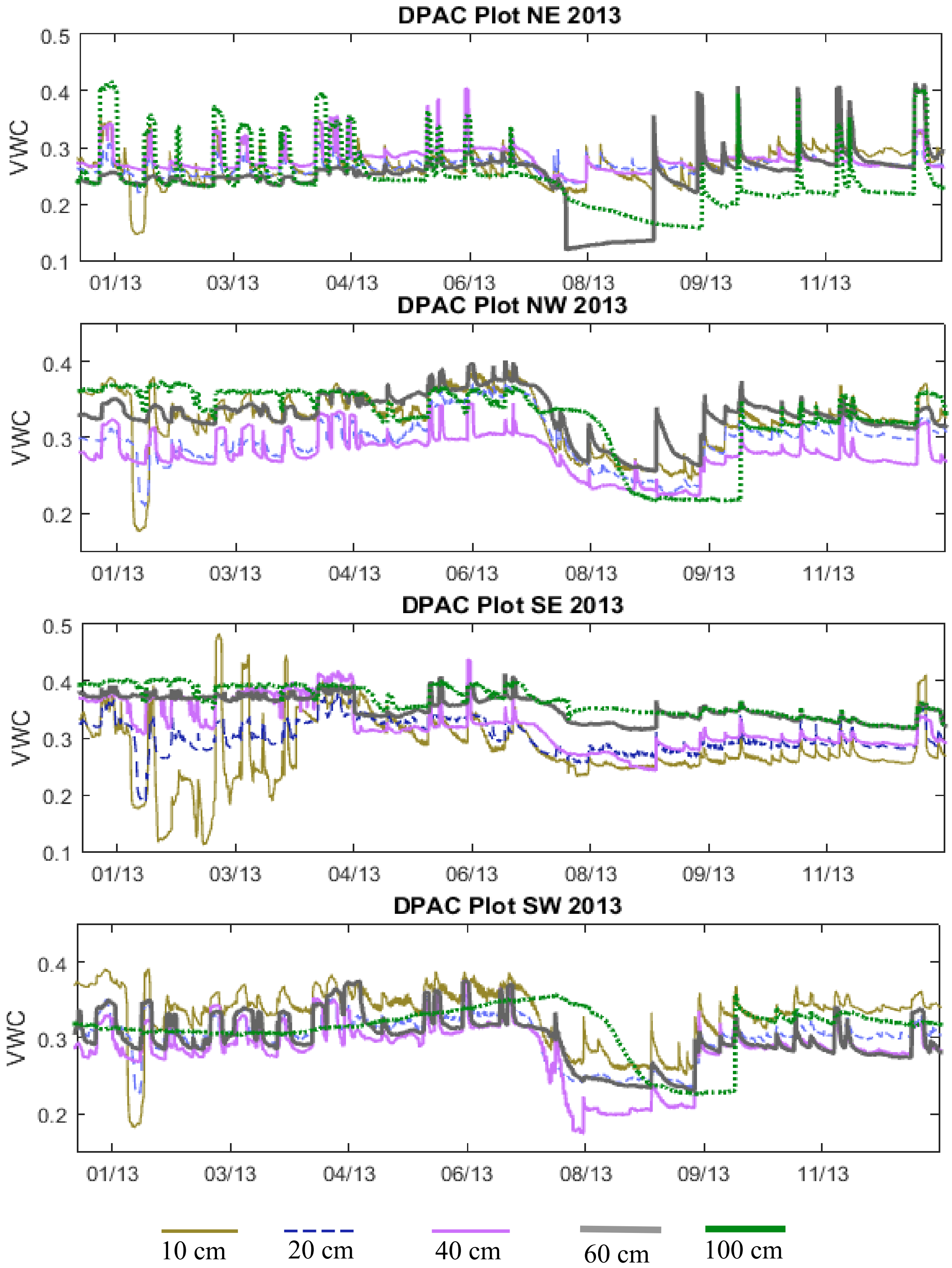

Figure 2.9 Filled volumetric soil moisture data from DPAC for 2013 at the 10, 20, 40, 60, and 100 cm depths

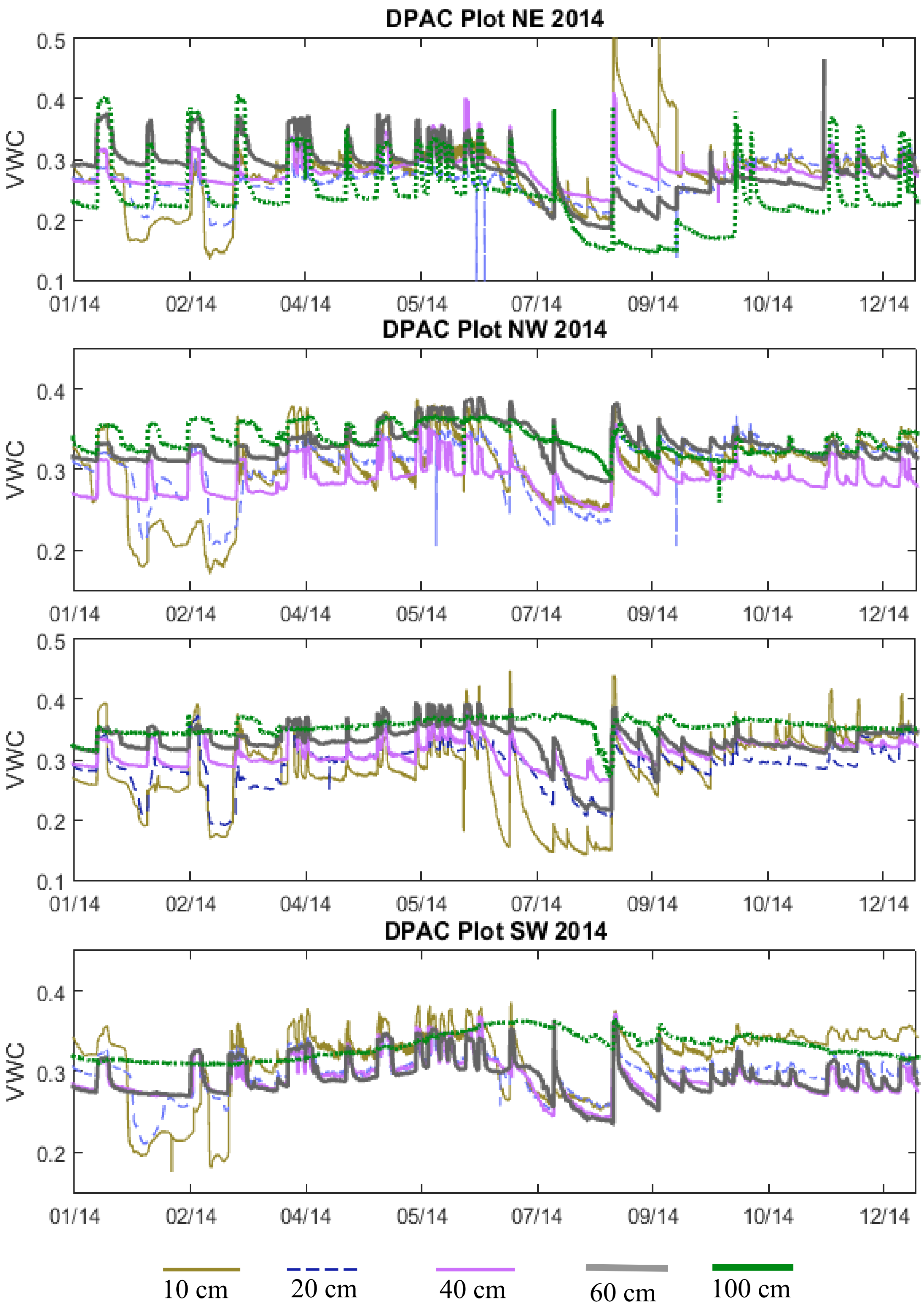

Figure 2.10 Filled volumetric soil moisture data from DPAC for 2014 at the 10, 20, 40, 60, and 100 cm depths

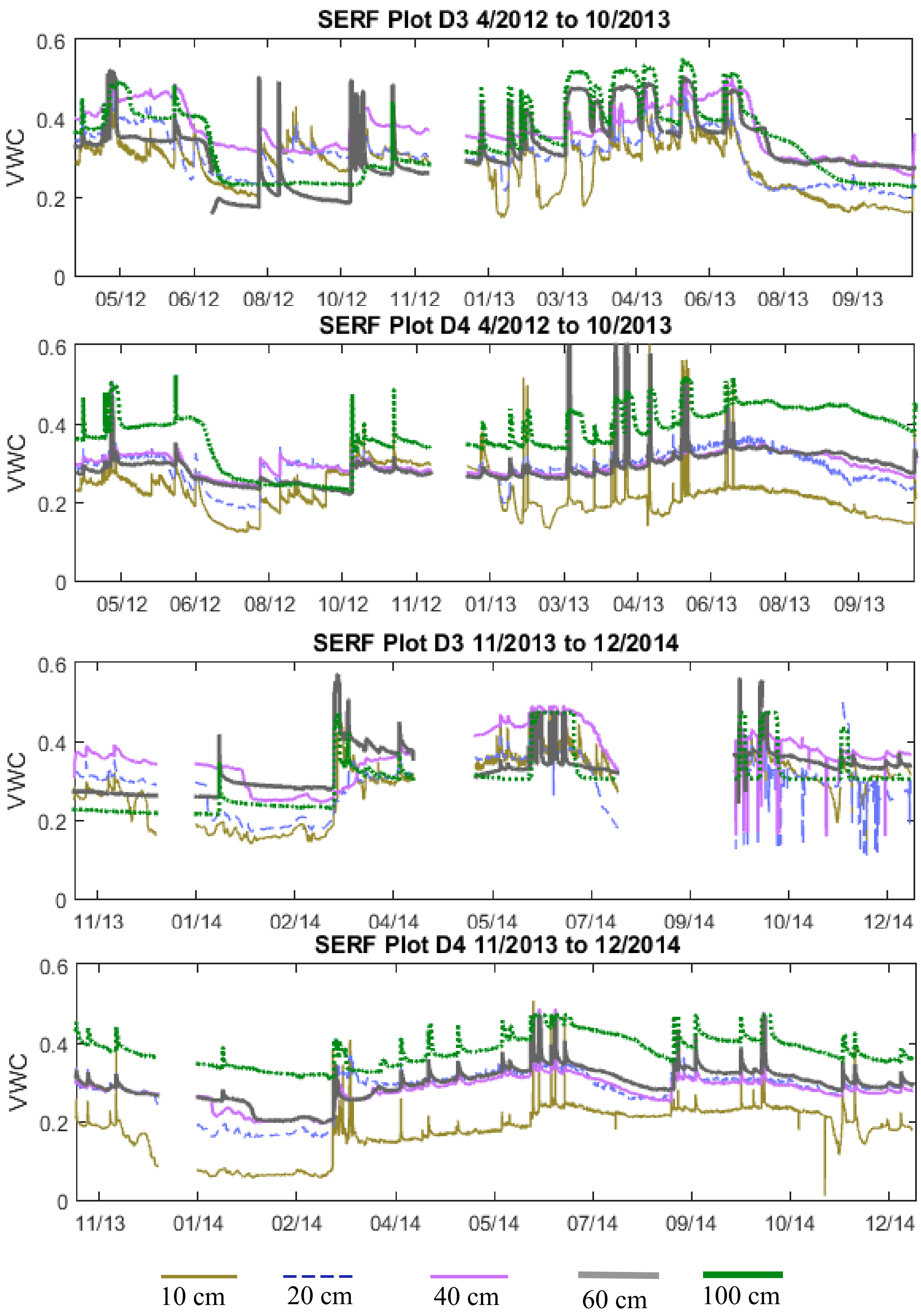

Figure 2.11 Filled volumetric soil moisture data from the controlled plots of SERF from April 22, 2012 to October 31, 2013 and November 1, 2013 to December 31, 2014

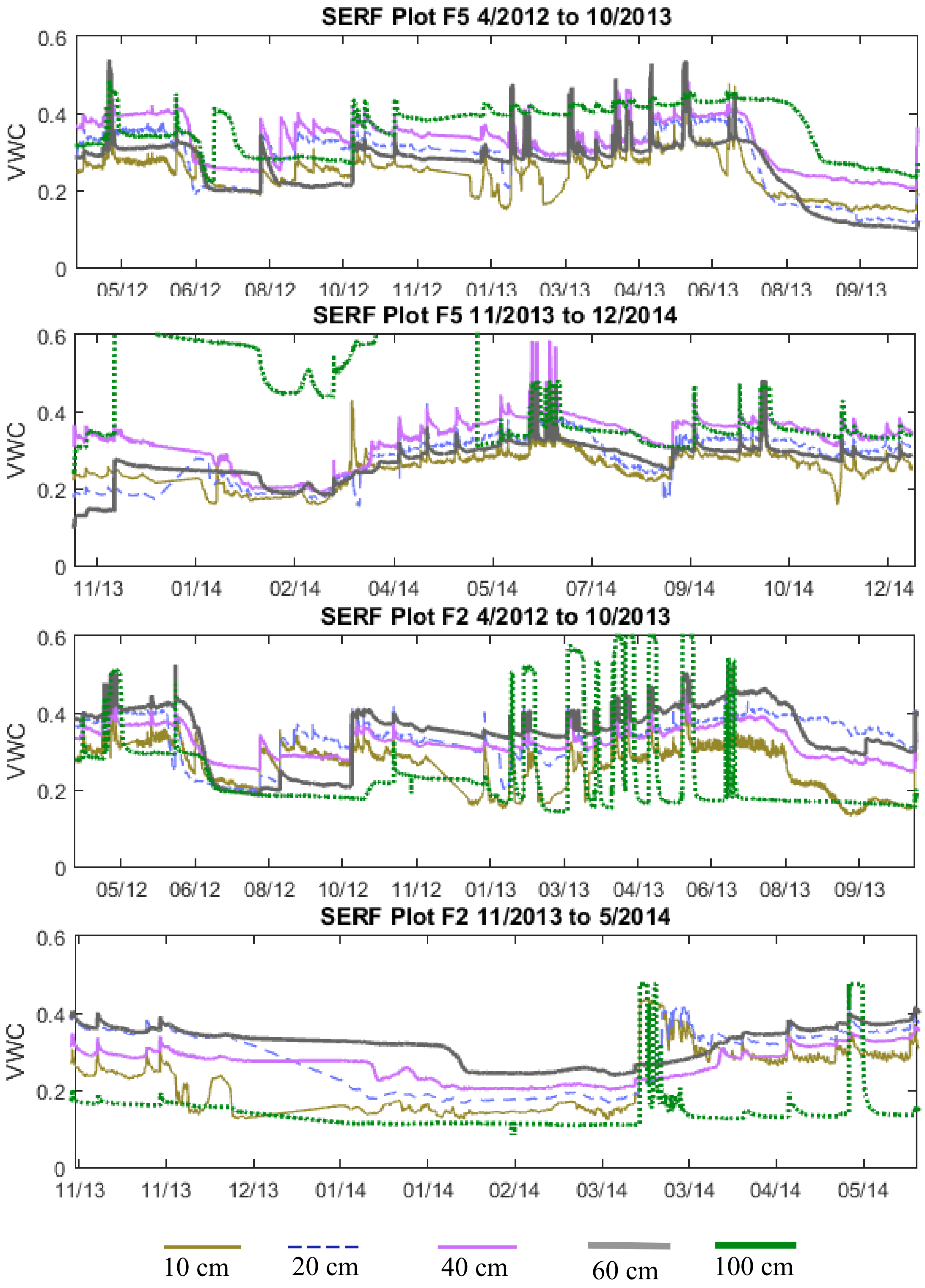

Figure 2.12 Filled volumetric soil moisture data from the free-draining plots of SERF from April 22, 2012 to October 31, 2013 and November 1, 2013 to December 31, 2014

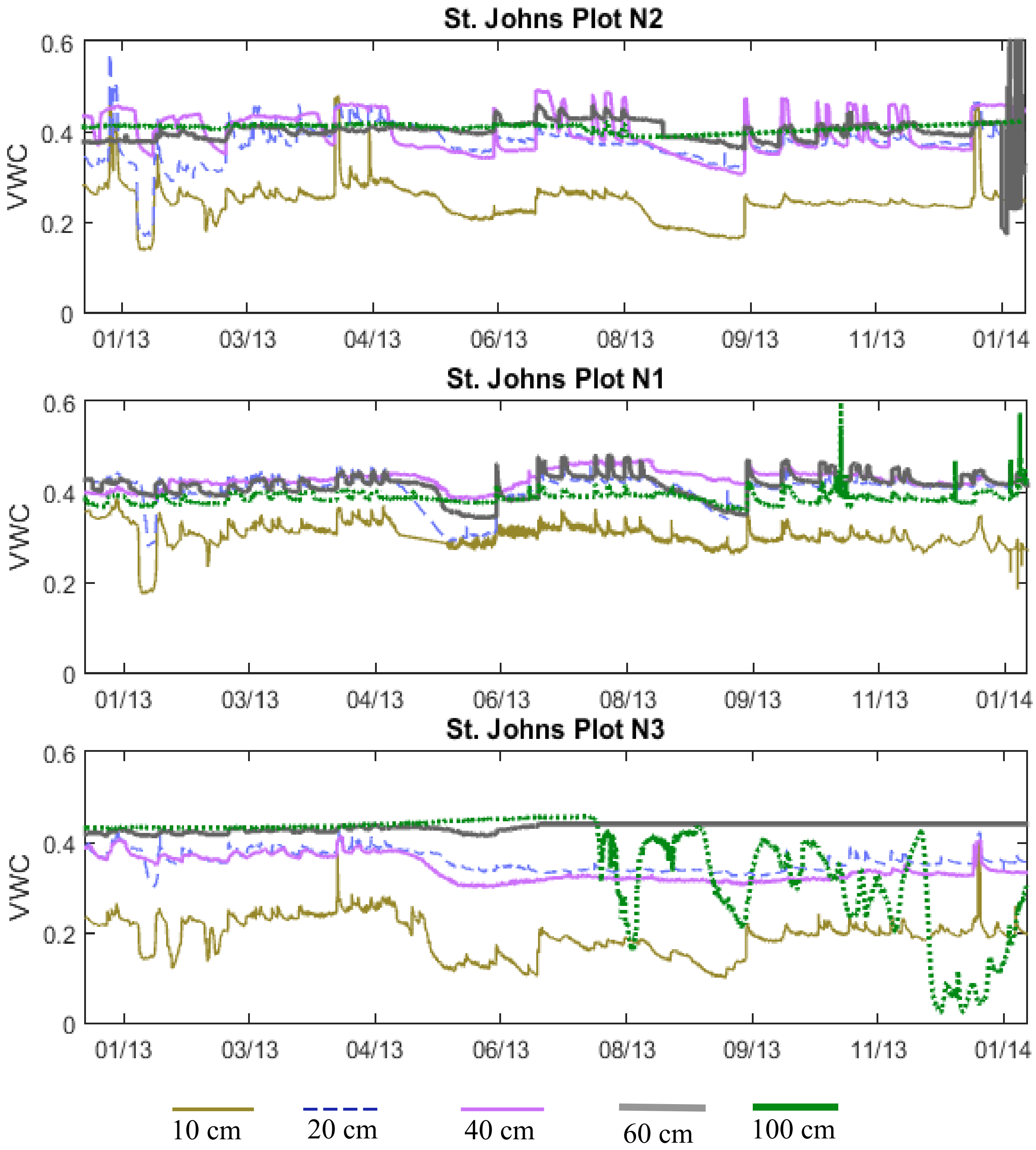

Figure 2.13 Filled volumetric soil moisture data from the controlled plot of St. Johns for 2013.

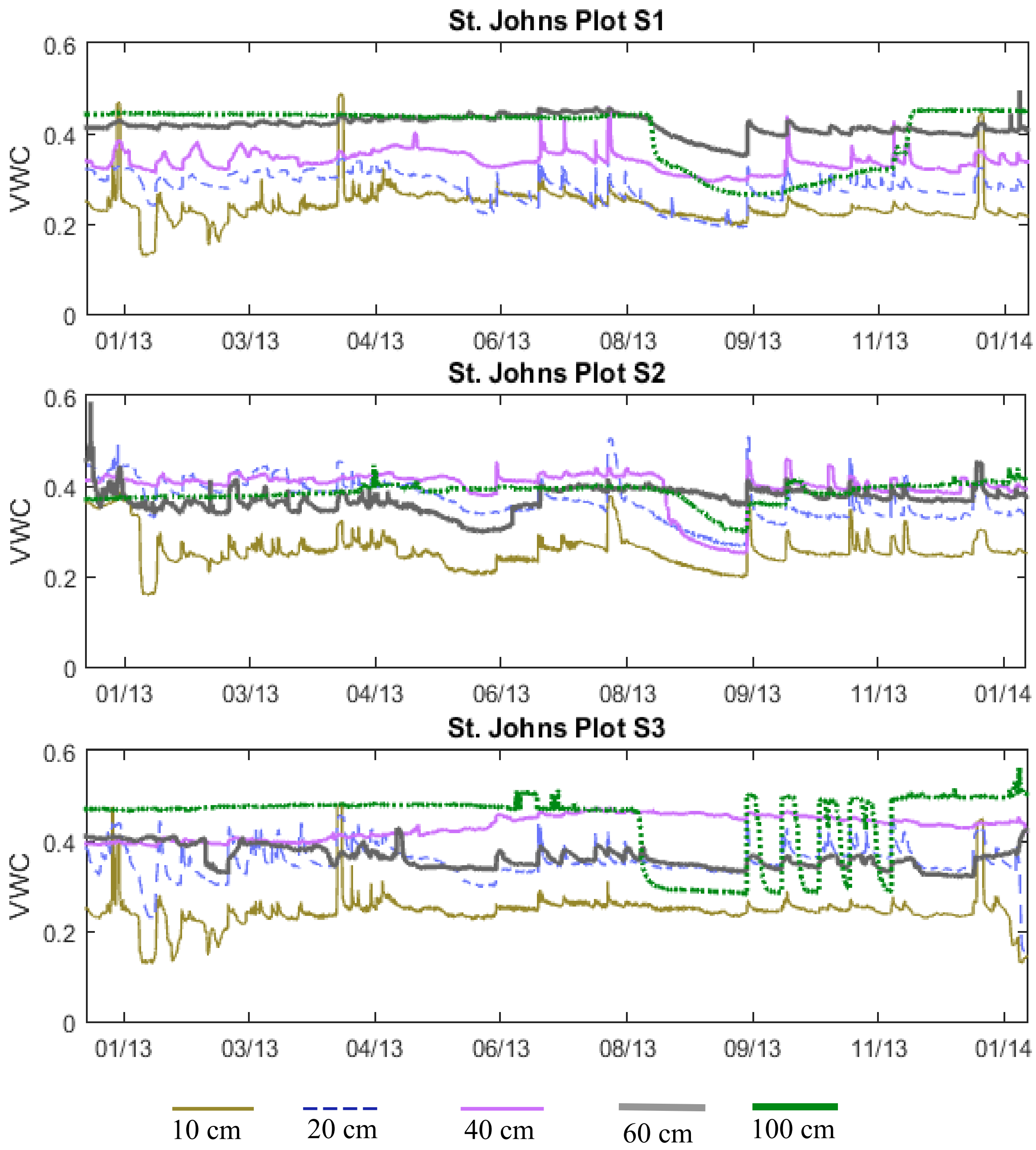

Figure 2.14 Filled volumetric soil moisture data from the free-draining plot of St. Johns for 2013.

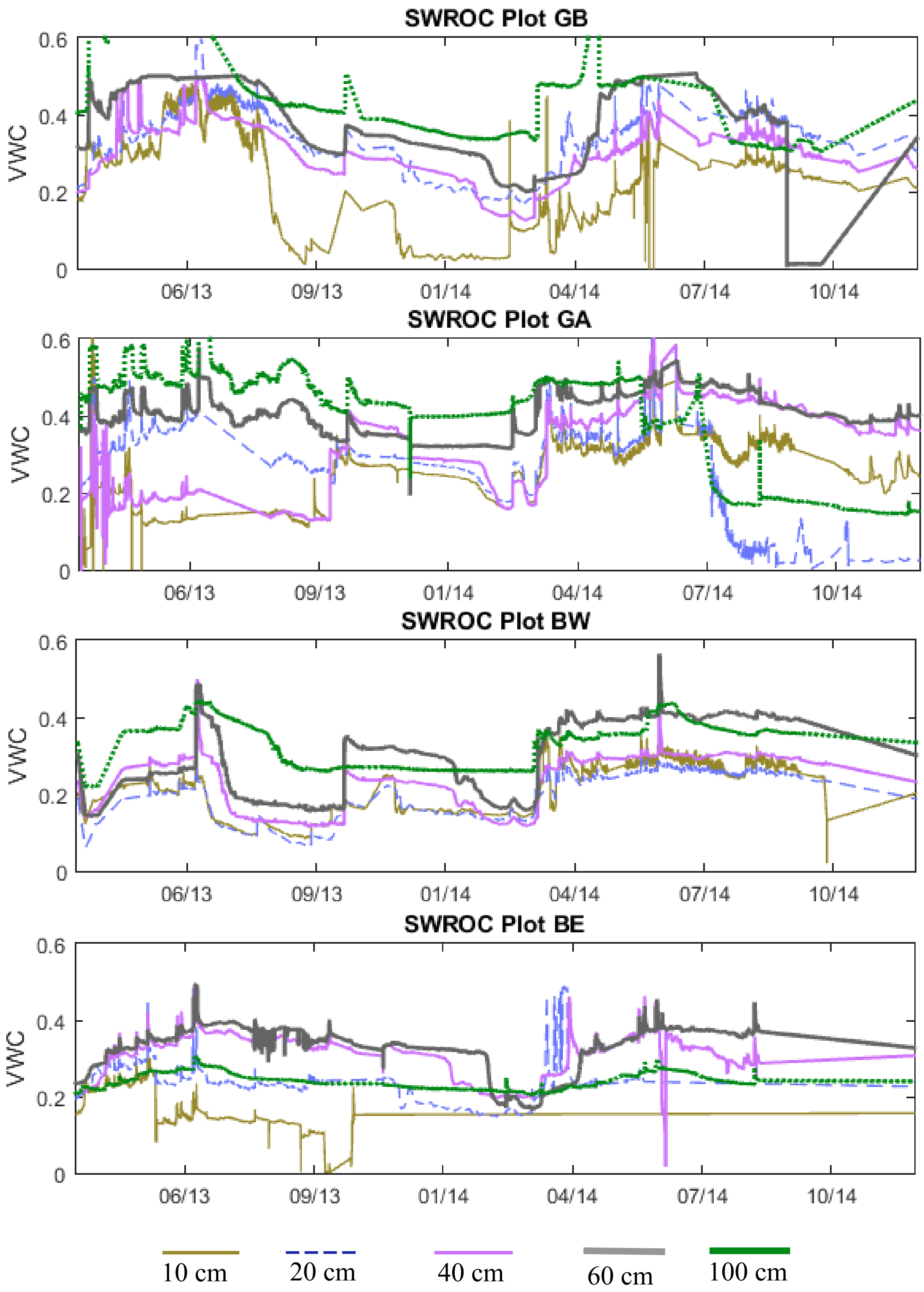

Figure 2.15 Filled volumetric soil moisture data from SWROC from January 1, 2013, to December 31, 2014 at the 10, 20, 40, 60, and 100 cm depths

2.5 Effect of filling on data quality

The effect of the filling procedure on data quality was investigated by comparing measured values and estimated values in periods when no outage actually occurred. Twenty gaps of 15 days duration and 20 gaps of 30 days duration were created in the hourly-resolution time series of each sensor at DPAC starting at randomly-selected times. These artificial gaps were created only during the 2012 or 2014 growing season during times without gaps in the record of the outage sensor and at least one of the two replacement sensors. Bias was calculated as the mean of the difference between the estimated and the observed data. A total of 40 values for bias were calculated for each treatment (20 from each of two quadrants) and an average bias was determined for these 40 values.

The overall average bias was fairly close to zero regardless of the duration of the outage in both free and managed plots. However, soil moisture was both over- and under-estimated; values were close to 30% for some of the test periods at the 100 cm depth (Figure 2.16).

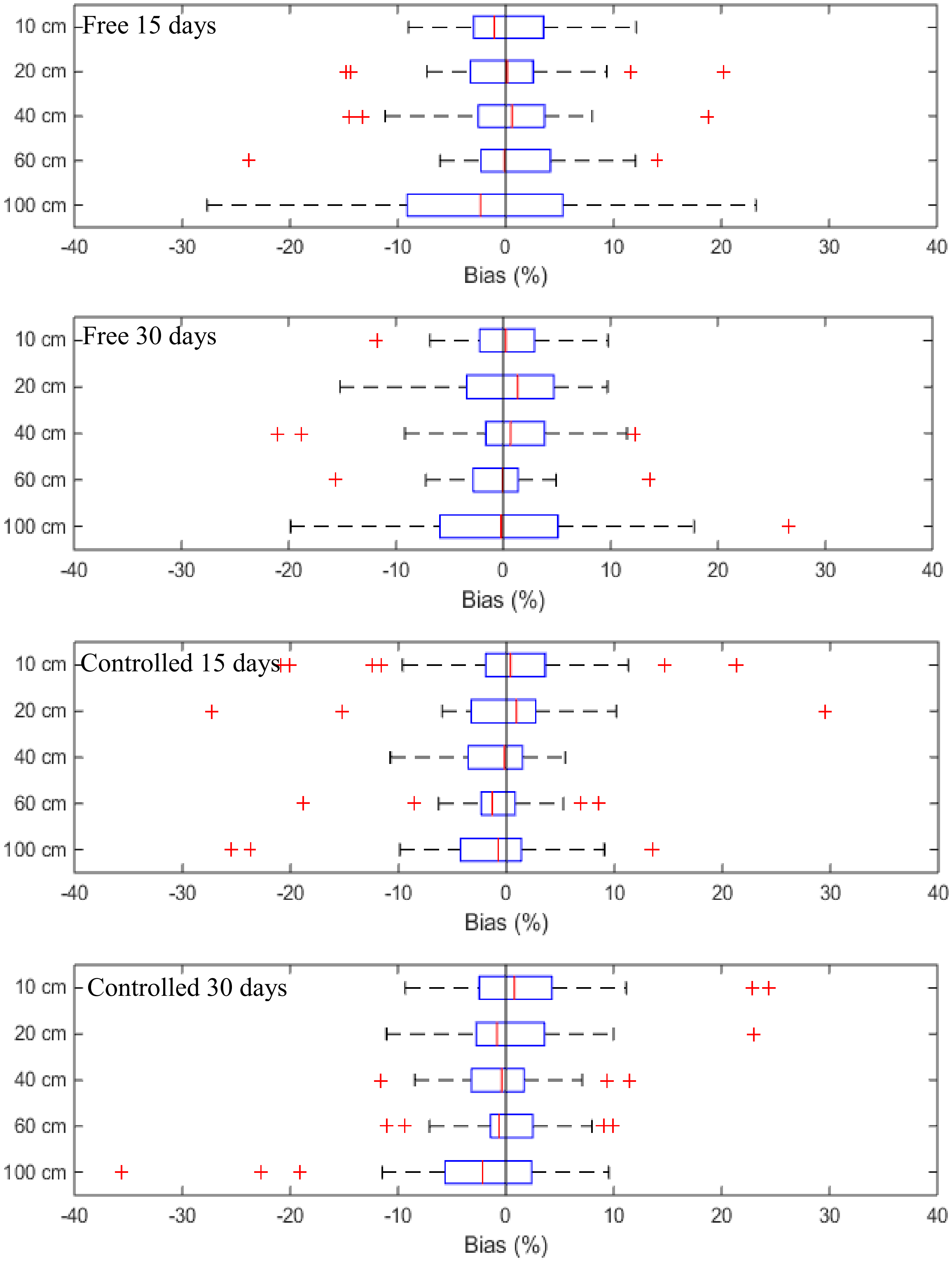

Figure 2.16 Spread of bias values from 40 test periods lasting 15 or 30 days in free and controlled plots

While the values that were estimated for the artificial gaps were often very close to the observed values (examples shown in Figure 2.17a for a 10 cm sensor and 2.17b for a 60 cm sensor), discrepancies also occurred. Estimations of soil moisture at the 10 cm depth can be overestimated, as in Figure 2.17c, which occurred during late summer, because soil was drying but is drying faster at the 10 cm depth than at the 20 cm depth from which estimates were being calculated. The 10 cm sensor also tends to show greater sensitivity to precipitation and greater variability than the 20 cm sensor, resulting in some estimated values, such as Figure 2.17d, that do not capture the peaks in the 10 cm record. Sometimes a large change in soil moisture in the replacement or the observation record result in a sudden jump in soil moisture at the end of the filing period, as shown in Figure 2.17e.

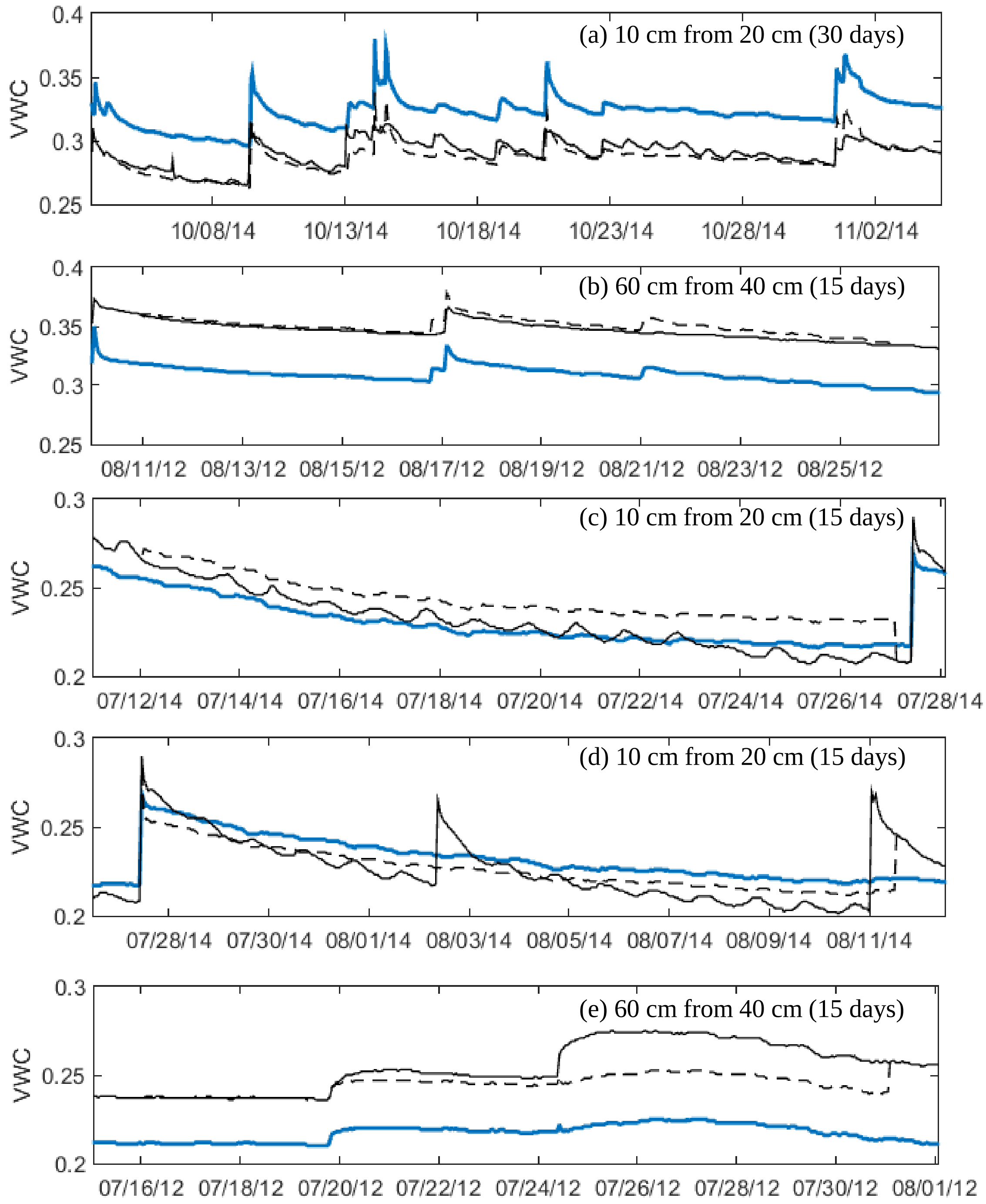

Figure 2.17 Comparison of estimated to observed soil moisture (a) 10 cm with 20 cm replacement (b) 60 cm with 40 cm replacement (c) 10 cm with 20 cm replacement (d) 10 cm with 20 cm replacement and (e) 60 cm with 40 cm replacement.

2.6 Converting volumetric water content to equivalent depth

The final step to prepare soil moisture data for growing season analysis was to convert the volumetric water content measurements to equivalent depth and aggregate the measurements to represent the entire soil profile or different sections of the soil profile. Each soil moisture sensor was assumed to represent the midpoint of a layer of soil with thickness ranging from 15 to 30 cm (Table 2.7). Equivalent depth was calculated by multiplying the volumetric measurement by the thickness of the represented layer. To analyze multiple layers, the equivalent depths determined at each layer were added.

As described in section 3.3, core samples were taken from each field site in order to determine water retention properties at 0 – 10 cm, 10 – 20 cm, 20 – 40 cm, and 40 – 60 cm. Each sampling location was assumed to represent one of the same layers as the soil moisture sensors.

Table 2.7 Soil layers and thicknesses represented by soil moisture sensors and core samples

Soil Layer (thickness)	Core measurement depth	Soil moisture sensor depth
0 – 15 cm (15 cm)	0 – 10 cm	10 cm
15 – 30 cm (15 cm)	10 – 20 cm	20 cm
30 – 50 cm (20 cm)	20 – 40 cm	40 cm
50 – 80 cm (30 cm)	40 – 60 cm	60 cm
80 – 100 cm	none	100 cm

2.6 Soil moisture comparison with water table

The quality of the datasets produced by the filling methods described in this chapter were further explored by comparing soil moisture to water table. Filled soil moisture from DPAC and water table measured in the same locations were plotted to illustrate their relationship (Figures 2.18– 2.19). Values that occurred at least 48 hours since any rainfall and under non-frozen soil conditions are highlighted in the figures in black. As expected, the volumetric water content measurements at the 10 cm depth show almost no relationship with water table. Weak correlation between surface soil moisture and soil moisture at other depths were also found by Mahmoud and Hubbard (2007) under rainfed corn; surface soil moisture is influenced by different processes than subsurface soil moisture (Vereecken et al 2014; Vienken 2013). At the 60 cm depth, the agreement between the measurements is slightly clearer, especially in the managed plots (NW and SE), where the water table is often closer to the 60 cm depth. Finally, soil moisture as equivalent depth for a 0 – 100 cm soil column, more of the scatter in the relationship is removed. It was determined from the test periods described in section 2.3 that estimations of soil moisture have a small bias on average, but that both overestimation and underestimation occur in individual data outages. When four sensor measurements are used together, the overestimation by one sensor may be offset by underestimation in another sensor, resulting in what appears to be a more reliable dataset.

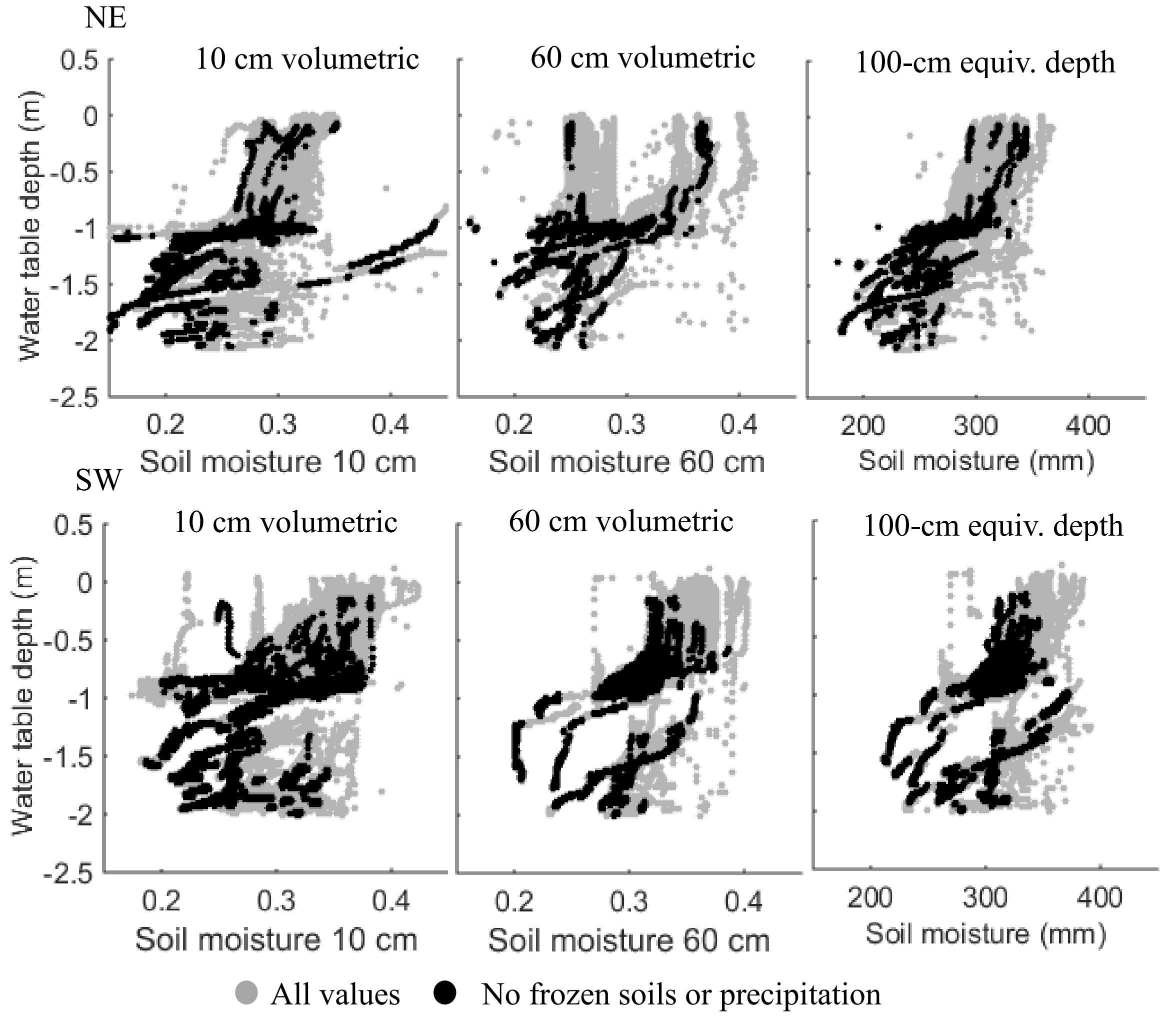

Figure 2.18 Water table vs. soil moisture in the free-draining DPAC plots for volumetric water content of the 10 cm sensor, volumetric water content of the 60 cm sensor, and total column soil moisture

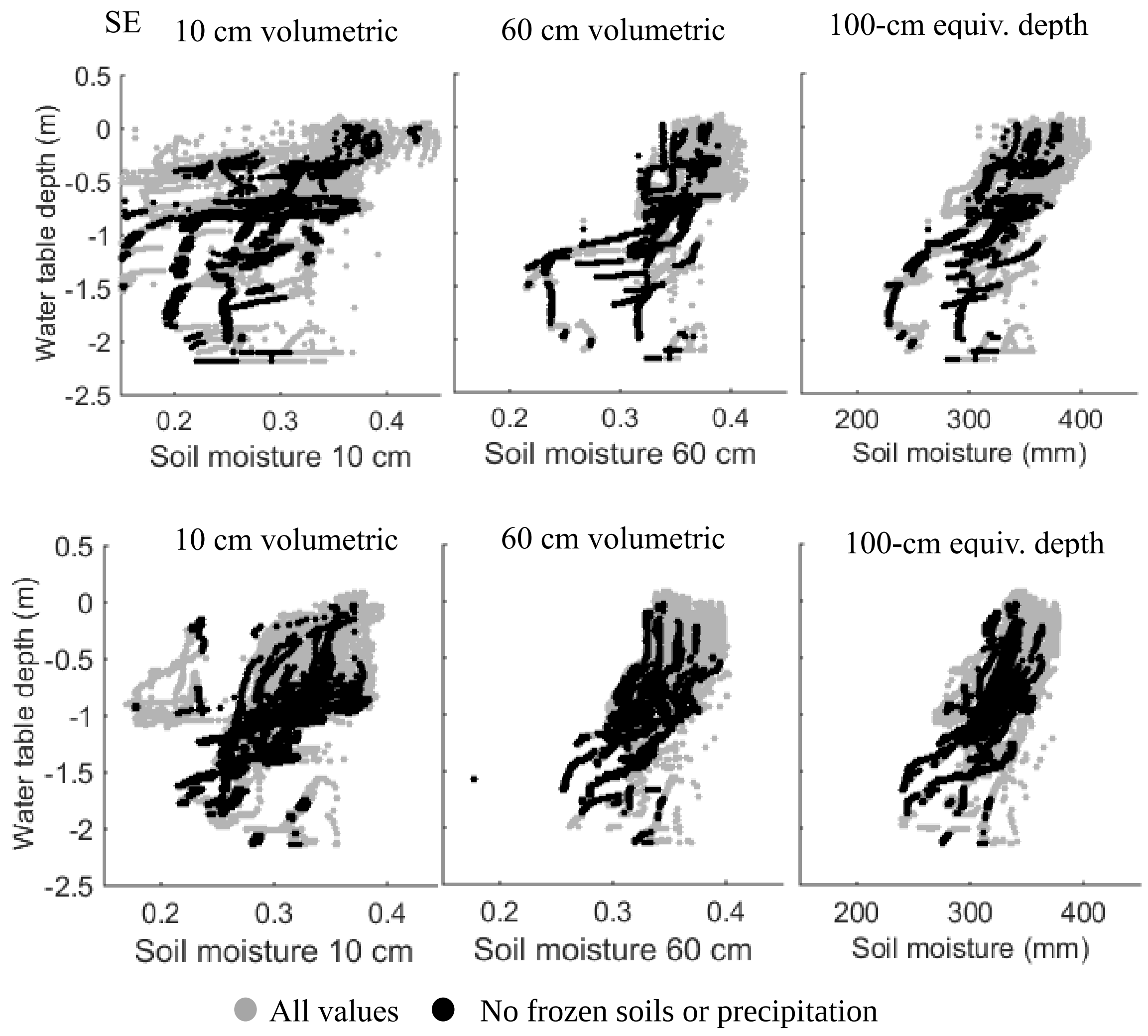

Figure 2.19 Water table vs. soil moisture in the controlled DPAC plots for volumetric water content of the 10 cm sensor, volumetric water content of the 60 cm sensor, and total column soil moisture

2.7 Conclusions

Despite efforts to maintain the monitoring systems established at the four field sites, data gaps occurred at all sites. These gaps were handled by estimating data from working sensors whenever possible, requiring an investigation into the relationships between all the sensors. Developing implementing, and evaluating the filling method resulted in these key findings:

- Using a processing script to fill all gaps in the soil moisture record with a single method allowed for more thorough detection of gaps than treating each gap separately, and may be essential for managing large datasets, though it also results in some gaps being left behind. Opportunities to improve the method are discussed in Chapter 4.
- Sensors were correlated with others at different depths generally just as well as with others at different locations and the same depth. This is somewhat inconsistent with the findings of Dumedah and Coulibaly (2011), who found that estimation from a different location at a similar depth was more accurate than estimation from the same location at a deeper or shallower depth.
- Different soil properties at each site influence soil moisture. For example, DPAC and St. Johns receive similar amounts of rainfall due to their close proximity, but soil moisture at DPAC has a smaller range.
- Bias values resulting from 15-day outages and 30-day outages were similar. Though Kornelson and Coulibaly (2014) found that the quality of their best-performing filling methods declined steadily after gap lengths of a maximum of 100 hours, the longer gaps at the sites in this study were much longer than that, suggesting that there may also be a gap length beyond which the performance of the filling method will remain constant.
- Estimated data should not be used to analyze events on a sub-daily time scale.

CHAPTER 3 QUANTIFYING SOIL MOISTURE STRESS TO ASSESS YIELD EFFECTS OF CONTROLLED DRAINAGE

3.1 Background

Because controlled drainage reduces the amount of water leaving fields through the drainage system, additional water in the soil profile may be used during the growing season to benefit crop growth. In a water balance assessment of the DPAC drainage site, Brooks (2013) found that the controlled plots had 12% higher total soil moisture on an annual scale and may have also had higher ET based on unmeasured terms of the water balance. With less loss of water through drainage and more soil moisture in the root zone, fields with controlled drainage could prevent water shortages to crops and provide a yield benefit compared to freely draining fields.

Field studies of the yield impacts of controlled drainage have shown mixed results. Of eight field studies reviewed by Skaggs et al. (2012) examining the effects of controlled drainage on corn yields, four studies found no statistically significant effect, one found a yield reduction, and three found yield increases.. Helmers et al. (2012) found that controlled drainage resulted in slightly reduced corn yields in a 4-year field study in Iowa. Ghane et al. (2012) found a yield increase in 6 out of 9 observations in 1-2 year studies of cornfields in Ohio. Poole (2011) found yield improvements in a 6-year study of corn. Delbecq et al. (2012) found an in increase between 5.8 and 9.8% during 5 years.

Modeling studies have predicted that controlled drainage could reduce corn yields due to excess soil moisture during the spring. The Stress Day Index concept to describe the effect of excess moisture on crop yields was initially proposed by Hiler (1969). The stress day index is the product of the amount and duration of excess water, the “stress day factor,” as well as a “susceptibility factor,” which is related to the ability of the crop to withstand stress at a particular time. Hardjoamidjojo et al. (1982) used SEW_{30} as the stress day factor, the total cm-days of water table depth shallower than 30 cm below the soil surface, and developed crop susceptibility factors for corn using observed yields in Ohio and other field studies of excess water stress such as Chaudhary (1975) and Ritter and Beer (1969). The resulting linear model related Stress Day Index to relative yield, explaining between 75% and 79% of variation in crop yields, and was incorporated into DRAINMOD. Ale (2008) simulated a drainage water management strategy for 15 years using the Hardjoamidjojo model within DRAINMOD and found that controlled drainage resulted in a decrease in relative yield of 0.5%, which was not statistically significant; yields increased in plots with controlled drainage in some years of the simulation and decreased in others. Singh et al. (2007) also simulated yield response to controlled drainage with DRAINMOD and found yield reductions due to delayed planting and excess water stress.

Corsi and Shaw (1971) proposed indices of deficit stress to crops, and concluded that the best one for predicting corn yield in Iowa was one minus the ratio of evapotranspiration to potential evapotranspiration. Shaw (1974) determined weighting factors for this index based on growth stages of crops, emphasizing the sensitivity of the silking period and applying additional weighting factors to account for the cumulative effects of extreme stress.

Liang, et al. (1994) developed a metric based on soil moisture to indicate transpiration stress in the VIC model called the stress factor. The factor is calculated as follows:

$$g = \frac{VWC - WP}{Wcr - WP}$$

Where WP is permanent wilting point and W_{cr} is the critical point or stress threshold, which they took to be 70% of field capacity. The stress factor is 0 if VWC falls below the wilting point and 1 when VWC is above the deficit threshold.

While field studies have identified some yield effects from controlled drainage, they have often not related yields to the other environmental conditions monitored, such as periods of high water table that have been explored by modeling studies. More insight is needed into the conditions in the field that result in inconsistent yield effects of controlled drainage. By comparing both yield and soil moisture conditions in controlled and free-draining plots, it is possible to gain a better understanding of why the controlled plots may either improve or reduce yields. The objective of this chapter is to identify potential for yield benefits of controlled drainage by comparing soil moisture stress between managed and free-draining plots and relating that stress to corn yield.

3.2 Soil moisture data

Soil moisture was analyzed for the DPAC, SERF, St. Johns, and SWROC drainage sites during the years when corn was grown. Combining data from all sites and available years resulted in a total of 28 soil moisture data sets, of which 14 came from conventionally drained plots and 14 came from managed plots (Table 3.1).

Corn was grown every year at SERF, but there are large amounts of missing data in two of the SERF plots in 2014, so only 2012 and 2013 were analyzed in plots F2 and D3. Although corn was grown every year at SWROC, consistent monitoring of soil moisture did not begin until 6 weeks after planting in 2012, so only data from 2013 and 2014 were considered. Some data quality issues at SWROC could not be addressed by the data handling methods described in Chapter 2. Gaps of duration longer than 30 minutes with at least 4 of the 5 sensors recording no data occurred in plot GB 2014 and GA 2013. The soil moisture data record also ended more than 30 days prior to the maturity of the corn crop in 2014 plots BE and BW. As a result, the plot-years analyzed from SWROC were BE 2013, BW 2013, GA 2014, and GB 2013.

Table 3.1. Available soil moisture data when corn was grown

	Number of plots	Crop			Total plot-years used
		2012	2013	2014	
IN, DPAC	4	Corn	Soybean	Corn	8
IA, SERF	4	Corn	Corn	Corn[b]	8
OH, St. Johns	2	Wheat	Corn	Soybean	2 (6 sensors)
MN, SWROC	4	Corn[a]	Corn[b]	Corn[b]	4

[a]data not used due to gaps in monitoring
[b]some data used

3.3 Soil moisture stress metrics

Metrics were developed to quantify soil moisture excess and deficit periods based on soil moisture falling above or below a threshold value. Because the relationship between crop stress and soil moisture was unknown and crop stress was not directly monitored, many different stress metrics were initially calculated. Four characteristics were used to develop soil moisture metrics: a threshold determining the severity of the stress; the soil depth range over which the metric was considered; the crop growth stage in which the stress occurred; and way the stress was integrated (Table 3.2). Each metric consisted of a unique combination of these four components.

Table 3.2 Thresholds, depths, growth stages, and integration methods combined to create soil moisture metrics

Thresholds	Depths	Growth stages	Integration methods
Excess: • .05 bar water retention Deficit: • 60%, 70%, and 80% of 0.1 bar water retention (“field capacity”) • 45%, 50%, 55% and 60% of 0.1 bar water retention – 15 bar water retention (“plant available water”)	0 – 30 cm 0 – 50 cm 40 – 60 cm 0 – 80 cm	Plant – VE VE – V6 V6 – V16 V16 – R3 R3 – R5 R5 – R6 Early: VE – V6 Late: R3 – R6 Whole: Plant – R6	Time Magnitude

3.3.1 Thresholds and depths

Thresholds and depths were considered together in determining stress metrics. The thresholds were based on water retention data at different pressures, which were assumed to represent soil qualities like field capacity, wilting point, and plant available water. In total, 21 thresholds of excess and deficit were initially tested (Table 3.3).

Table 3.3 Initial excess and deficit thresholds and depths used to create soil moisture metrics

#	Value	Depth analyzed	Layers used
Deficit Thresholds			
1	60% of retention at .1 bar	0 - 80 cm	0 – 15 15 – 30 30 – 50 50 – 80
2	65% of retention at .1 bar		
3	70% of retention at .1 bar		
4	75% of retention at .1 bar		
5	80% of retention at .1 bar		
6	70% of retention at .1 bar	0 - 30 cm	0 – 15 15 - 30
7	70% of retention at .1 bar	30 - 80 cm	30 – 50 50 - 80
8	45% of plant available water	0 - 80 cm	0 – 15 15 – 30 30 – 50 50 – 80
9	50% of plant available water		
10	55% of plant available water		
11	60% of plant available water		
12	50% of plant available water	30 - 80 cm	30 – 50 50 - 80
Excess thresholds			
13	90% of retention at .05 bar	0 - 30 cm	0 – 15 15 – 30
14	95% of retention at .05 bar		
15	100% of retention at .05 bar		
16	90% of retention at .05 bar	0 - 50 cm	0 – 15 15 - 30 30 – 50
17	95% of retention at .05 bar		
18	100% of retention at .05 bar		
19	90% of retention at .05 bar	0 - 80 cm	0 – 15 15 – 30 30 – 50 50 – 80
20	95% of retention at .05 bar		
21	100% of retention at .05 bar		

The deficit threshold was meant to capture the critical point at which crops begin experiencing transpiration limitation due to decreasing matric potential of the soil water. When soil moisture falls below the threshold value of readily available water (RAW), roots cannot extract moisture fast enough to keep up with transpiration and the plant will begin to suffer stress (Allen 1998). Readily available water is related to total plant available water (PAW) by a factor p that varies from crop to crop, but is about 0.55 for grain corn (Allen 1998):

$$\text{RAW} = \text{pPAW}$$

Total plant available water is often assumed to be equal to the difference between field capacity and the wilting point in the root zone.

Field capacity was defined by Veihmeyer and Hendrickson (1931) as the amount of moisture remaining in soil “after excess water has drained away,” and it is most commonly estimated based on water retention at benchmark pressures; 0.33 bar tension is often used for fine-grained soils and 0.1 bar tension for course-grained soil (Twarakavi, et al. 2009). Some researchers have proposed flux-based estimations of field capacity; for example, the amount of water remaining once drainage flux from the soil slows to 0.05 cm/day (Hillel 1998).

In this study, soil moisture at 0.1 bar tension was used for field capacity. The choice of 0.1 bar to estimate field capacity in this study follows the logic of estimating field capacity based on flux. The artificial drainage in the fields studied result in excess water draining until the water table reaches the depth of the tiles, at approximately 100 cm below the surface. Thus matric potential at the soil surface is approximately 0.1 bar tension when the drain flow approaches zero.

Because water content at field capacity and therefore the deficit threshold are uncertain, the factor p was varied to 0.45, 0.50, 0.55, and 0.60. The deficit thresholds based on plant available water were calculated as follows:

$$Threshold = p(Field\ Capacity - Wilting\ point) + Wilting\ point$$

where wilting point was estimated as water retention at 15 bar tension.

Researchers have also estimated that the relationship between the ‘critical point’ of limited evapotranspiration and the field capacity of the soil is between 0.5 and 0.8 (Shuttleworth 1993), which makes for an even simpler soil moisture deficit threshold. Thresholds of 60, 70, 75, and 80% of field capacity were tested. In soils with high water contents at their wilting points, the threshold based on readily available water was higher than the one based on field capacity alone.

The excess threshold is based on assumption that plant roots will be affected by low oxygen conditions when the equilibrium water table is within 50 cm. For this reason, water retention at 0.05 bar tension was selected as the basis for the excess stress threshold. As listed in Table 3.3, excess thresholds were varied to 90%, 95%, and 100% of the water retention at .05 bar.

Stress was quantified at different depths in the soil profile. During the early growing season, when excess stress was expected to occur the most, the roots of the corn plants most likely do not extend throughout the entire 80 cm depth of the soil profile. It was unknown whether excess water at depths below the extent of the root zone would affect crops or not, so stress was quantified at the surface (0 – 30 cm) and the top half of the root zone (0 – 50 cm) in addition to the entire profile (0 – 80 cm). Because of the variation in soil moisture with depth driven by different interactions with the atmosphere, drain, and water table, the location of deficit stress measurements were also varied to include a surface layer (0 – 30 cm) and the bottom half of the root zone (40 – 80 cm).

3.3.2 Water retention data used to determine thresholds

Water retention at .05, 0.1, and 15 bar tension was measured using sand tables on core samples from each field site in 2011. Samples were taken from 0 – 10 cm, 10 – 20 cm, 20 – 40 cm, and 40 – 60 cm depths. Each sample was assumed to represent a soil layer also represented by one of the soil moisture sensors (Table 2.7). Volumetric water retention was converted to an equivalent depth for each of these layers in a manner similar to that used for the conversion of soil moisture data (Tables A.1 – A.4).

The values the excess and deficit thresholds were unique at each plot due to variations in water retention characteristics (Figure 3.1). Thresholds based on plant available water always falls between wilting point and field capacity, but the threshold of 70% of field capacity alone falls below wilting point at St. Johns, where wilting point was higher than at the other sites. At SERF and SWROC, the thresholds of 50% of plant available water and 70% of field capacity were almost the same.

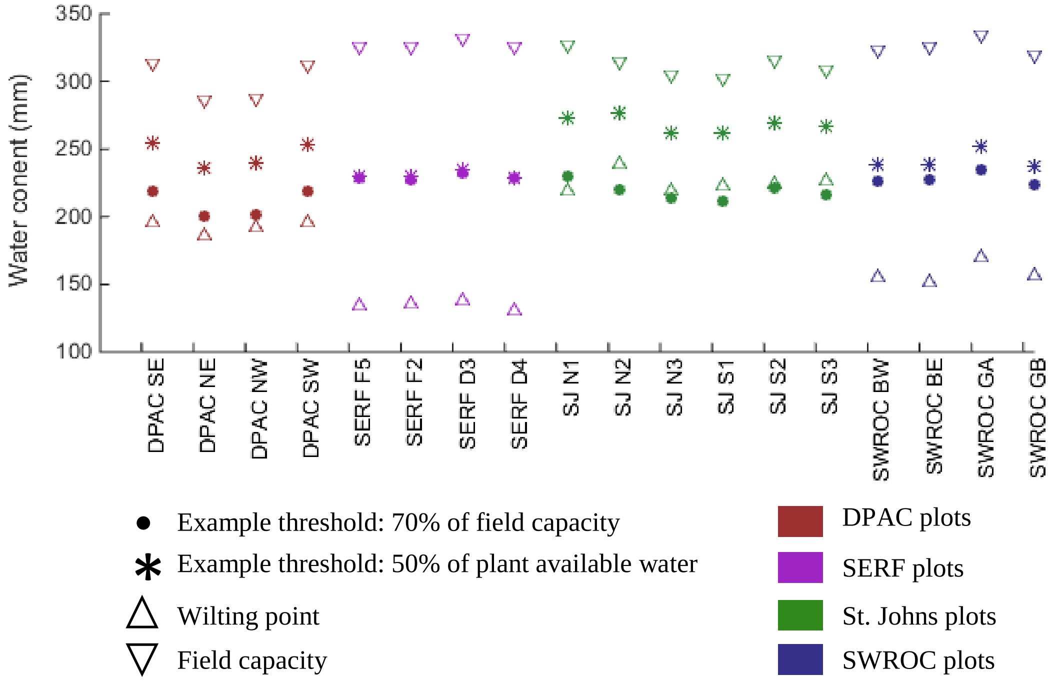

Figure 3.1 Field capacity, wilting point, and sample thresholds of 50% of plant available water and 70% of field capacity at each plot

At SERF and SWROC, water retention data was not measured at all depths and pressures. At SERF, water retention data was not measured for .05 bar, 0.1 bar, or 1 bar pressure at the 20 – 40 and 40 – 60 cm depths. At SWROC, water retention was not measured for 15 bar pressure at the 20 – 40 and 40 – 60 cm depths. The Rosetta program (Schapp et al. 2001) was used to estimate the parameters of the Van Genuchten water retention curve at these locations based on measurements of bulk density and percent sand, silt, and clay that were taken at those depths (Table 3.4). Water content at the pressures needed were calculated based on these parameters.

The values estimated by Rosetta for the 20 – 40 and 40 – 60 cm depths are higher than those measured at the 0 – 20 and 10 – 20 cm depths (Table 3.4). If the water content at wilting point were actually lower than what was estimated, the thresholds based on plant available water would be lower, resulting in less deficit stress at SERF and SWROC. Using estimated wilting points may have resulted in overestimating deficit stress at SERF and SWROC for the deficit thresholds based on plant available water. The uncertainty surrounding the exact value of soil moisture where crops begin experiencing stress highlights the importance of testing a variety of thresholds.

Table 3.4 Measured and estimated volumetric water retention at 15 bar at SERF and SWROC

Location	SERF (all plots average)		SWROC (Field G average)	
	Water Retention	% Sand, Silt, Clay	Water Retention	% Sand, Silt, Clay
0 - 10 (measured)	0.11	13/48/39	0.12	2/45/53
10 - 20 (measured)	0.09	12/48.5/38.5	0.12	3/44/53
20 - 40 (estimated)	0.21	14/46/40	0.25	2.5/45.5/52
40 - 60 (estimated)	0.21	13/47/40	0.26	1/46/53

3.3.3 Growth stages

Each soil moisture time series was divided into periods based on an estimation of corn growth stages at that site. Crop growth and development were estimated from growing degree days, calculated as the average of daily high and low temperatures above 50 degrees (Fahrenheit):

$$GDD = \frac{T_{max} - T_{min}}{2} - 50$$

where T_{max} is the smaller of the high temperature for the day or 86 F, and T_{min} is the larger of the minimum temperature for the day or 50 F.

The GDD required to reach the various growth stages for corn crops were based on Abendroth et al. (2011), which assumes that seedling emergence occurs 105 GDD after planting; that one new leaf appears every 84 GDD from VE to V10; that one new leaf appears every 56 GDD from V10 to V18; and that start of the V18 growth stage coincided with R1 (Table 3.5). The additional GDD required to reach additional reproductive stages from the start of R1 were based on data from research trials conducted in Iowa (Abendroth et al. 2011). The V16 through R3 period was used to represent the entire transition from vegetative to reproductive growth, including tassel emergence and silking, because the sequence of development can vary during this period. A total of nine growth stages were considered. The estimation of growth stages is approximate and does not take into account the differences between crop varieties planted at each site. At Minnesota in 2014, R6 was allowed to occur after only 2400 days because the harvest date occurred before 2645 growing degree days had accumulated. The calendar day for each growth stage to be reached varied for each year and site (Table 3.6).

Table 3.5 Growing Degree Days (GDD) from planting for selected growth stages

Growth Stage	GDD for stage
Planting to VE	0 - 105
VE to V6	105 - 609
V6 to V16	610 - 1279
V16 to R3	1280 - 1792
R3 to R5	1793 - 2042
R5 to R6	2043 - 2645
Entire early season (Planting – V6)	0 - 609
Late reproductive (R3 – R6)	1793 - 2645
Entire growing season (Planting – R6)	0 - 2645

Table 3.6 Planting dates and calendar dates of the start of growth stages estimated from growing degree days for each site and year

	Plant	VE	V6	V16	R3	R5	R6
DPAC 2012	04/23	05/04	06/08	07/06	07/26	08/06	09/06
DPAC 2014	04/27	05/08	06/12	07/13	08/12	08/24	10/27
SERF 2012	04/18	05/04	06/04	07/04	07/23	08/02	09/01
SERF 2013	05/02	05/14	06/14	07/13	08/06	08/20	09/16
SERF 2014	05/06	05/12	06/13	07/13	08/08	08/20	09/27
St. Johns 2013	05/09	05/17	06/16	07/15	08/10	08/23	09/28
SWROC 2013	05/24	06/06	07/01	08/01	08/28	09/08	10/10
SWROC 2014	05/07	05/22	07/19	07/22	08/18	09/31	10/19*

*Using 2400 GDD days to reach maturity

3.3.4 Metric integration methods

Two methods were used to integrate excess or deficit stress, which was calculated at every hour, into a single value. In the “magnitude” method, stress was calculated as the absolute value of the difference between the threshold and the present water content (mm), then summed over the length of the growth stage (hours). This integration method results in stress in mm-hours.

For the “time” method, time in excess or deficit was integrated by summing the number of hours during each growth stage that the water content fell above (excess) or below (deficit) the threshold and dividing by the duration of the growth stage to account for the variation in the duration of each growth stage due to temperature variation.

The stress analysis resulted in one set of stress quantities for each of 9 growth periods and two integration methods. There were 12 deficit thresholds, resulting in a total of 216 different metrics of deficit stress, and 9 excess thresholds, for 162 different metrics of excess stress.

Figures 3.2 to 3.6 show a time series of soil moisture as equivalent depth for the 0 – 80 cm soil column for every plot-year. Vertical lines indicate the VE, V6, V16, R3, and

R5 growth stages. The duration of each plot extends from the planting date that actually occurred on the field that year until the R6 growth period was reached, regardless of harvest date, which occurred after the corn reached R6. Field capacity, wilting point, the aeration stress level, and two sample thresholds are also included. Soil moisture at DPAC fell below wilting point for portions of 2012 and 2014. While soil moisture was expected to be low during 2012, there may also be measurement errors that cause discrepancies between the water retention and soil moisture data. The lack of site-specific calibration in the sensors installed at the study sites is one source of error. Volumetric water content measurements by decagon's 5TE soil moisture probes can be influenced by salt content and soil temperature when using the manufacturer-supplied calibration functions, and may only reach manufacturer-specified accuracy when calibrated for a specific soil type and field location (Varble and Chavez 2011). Four different low-cost soil moisture sensors in a clay loam soil in Switzerland were found not to measure manufacturer-specified accuracy when compared against a high-quality TDR measurement system (Mittelbach et al. 2014). Another source of error is that core samples and soil probes measure soil properties in a small volume of soil but are assumed to represent larger volumes. Water retention values at DPAC at 15 bar tension were as high as 0.28 at the 40 – 60 cm depth in the NW plots, with values above 0.2 reported in at least one of the soil layers in all plots (Table A.1).

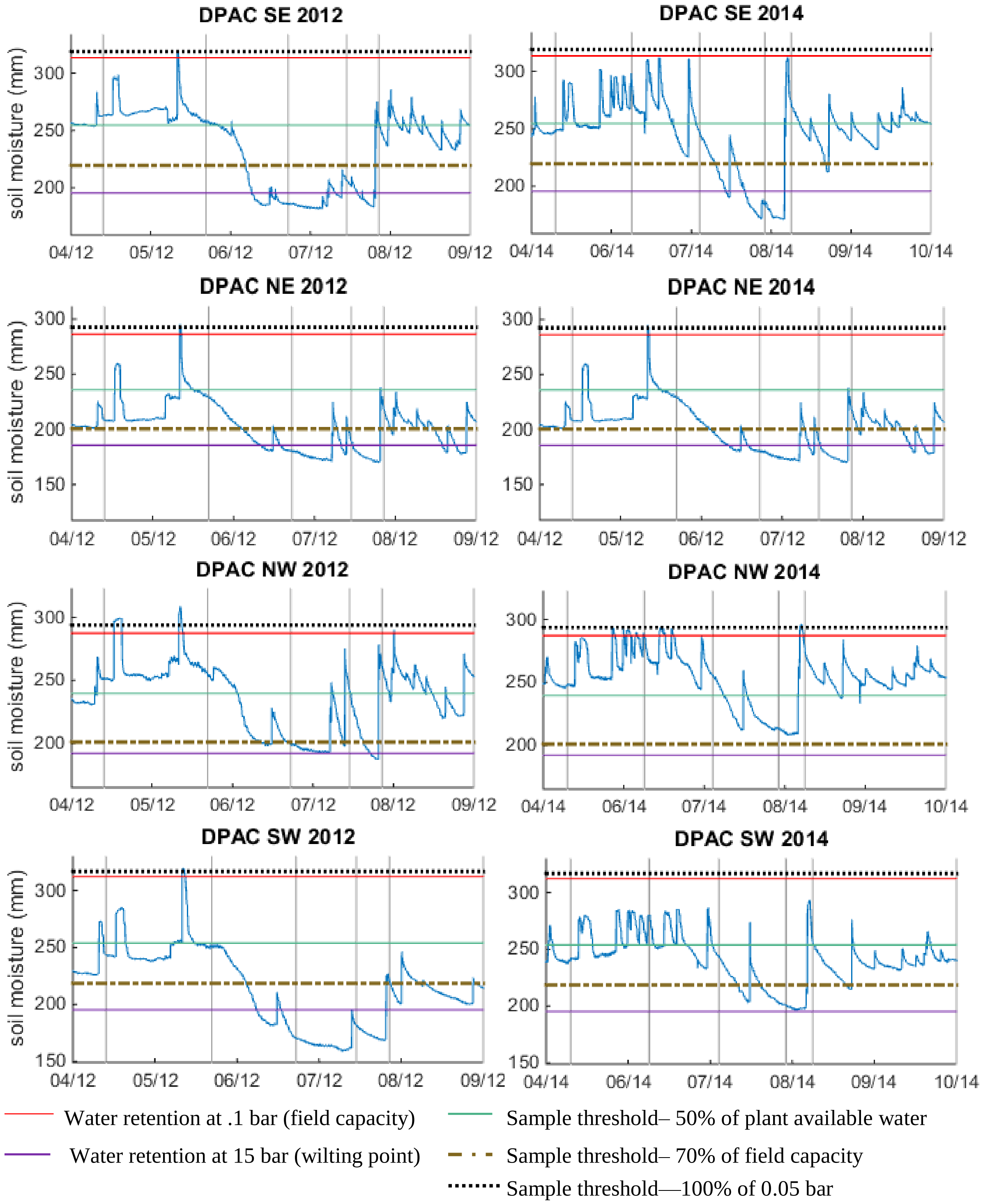

Figure 3.2 DPAC soil moisture time series for the GDD-estimated growing season based on 0 – 80 cm soil column for each plot-year with water retention 0 .1, and 15 bar tension, three sample thresholds, and vertical lines indicating the start of growth stages VE, V6, V16, R3, and R5

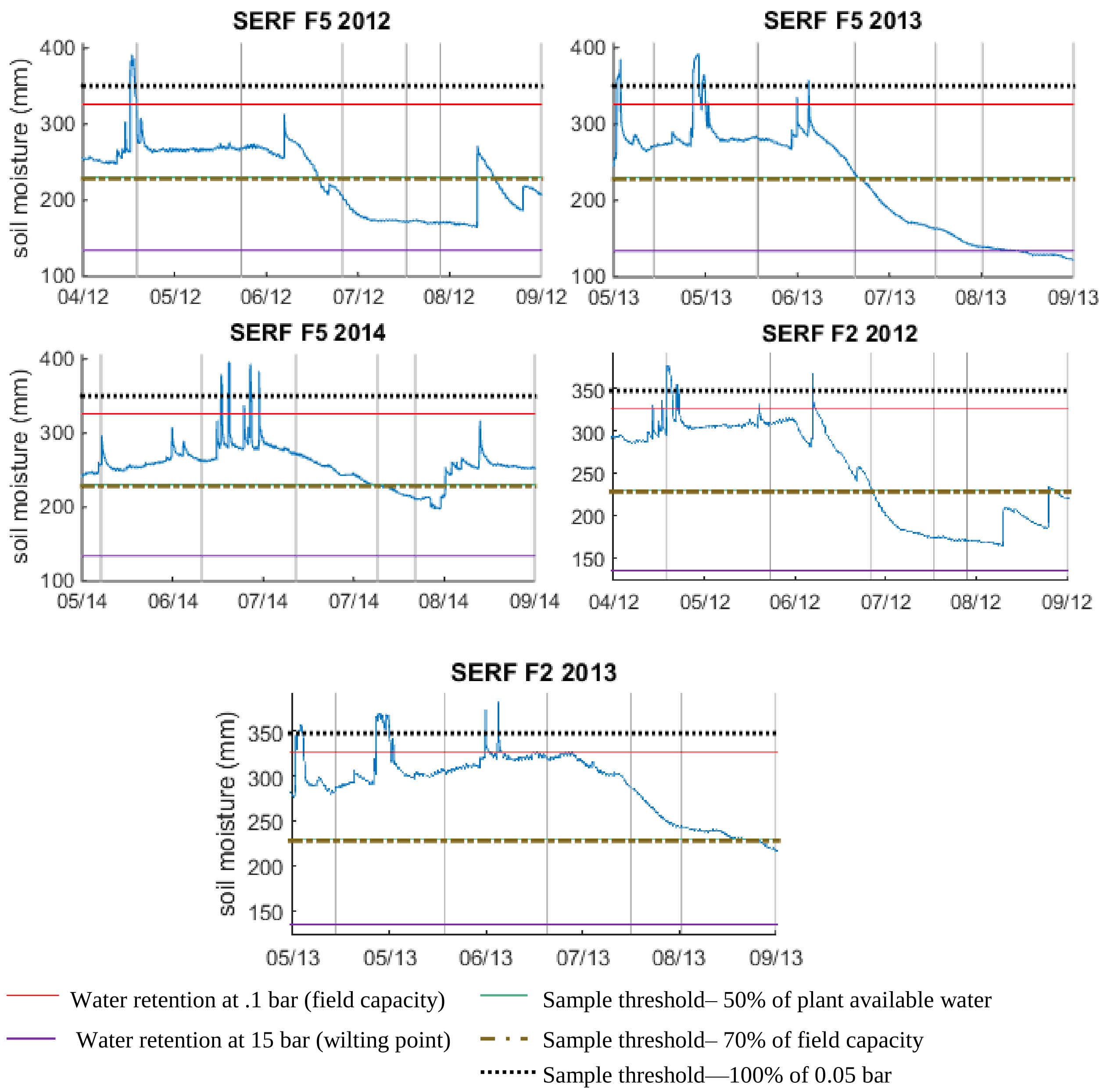

Figure 3.3 SERF soil moisture time series based on 0 – 80 cm soil column for each free-draining plot-year with growth stages VE, V6, V16, R3, and R5 indicated with vertical lines, water retention values at .05, .1, and 15 bar tension, and two sample deficit thresholds

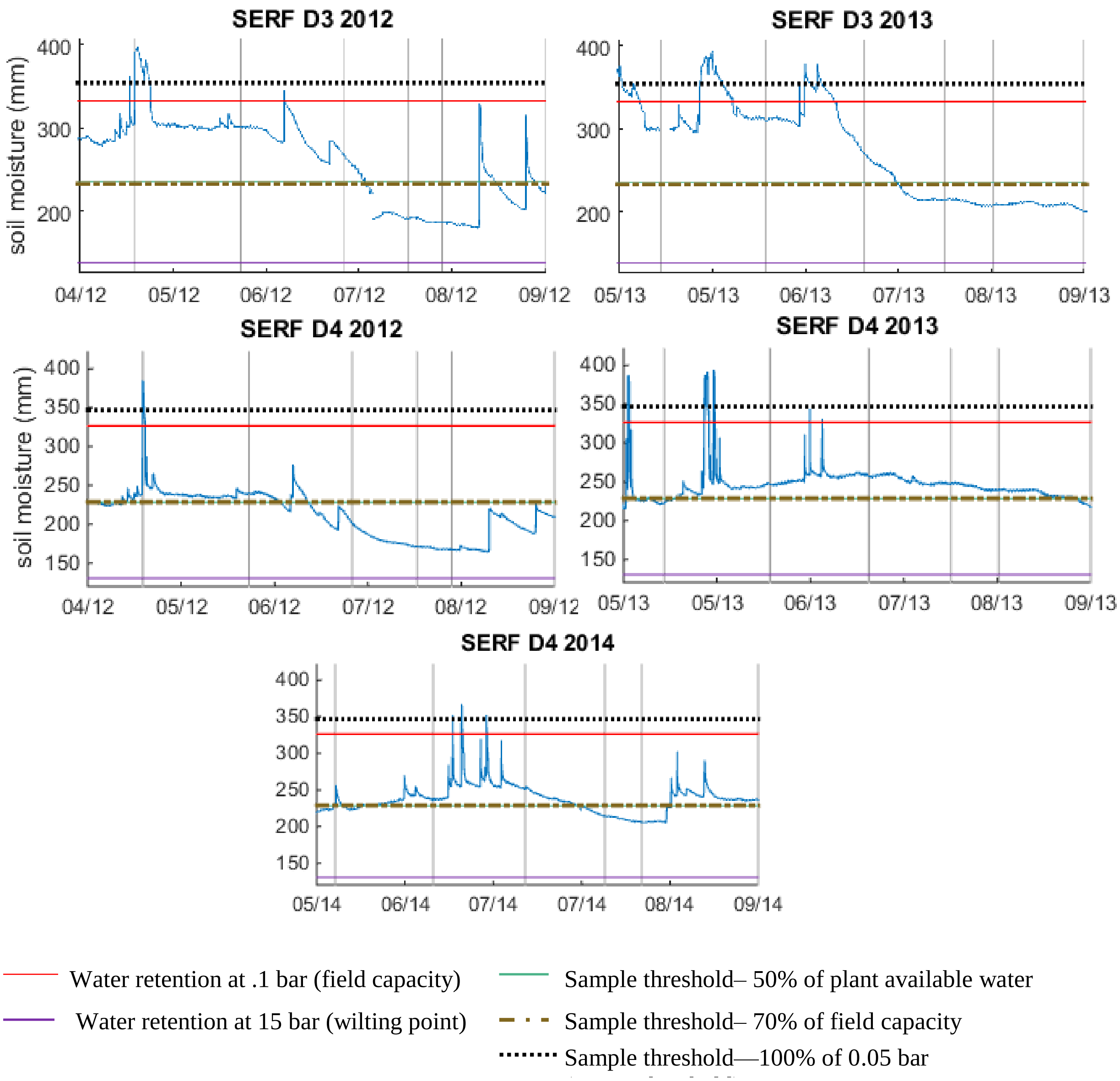

Figure 3.4 SERF soil moisture time series for the GDD-estimated growing season based on 0 – 80 cm soil column for each controlled-drainage plot-year with water retention 0 .1, and 15 bar tension, three sample thresholds, and vertical lines indicating the start of growth stages VE, V6, V16, R3, and R5

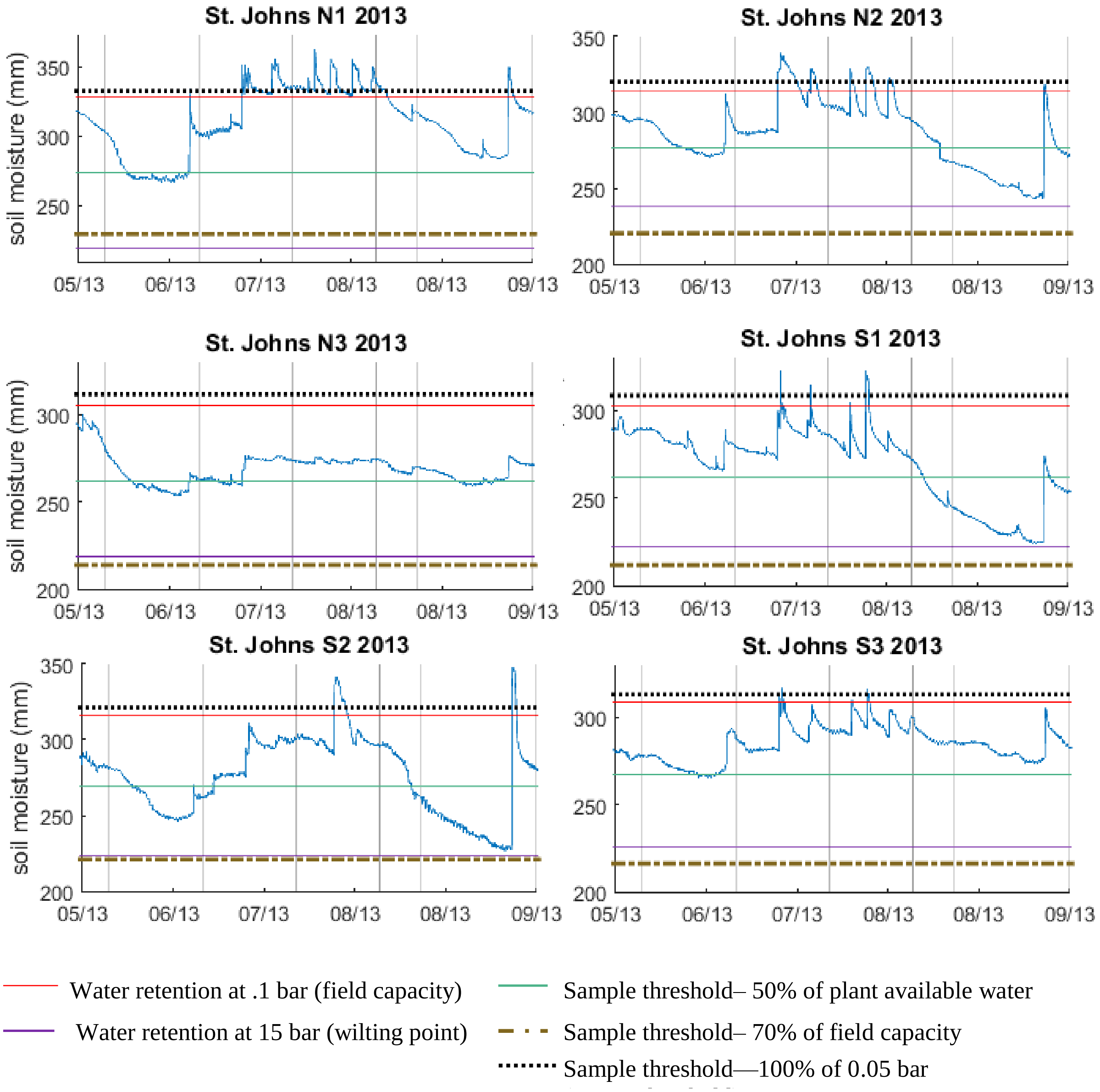

Figure 3.5 St. Johns soil moisture time series for the GDD-estimated growing season based on 0 – 80 cm soil column for each plot-year with water retention 0 .1, and 15 bar tension, three sample thresholds, and vertical lines indicating the start of growth stages VE, V6, V16, R3, and R5

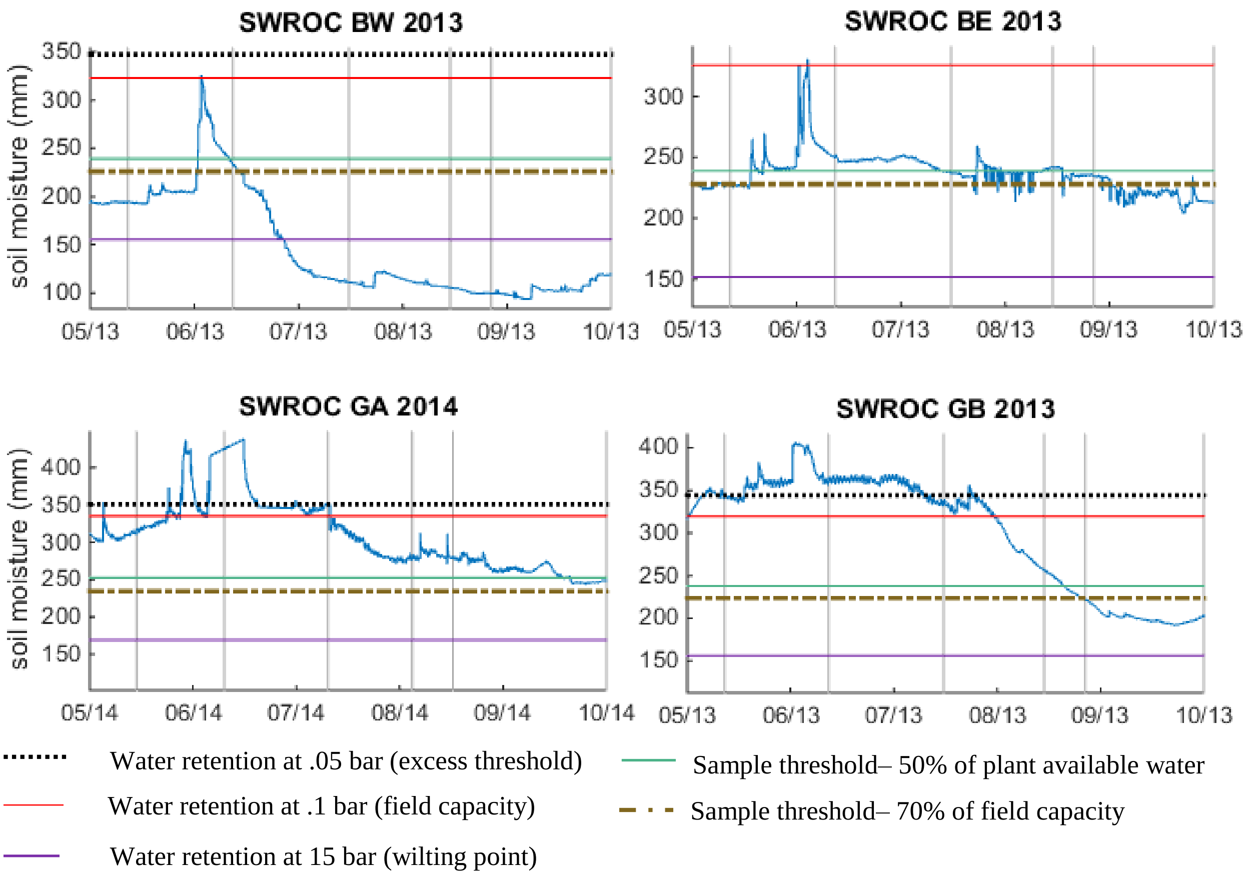

Figure 3.6 SWROC soil moisture time series for the GDD-estimated growing season based on 0 – 80 cm soil column for each plot-year with water retention 0 .1, and 15 bar tension, three sample thresholds, and vertical lines indicating the start of growth stages VE, V6, V16, R3, and R5

3.4 Yield data

Yield was determined as kg/ha at 15.5% moisture for each plot (Table 3.7). At SERF, St. Johns, and SWROC, only average yield for each plot was available. Yield monitor data at DPAC allowed for yield to be determined in a small area near the soil moisture sensor so that yield values represent a similar area to that which was measured by the soil moisture sensors. A circular areas with radius 15 m was selected to stay within the field boundaries, which included about 60 data points in each quadrant (Figure 3.7).

Table 3.7 Yield for each plot-year

Controlled plot-years		Free-draining plot-years	
Plot & Year	Yield (kg/ha)	Plot & Year	Yield (kg/ha)
DPAC SE 2012	8,220	DPAC NE 2012	7,372
DPAC SE 2014	11,293	DPAC NE 2014	11,570
DPAC NW 2012	7,023	DPAC SW 2012	7,745
DPAC NW 2014	10,262	DPAC SW 2014	9,315
SERF D4 2012	8,976	SERF F5 2012	4,896
SERF D4 2013	7,982	SERF F5 2013	6,128
SERF D4 2014	12,588	SERF F5 2014	13,736
SERF D3 2012	5,753	SERF F2 2012	7,095
SERF D3 2013	4,146	SERF F2 2013	6,503
SJ WN 2013	14,248	SJ WS 2013	14,427
SWROC BW 2013	8,859	SWROC BE 2013	8,735
SWROC GB 2013	8,190	SWROC GA 2014	0

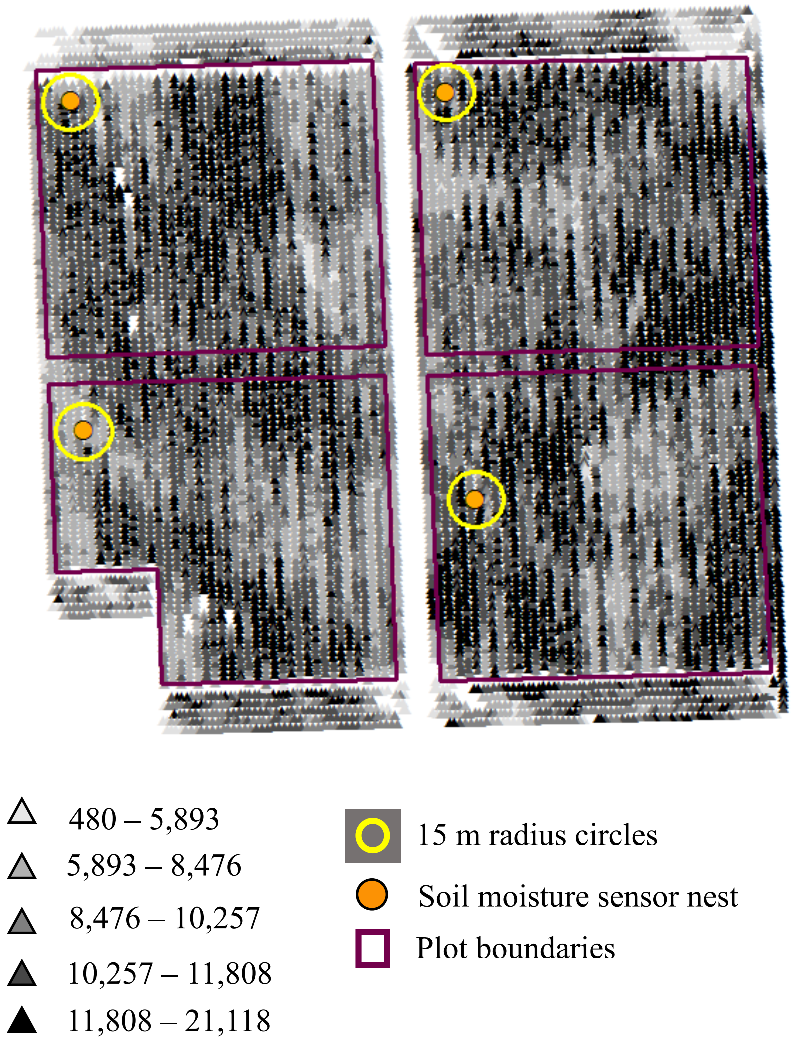

Figure 3.7 Yield monitor data (kg/ha) at DPAC in 2014, locations of soil moisture sensors, and the 15 m radius circles used to determine local yield values.

A paired t-test was used to determine that there was no statistically significant difference between yield at the controlled plots and yield in the conventionally drained plots at all sites (p = 0.82), with a mean difference between pairs of 112 kg/ha higher in the controlled plots.

3.5 Evaluation of outliers

The plots and years with the most stress were compared to determine whether the values seemed reasonable or suggested a problem with measurement such as a lack of contact between sensors and soil. The plot-years with the highest values of stress across all excess thresholds and all deficit thresholds, both integration methods, and all periods, were identified based on the magnitude of stress at each as a factor of the median stress. A median stress value was found across all plot-years and the stress at each individual plot-year was divided by this value to determine stress as a factor of the median.

The top three plot-years with high wet stress had similar values of stress as a factor of the median (Table 3.8). These three plot-years were also known to be wetter than others. The area of the field where the soil moisture sensors are located in the NW quadrant of DPAC is known to have ponded water when the rest of the field at DPAC does not. Field G at SWROC had no crop over the entire field in 2014 due to flooding as well as in one sample area of Plot A during 2013, so this field is also expected to have very high levels of excess stress. Based on these observations and the check for extreme values, it was determined to be likely that the measurements taken at these fields were describing the soil moisture conditions with reasonable accuracy.

Table 3.8 Plot-years with extremely high deficit and stress

Deficit		Excess	
Plot-year	Stress magnitude as factor of the median	Plot-year	Stress magnitude as factor of the median
SWROC BW 2013	8.65	DPAC NW 2014	4.00
DPAC SW 2012	1.87	SWROC GA 2014	4.21
SERF D4 2012	1.69	SWROC GB 2013	3.19

Three plot-years had high deficit stress, but Field B, plot W at SWROC stood out with deficit stress of 8.65 times the median (Table 3.7). DPAC, and SERF received similar amounts of rainfall during these growing seasons (exact values in Table 3.20), but did not have similar values of deficit stress to this plot-year at SWROC. In fact, the total column soil moisture fell below permanent wilting point from July to the end of the growing season, but the recorded yield of 8,859 kg/ha, similar to the yield of 8,735 kg/ha in Plot E of the same field, does not reflect any serious problems with crop growth. For these reasons, it was determined that Field B, Plot W had such unusually low soil moisture that it should be excluded from further analysis.

3.6 Identifying useful stress metrics

Stress was quantified a total of 378 different ways, each with a unique threshold or depth, period of the growing season, and method of integration (magnitude or time). Table 3.9 shows the mean stress magnitudes for controlled and free-draining plot-years from all deficit metrics and all excess metrics at each growth period.

Table 3.9 Mean stress magnitudes (cm-days) for all excess and deficit metrics at each growth stage

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
Deficit--controlled	3.24	5.63	12.00	31.65	21.87	36.05	8.86	57.9	110.3
Deficit--free	4.00	6.49	13.49	43.64	28.10	62.30	10.48	92.6	157.8
Excess--controlled	1.11	8.47	6.98	3.22	0.98	1.35	9.67	2.38	22.07
Excess--free	0.60	5.33	5.62	1.59	0.55	0.63	5.92	1.18	14.28

Some initial insights can be drawn from this summary of quantified stress. The controlled plots, on average, show less deficit stress in every stage of the growing season but more excess stress than the free-draining plots. Deficit stress is more prevalent in the mid to late season than the early season.

Due to the large number of different stress metrics, it was necessary to narrow them down to the ones that offered the most insight in the relationship between soil moisture, yield, and controlled drainage. Statistical analysis was conducted to identify stress metrics that (1) correlated with yield and (2) showed differences in stress between free and controlled drainage. A Pearson correlation coefficient was determined to relate yield to the stress metrics without distinguishing between free and controlled drainage. A paired t-test was used to compare stress quantities between free and controlled drainage (pairs in Table 3.10). Because it was common for many plot-years to have zero stress at certain times, some stress metrics were not considered in this analysis; the small sample size would reduce the power of hypothesis testing. Only those stress metrics with at least 10 plot-years having some amount of stress were included.

Table 3.10 T-test pairs of free and controlled plot-years

Controlled plot-year	Free-draining plot-year
DPAC SE 2012	DPAC NE 2012
DPAC SE 2014	DPAC NE 2014
DPAC NW 2-12	DPAC SW 2012
DPAC NW 2014	DPAC SW 2014
SERF D4 2012	SERF F5 2012
SERF D4 2013	SERF F5 2013
SERF D4 2014	SERF F5 2014
SERF D3 2012	SERF F2 2012
SERF D3 2013	SERF F2 2013
St. Johns N1 2013	St. Johns S1 2013
St. Johns N2 2013	St. Johns S2 2013
St. Johns N3 2013	St. Johns S3 2014

Pearson correlation coefficients relating stress to yield for all soil stress metrics are included in Tables A.5 and A.6 in the appendix. Many metrics showed statistically significant correlation with yield despite low correlation coefficients. Excess stress during the VE – V6 period and Early (Planting – V6) period showed statistically significant correlation with yield at a significance level of alpha = 0.05 for almost all of the thresholds when measured in both time and magnitude. Deficit stress during the R3 – R5, R5 – R6, and late season periods (R3 – R6) were often correlated with yield regardless of the threshold or whether measured in time or magnitude. Tables 3.11 and 3.12 show which thresholds and periods resulted in significant yield correlations using time as the metric, and 3.13 and 3.14 show results for magnitude. Late-season excess stress and early-season deficit stress were uncommon and almost never correlated with yield, so they are excluded from Tables 3.11 through 3.14, but are included in the Appendix.

For the paired t-test, each controlled plot-year was matched with a free-draining plot-year from the same site, and the test is used to determine if the mean difference in stress of all the pairs is significant. The p-values, test statistics, and mean difference in stress from the paired t-test are also included in Tables A.5 and A.6 in the appendix. The fields at SWROC were excluded from this test because they could not be paired; pairs are shown in Table 3.9. Significant differences in stress between controlled and free-draining plot-years were less common than correlation with yield (Tables 3.11 – 3.14). A total of five different excess stress metrics during the early season were found to show significant differences between treatments; meanwhile, 43 metrics from this same period correlated with yield. Late-season deficit was more often found to show significant differences in stress levels between treatments.

Table 3.11 Statistical significance of yield correlation and difference in stress between free and controlled drainage pairs-- deficit metrics, integrated as time

Threshold:		1	2	3	4	5	6	7	8	9	10	11	12
V16 - R3	Yield Correlation	*	*	**	*	*	*	*	*	*	*	*	
	Difference in Stress												
R3 - R5	Yield Correlation		*	**	**	**	**	*	*	*	*	**	*
	Difference in Stress												
R5 - R6	Yield Correlation	*	**	**	**	**	*	**		**	**	**	**
	Difference in Stress					**		**	*				**
Late Season	Yield Correlation	*	**	**	**	**	**	**	**	**	**	**	**
	Difference in Stress					**		**					*
Whole Season	Yield Correlation	*	**	**	**			*					
	Difference in Stress							**	*				

** indicates significance at alpha = 0.05

*indicates significance at alpha = 0.1

Threshold values and numbers are given in Table 3.4

Table 3.12 Statistical significance of yield correlation and difference in stress between free and controlled drainage pairs-- excess metrics, integrated as time

Threshold:		13	14	15	16	17	18	19	20	21
Plant - VE	Yield Correlation	*	**						**	**
	Difference in Stress									
VE - V6	Yield Correlation	**	**	**	**	**	**		**	**
	Difference in Stress								*	
Early Season	Yield Correlation	**	**	**	**	**	**		**	**
	Difference in Stress									
V6 - V16	Yield Correlation									
	Difference in Stress									

** indicates significance at alpha = 0.05

*indicates significance at alpha = 0.1

Threshold values and numbers are given in Table 3.4

Table 3.13 Statistical significance of yield correlation and difference in stress between free and controlled drainage pairs-- deficit metrics, integrated as magnitude

Threshold number:		1	2	3	4	5	6	7	8	9	10	11	12
V16 - R3	Yield Correlation		*	*	*	*							
	Difference in Stress						*		*				**
R3 - R5	Yield Correlation		*	*	**	**	**	*			*	**	
	Difference in Stress							*					*
R5 - R6	Yield Correlation		*	**	**	**	*		*	*	**	**	
	Difference in Stress								**	**	**	**	**
Late Season	Yield Correlation		*	**	**	**	*		*	**	**	**	
	Difference in Stress								*	*	*	*	**
Whole Season	Yield Correlation			**	**	**		*		*	*	*	
	Difference in Stress									*	*		**

* indicates significance at alpha = 0.05
**indicates significance at alpha = 0.1
Threshold values and numbers are given in Table 3.4

Table 3.14 Statistical significance of yield correlation and difference in stress between free and controlled drainage pairs-- excess thresholds, integrated as magnitude

Threshold number:		13	14	15	16	17	18	19	20	21
Plant - VE	Yield Correlation	**	**			*		**	**	**
	Difference in stress									
VE - V6	Yield Correlation	**	**	*	**	**	*	**	**	
	Difference inStress					*	*		*	
Early Season	Yield Correlation	**	**	*	**	**	*	**	**	**
	Difference in Stress						*			
V6 – V16	Yield Correlation									
	Difference in Stress									

** indicates significance at alpha = 0.05
*indicates significance at alpha = 0.1
Threshold values and numbers are given in Table 3.4

Seventeen deficit metrics and five excess metrics met the criteria for both correlation with yield and difference in stress between treatments; they are highlighted in Tables 3.11 – 3.14 and listed in Tables 3.15-17. Excess stress was higher in the controlled plots and deficit stress was higher in the free-draining plots, as indicated by the mean differences. The difference in stress between the paired plot-years for the five metrics with the highest correlations are shown in Figures 3.8 and 3.9. Two of the best-correlated metrics were deficit stresses that used a threshold of 80% of field capacity over the whole soil column and measured stress in time during the R5 – R6 period and the late season. Third was a deficit stress metric that used a threshold of 50% of plant available water in the 40 – 60 cm soil layer and measured stress in time during the R5 – R6 period. Two excess stress metrics were also identified as having a high correlation coefficient, both using 95% of aeration stress over the whole soil column as a threshold, with stress measured in either magnitude or time during the VE – V6 period.

Table 3.15 Metrics of stress resulting in yield correlation and difference between treatments—deficit metrics integrated as time

Period	R (yield)	Mean Difference in Stress
Deficit threshold 5: 80% of field capacity, 0 – 80 cm		
R5 – R6	-0.56**	0.30** hr/hr
Late Season	-0.63**	0.22** hr/hr
Deficit threshold 7: 70% of field capacity, 40 – 60 cm		
R5 – R6	-0.40**	0.25** hr/hr
Late Season	-0.41**	0.23** hr/hr
Whole season	-0.38*	.11** hr/hr
Deficit Threshold 12: 50% of plant available water, 40 – 60 cm		
R5 – R6	-0.57**	0.27** hr/hr
Late season	-0.53**	0.20* hr/hr

**statistically significant at alpha = 0.05
*statistically significant at alpha = 0.1

Table 3.16 Metrics of stress resulting in yield correlation and difference between treatments—deficit metrics integrated as magnitude

Period	R (yield)	Mean difference in stress
Deficit threshold 8: 45% of plant available water, 0 – 80 cm		
R5 – R6	-0.35*	52.0** cm-days
Deficit threshold 9: 50% of plant available water, 0 – 80 cm		
R5 – R6	-0.38**	58.8** cm-days
Late Season	-0.40**	71.788* cm-days
Whole Season	-0.34*	112.1* cm-days
Deficit threshold 10: 55% of plant available water, 0 – 80cm		
R5 – R6	-0.42**	63.8** cm-days
Late Season	-0.43**	77.0* cm-days
Whole Season	-0.35*	117.7* cm-days
Deficit Threshold 11: 60% of plant available water 0 – 80 cm		
R5 – R6	-0.45**	65.9* cm-days
Late Season	-0.46**	79.0 cm-days*

**statistically significant at alpha = 0.05
*statistically significant at alpha = 0.1

Table 3.17 Metrics of stress resulting in yield correlation and difference between treatments—excess metrics

Threshold	R (yield)	Mean difference in stress
Excess threshold 17: 95% of aeration threshold, 0 – 30 cm		
VE – V6	-0.46**	-1.45* cm-days
Excess threshold 18: 100% of aeration threshold, 0 – 50 cm		
VE – V6	-0.34*	-0.54* cm-days
Plant – V6	-0.35*	-0.54* cm-days
Excess threshold 20: 95% of aeration threshold, 0 – 80 cm (magnitude)		
VE – V6	-0.58**	-3.19* cm-days
Excess threshold 20: 95% of aeration threshold, 0 – 80 cm (time)		
VE – V6	-0.59**	-0.06* hr/hr

**statistically significant at alpha = 0.05
*statistically significant at alpha = 0.1

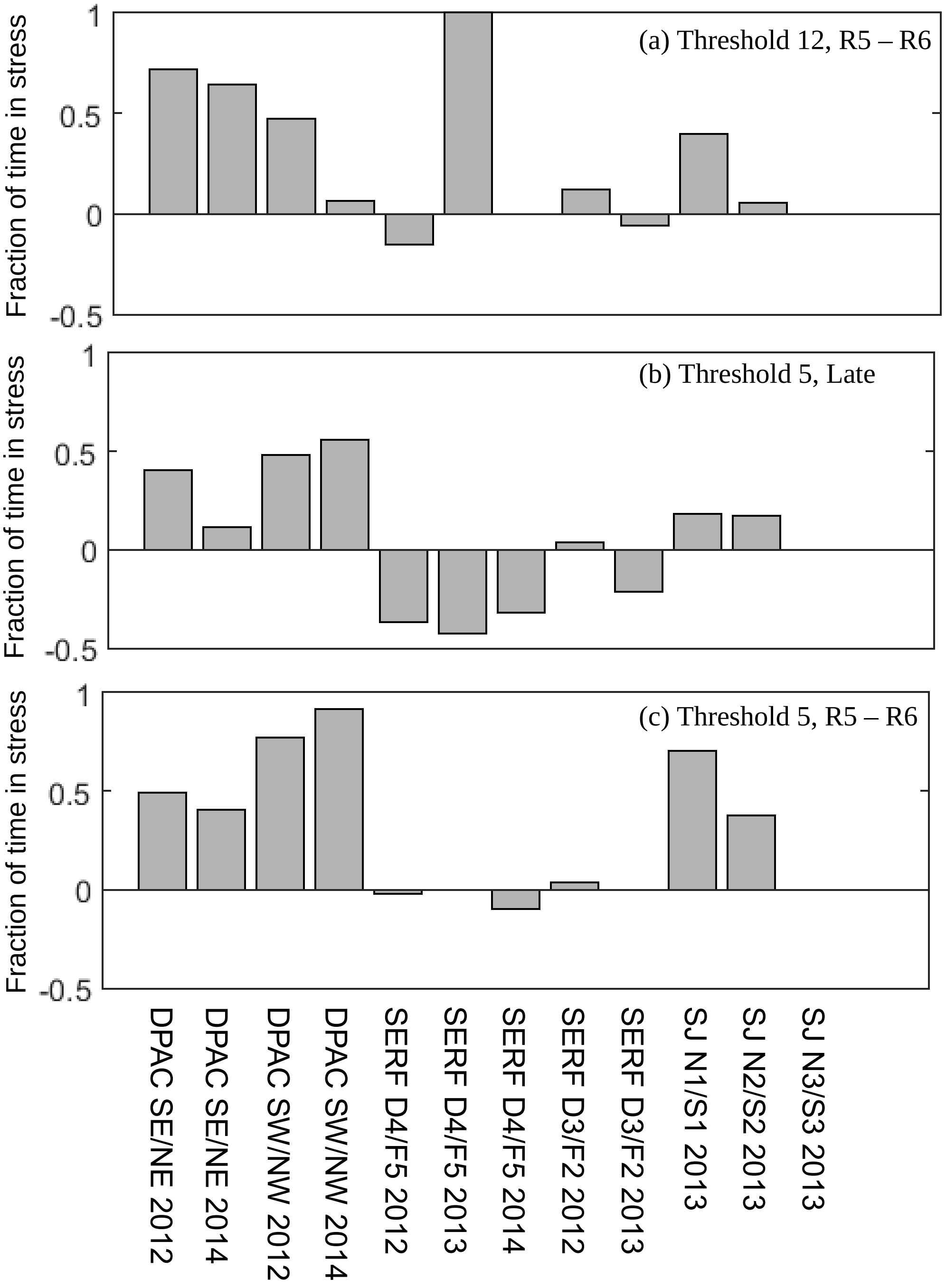

Figure 3.8 Difference in stress between pairs for the best-correlated deficit metrics: (a) Threshold 12 R5 – R6, (b) Threshold 5 R5 – R6, (c) Threshold 5 Late Season.

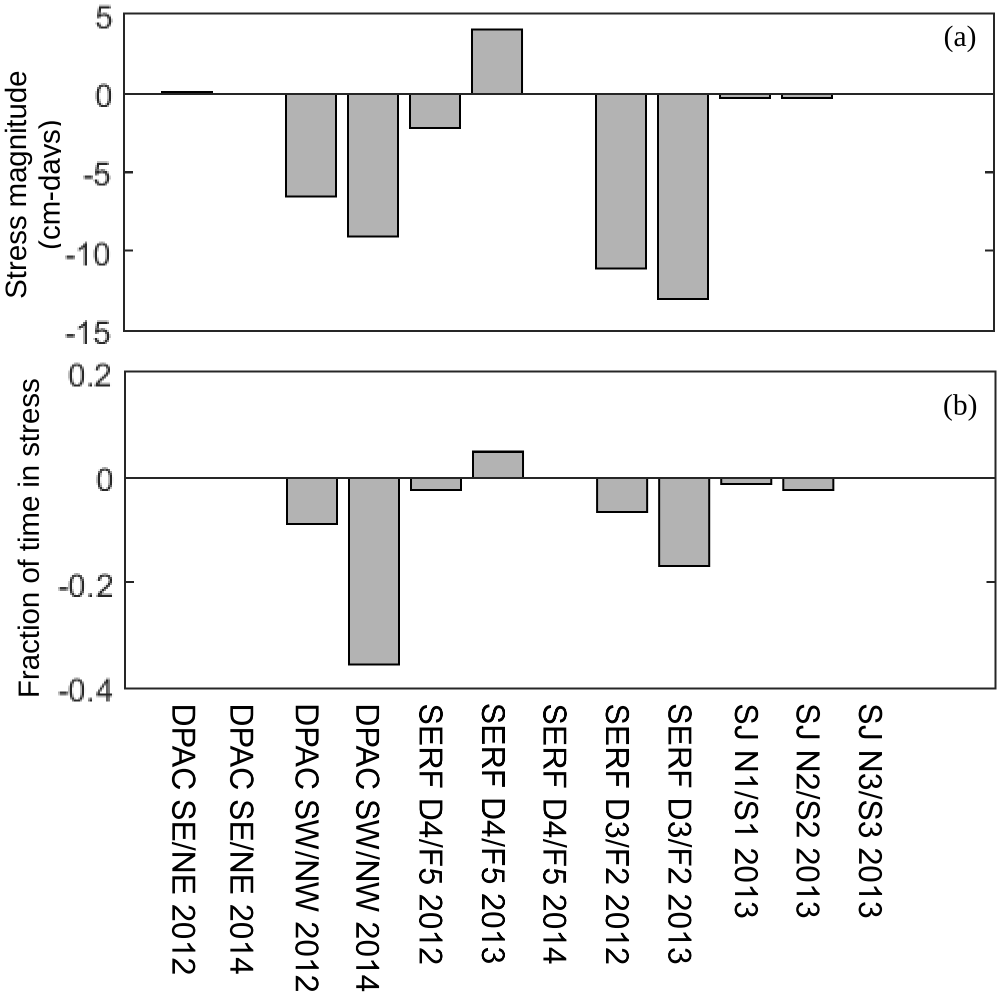

Figure 3.9 Difference in stress between pairs for the best-correlated excess metrics: (a) Threshold 20 VE – V6, time, and (b) Threshold 20, VE – V6 (magnitude).

The relationship between stress and yield for the five best-correlated stress metrics are shown in Figure 3.10 (deficit stress) and 3.11 (excess stress). A number of plot-years had zero excess stress but a large range of yields. A low yield despite zero excess stress indicates that other factors were influencing yield. High deficit stress later in the season may have been one of those factors. For example, three plots showed very low values of early-season excess and very high values of late-season deficit: free-draining plot F5 in 2012 at SERF; controlled plot D4 in 2014 at SERF; and free-draining plot BE in 2013 at SWROC.

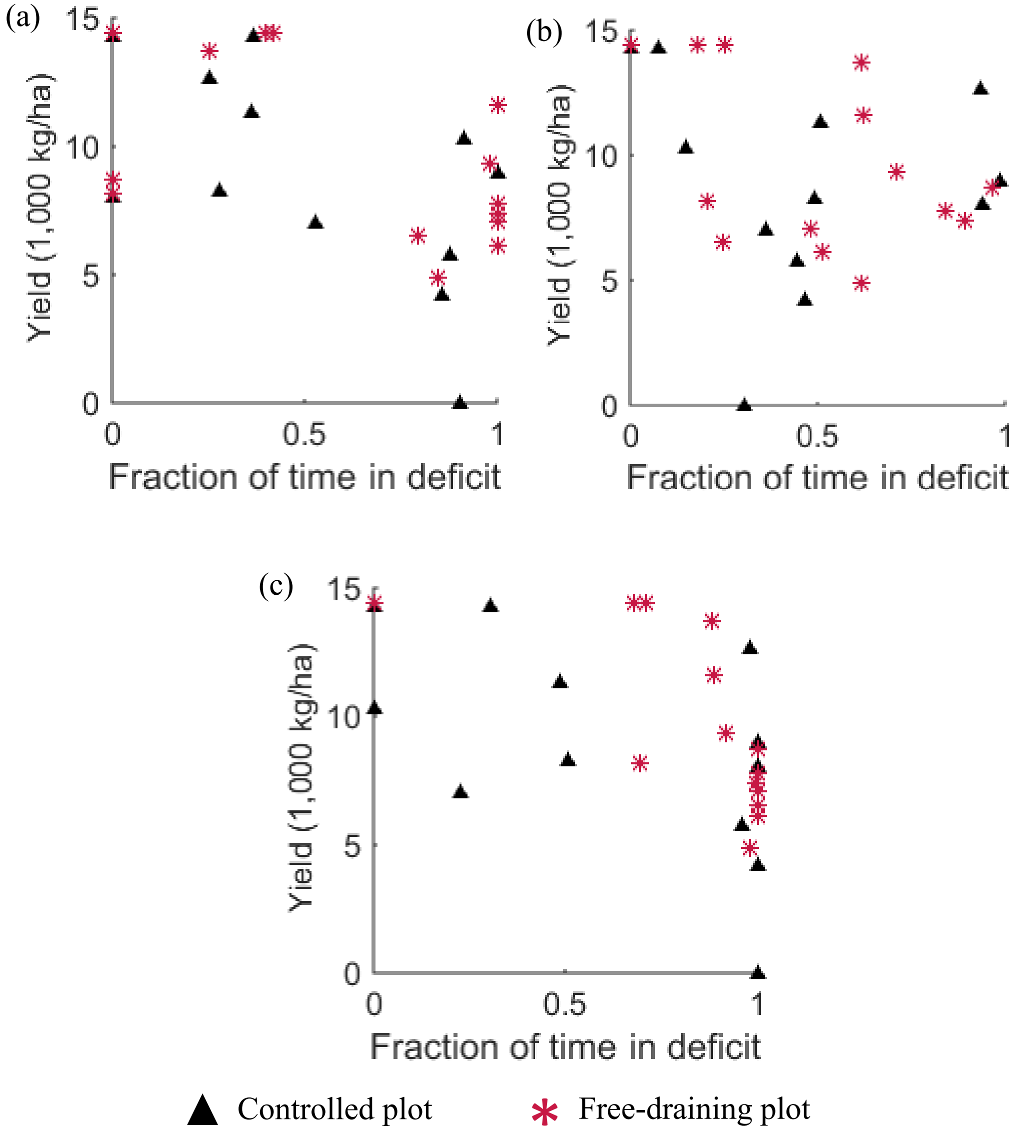

Figure 3.10 Stress-yield relationships for the best-correlated deficit metrics: (a) Threshold 12 R5 – R6, (b) Threshold 5 Late Season, (c) Threshold 5 R5 – R6

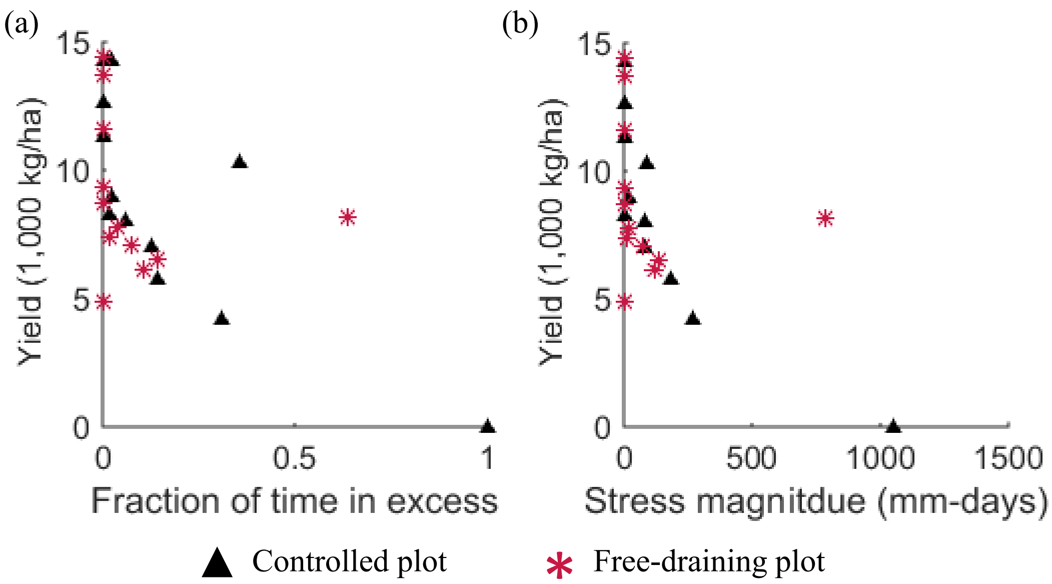

Figure 3.11 Stress-yield relationships for the best-correlated excess metrics: (a) Excess threshold 20 VE – V6, time, and (b) Excess threshold 20, VE – V6 (magnitude).

3.6.1 Combination stress metrics

Yield can be affected by both excess and deficit in the same season, suggesting that metrics that capture both excess and deficit could be more useful than either on their own. Combination metrics were created by adding together stress as quantified using the original deficit and excess thresholds listed below:

- Deficit 5: 80% of field capacity 0 – 80 cm (significant on its own)
- Deficit 6: 70% of field capacity 0 – 30 cm
- Deficit 9: 50% of plant available water 0 – 80 cm
- Deficit 12: 50% of plant available water 40 – 60 cm (significant on its own)
- Excess 14: 95% of 0.05 bar water retention, 0 – 30 cm
- Excess 17: 95% of 0.05 bar water retention, 0 – 50 cm
- Excess 20: 95% of 0.05 bar water retention, 0 – 80 cm (significant on its own)

These seven represented all the different depths in the soil profile originally tested and the three soil characteristics on which thresholds were based (field capacity, plant available water, and aeration limit). There were 12 combination thresholds based on these four deficit and three excess thresholds, and stress was determined for all nine growth periods and both integration methods for a total of 24 new combination metrics. For magnitude, stresses were added. The time-based metrics were averaged because the values were normalized by the duration of growth stages with different lengths; they could be added if time were not normalized. The results of the statistical tests for the combination metrics are included in Tables A.5 and A.6.

Eight of the 24 combination metrics resulted in statistically significant yield correlation and also showed a significant difference in stress quantities between free and controlled plot-years with $p < 0.1$ (Table 3.18). All time-based combination stress metrics in Table 3.17 included deficit stress measured by Deficit 5 (threshold of 80% of field capacity at 0 – 80 cm). Deficit 5 was significant in these same periods when used to measure deficit stress only. These combination metrics were only significant during the R5 – R6 and late season periods, but during these times, excess stress was close to zero for most plot-years, so the stress quantified by these combination metrics was almost all due to the deficit stress. The dominance of the deficit stress in combination metrics 28, 29, and 30 suggest that the differences in deficit stresses are actually more important, especially since significance was found regardless of the excess threshold paired with it.

Stress measured over the entire season would be more likely to include substantial quantities of both excess and deficit stresses and would be the most logical combination metric. The combination metrics integrated as magnitude more often resulted in significance when including the whole season, and three of the five identified thresholds included excess threshold 20, which resulted in significant relationships when used to measure excess only, suggesting that both excess and deficits were represented by these combinations.

Table 3.18 Combination stress metrics resulting in yield correlation and difference between treatments

Stress metric		R (yield)	Mean stress, Free-draining	Mean stress, Controlled	Mean difference in stress[1]
Time-based (units of hr/hr)					
Combination threshold 22 (5 + 14)	R5 – R6	-0.57**	0.43	0.30	0.13**
	Late	-0.63**	0.40	0.33	0.13**
Combination threshold 23 (5 + 17)	R5 – R6	-0.63**	0.42	0.31	.09**
	Late	-0.58**	0.40	.33	.09*
Combination threshold 24 (5 + 20)	R5 – R6	-0.54**	0.42	0.30	0.12*
	Late	-0.61**	0.40	0.32	0.1**
Magnitude-based (units of cm-days)					
Combination threshold 28 (9 + 14)	R5 – R6	-0.38*	85.6	42.8	57.9**
	Late	-0.39**	123	70.8	71.0*
	Whole	-0.37*	220	140	107.6*
Combination threshold 29 (9 + 17)	R5 – R6	-0.37*	85.6	42.4	58.3**
	Late	-0.38*	126	71.2	70.6*
	Whole	-0.37*	225	146	104.2*
Combination threshold 30 (9 + 20)	R5 – R6	-0.7*	85.6	42.2	58.6**
	Late	-0.39*	123	70.9	70.6*
	Whole	-0.48**	235	167	98.8*
Combination threshold 33 (12 + 20)	Whole	-0.45**	165	109	80.73*

**statistically significant at alpha = 0.05

*statistically significant at alpha = 0.1

[1] As evaluated by the paired t-test, meaning that this value does not include SWROC fields. SWROC fields were included in the calculations of mean stress at free and controlled plots in this table.

3.6.2 Crop susceptibility factors

As discussed in the introduction, the Stress Day Index approach to yield-stress relationships uses not only magnitude to quantify stress but also a susceptibility factor that weights stress more heavily during sensitive growth stages of the crop. Hardjoamidjojo (1982) used 0.51 during vegetative growth, 0.33 during silking to soft dough, and 0.02 after soft dough as the susceptibility factors for excess moisture stress. The growing season was divided based on calendar days after planting. The effect of weighting the excess stress metrics based on growth stage was investigated by re-calculating whole-season stress for the excess metrics using the weighting factors listed in Table 3.19.

Table 3.19 Crop susceptibility factors assigned to growth periods for excess stress

General period	Value	Period for this paper
Vegetative	0.51	Planting through V16
Silking to soft dough	.33	V16 through R3
After soft dough	.02	R3 through R6

New Pearson correlation coefficients were calculated and an additional t-test was conducted using the weighted values of total season excess stress. Though correlations with yield remain low for this stress metric, the results do shift toward higher correlation coefficients and more statistically significant mean differences in stress (Table 3.20). Though the difference in stress appears to decrease as a result of weighting, this is due to the fact that each stress value was multiplied by a fraction less than 1, not because of a shift toward a smaller difference in stress between free-draining and controlled plots. In all cases, the free-draining plots exhibit less stress than the controlled plots, indicating that controlled plots have more excess stress not only in general but also at yield-critical times according to Hardjoamidjojo’s estimates of susceptibility.

Table 3.20 T-test and yield correlation statistics with and without weighting the excess stress by growth stage

Excess threshold		Correlation coefficients		Mean difference in Stress (mm-days)	
		Weighted	Unweighted	Weighted	Unweighted
90% of aeration threshold	40 - 60 cm	-0.35	-0.28	42.6*	132.6
95% of aeration threshold	0 - 30 cm	-0.35	-0.31	20.1*	47.4
100% of aeration threshold	0 - 30 cm	-0.28	-0.24	8.1	2.9
90% of aeration threshold	0 - 30 cm	-0.15	-0.04	52.8	114.5
95% of aeration threshold	0 - 50 cm	-0.19	-0.08	30.0	50.3
100% of aeration threshold	0 - 50 cm	-0.15	-0.07	9.8	18.1
90% of aeration threshold	0 - 50 cm	-0.31	-0.22	84.7	290.4
95% of aeration threshold	0 - 80 cm	-0.40	-0.33	55.3**	166.1
100% of aeration threshold	0 - 80 cm	-0.41	-0.36	13.0**	25.5

**statistically significant at alpha = 0.05
*statistically significant at alpha = 0.1

Sudar et al. (1979) determined crop susceptibility factors for deficit stress to corn by combining values from the literature, but did not report values for specific growth stages. In general, the peak vulnerability of corn occurs later for deficit stress than excess stress.

3.7 Precipitation and management

Precipitation variability from year-to-year affects crop growth but may also change the impact of controlled drainage. When there is no crop or boards are not in place, the controlled plots do not have the ability to impact yield, because precipitation occurring during these times is not conserved. More precipitation during the period when controlled drainage has the potential to impact yield may enhance benefits. In a field study of yield effects of controlled drainage, Poole et al. (2013) found that controlled drainage affected yield due to the amount of drainage water conserved and the timing of that conservation, rather than water table height or rainfall in the growing season. One of the greatest yield benefits during that study, when plots with controlled drainage yield 21% more than free-draining plots, occurred in a year with normal rainfall during the early growing season (January to April) followed by very little rainfall from May to August. Tan et al. (2002) found that controlled drainage with subirrigation produced significantly higher soil water content during dry years but not wet years. This finding is consistent with that of Poole's in suggesting that controlling the water table has a greater potential to provide benefits over free-draining fields when the free-draining plots are actually threatened by water deficit. In wet years, both treatments may have enough water late in the season to prevent any adverse yield effects, or excess stress in the controlled plots may negate the benefits of having higher soil moisture later.

Total precipitation at each field site during the yield impact period, defined as the time when boards were in place and a crop was growing on the field, was determined and found to range from about 25% to over half of annual precipitation (Table 3.21). At some sites, for example, SERF in 2012 and St. Johns in 2013, the amount of precipitation during the yield impact period was fairly low even though the total precipitation for the year was high or normal.

Table 3.21 Total precipitation, precipitation during yield impact period, and precipitation during the rest of the year for each site

	Yield impact (mm)	Other (mm)	Total (mm)
DPAC 2012	363	549	912
DPAC 2014	626	481	1107
SERF 2012	207	630	837
SERF 2013	348	575	923
SERF 2014	690	399	1089
St. Johns 2013	222	874	1096
SWROC 2013	330	251	581
SWROC 2014	520	394	914

Figure 3.12 shows how yield-impact precipitation in the years observed relate to the mean difference in stress between free-draining and controlled plots. The mean difference in stress is across all growth periods and all deficit thresholds and integrated as magnitude. For the period observed, there is no apparent relationship, suggesting that a wider range of precipitation values may be needed to explore the possible effects of precipitation on the performance of controlled drainage.

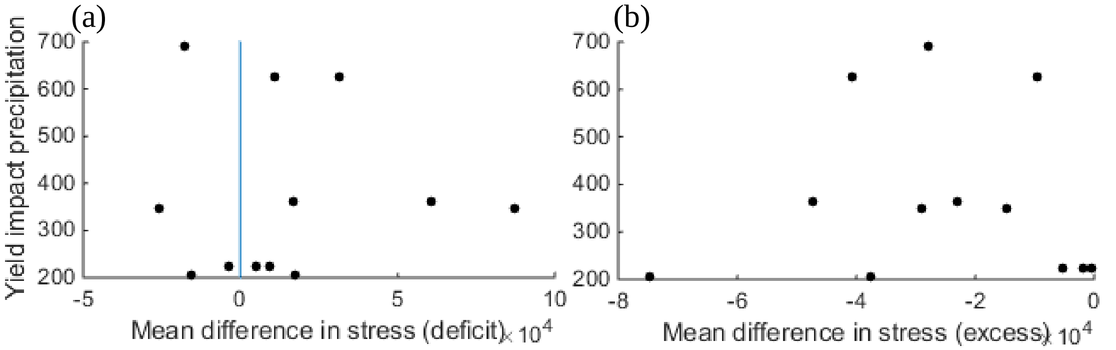

Figure 3.12. Relationship between precipitation during the yield impact period and the mean stress value across all thresholds for each plot-year, (a) for deficit and (b) for excess

3.8 Discussion

The analysis of the DPAC, SERF, St. Johns, and SWROC drainage sites revealed generally lower quantities of soil moisture deficit in plots with controlled drainage and higher quantities of excess stress. While both excess and deficit stress were related to yield reductions, late-season deficit stress showed the strongest differences between treatments. Meanwhile the amount of excess stress between the free-draining and controlled groups was usually not statistically significant.

The approximate division of the growing season into different developmental stages of the corn crops was intended to identify the periods most sensitive to moisture stresses, and worked well although the period expected to be most important, V16 – R3, did not result in significant correlations or differences in stress. Water stress during tasseling and silk formation have been found to greatly reduce crop yields, even in irrigated plots with only slight water deficits caused by omitted irrigation treatments (Cakir 2004). Meanwhile, Abrecht (1991) found that earlier water deficits could delay crop phenology and reduce plant height or biomass but not necessarily reduce grain yields. In the sites studied, the later season deficit stresses occurring from R3 until maturity were found to be more closely related to yield impacts, although they were not necessarily more prevalent. From the time series, it is apparent that soil moisture deficits did occur during the V16 – R3 stage. Soil moisture monitoring from V16 onward would be most useful in identifying differences between free-drainage and managed plots. Although only a few of the deficit thresholds resulted in stress metrics that met the criteria of statistically significant difference in stress and correlation with yield, there is little difference in general in the performance of the deficit thresholds in identifying stresses that show a statistically significant correlation with yield. Even the deficit threshold that only considered the top 30 cm of soil worked approximately as well as other thresholds during the R5- R6 period. If monitoring the entire soil profile is cost-prohibitive, soil moisture in the upper layers may be sufficient to get a general picture of whether or not stress is occurring.

Given the correlations between deficit stress and yield reductions, the effect of controlled drainage seems to depend on the amount of soil moisture conserved during the late growing season. Mejia, et al. (2000) found consistent yield increases a in water table management experiment that included subirrigation that maintained the water table at 0.5 or 0.75 m below the surface for the entire growing season as opposed to passively controlling the water table as is done with controlled drainage. Compared with subirrigation, water conservation with drainage water management is less predictable, but the cost and level of management required is also much less. The timing of precipitation and board removal will affect how much water is actually conserved in the controlled plots. As shown in Figure 2.2, boards in the controlled plots at SERF in 2013 and 2014 and DPAC in 2012 and 2014 were never removed during the planting period. Removing the boards during planting may have reduced the excess stress in the controlled plots during this time, particularly in years with more rainfall like 2014. However, leaving the boards in place could also have provided additional conservation of water from precipitation and snowmelt occurring before planting.

3.9 Conclusions

Despite the lack of significant differences in yields between the free-draining and controlled plots, the soil moisture data allowed instead for an assessment based on soil moisture conditions that were linked to yield. No single soil moisture stress metric could be identified as the best way to quantify stress and assess controlled drainage. However, the metrics that did satisfy criteria for significance were similar to each other, allowing some conclusions to be drawn on the relationships between stress, yield, and controlled drainage:

- Late-season deficit and early-season excess soil moisture were indicators of yield reductions. Measured with a variety of thresholds, excess that occurred early in the season and deficit that occurred late in the season resulted in correlation with yield.
- Though excess soil moisture stress is correlated with crop yield, very few significant differences were found in excess stress between free and controlled drainage. Thus yield reductions such as those predicted in simulations by Singh et al. (2007). were not realized at the years and sites studied. The fact that 2012 at all sites and 2013 at SERF and SWROC received little rainfall during the growing season may have contributed to the avoidance of excess moisture stress. The outlet managed outlet depths in this study ranged from 0.4 to 0.76 m below the surface for the growing season, similar to the depth used in Singh et al (2007).
- Low deficit stress thresholds, such as 60% of field capacity, that would represent a very severe deficit stress, were not found to correlate with yield or show differences in stress between fields, partly because the soil moisture often did not

fall below these thresholds. Meanwhile, the higher deficit thresholds did result in yield correlation, suggesting that yield can be affected even when extreme stress does not occur.

- In contrast to the results of the deficit analysis, the lower excess thresholds (representing less severe stress) were not as effective as those based on 95% or 100% of the aeration stress limit.
- The timing of excess stress is important, with statistical evaluation of the correlation of excess stress with yield as well as the difference in stress between free and controlled drainage improving when a weighting factor was applied to emphasize stress that occurs during early vegetative growth. This finding was consistent with the use of susceptibility factors as part of the stress day index model (Hiler 1969).
- Though the benefits of controlled drainage probably vary from year to year, the specific ways in which they were measured and the timing of precipitation at the sites and years studied failed to show these effects.
- The deficit and excess stress metrics are limited in the sense that each one ignores the impact of the other, and combination metrics that quantify stress over the entire growing season result in a more complete assessment of soil conditions, but the combinations should be comprised of an excess and a deficit threshold that each successfully quantify stress on their own.

CHAPTER 4 CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

4.1 Soil moisture and crop yield impacts

Through the analysis of soil moisture excesses and deficits, several relationships were identified between soil moisture stress metrics and crop yield where a difference was also found between the mean values of the stress metrics in the controlled and free-draining groups. Plots with controlled drainage were found to have more early-season excess stress than the free-draining plots and less late-season deficit stress. However, the differences in soil moisture stress was found to be more pronounced in late-season deficits than in early season excess. This suggests that controlled drainage may offer protection against yield reductions due to deficit stress in years when it is severe enough to be a problem, whereas in wet years when both free-draining and controlled plots have plenty of water, the ability of controlled drainage to abate deficit stresses may be immaterial.

Future research should continue to define the conditions under which controlled drainage will be beneficial. To do this, it will be necessary to investigate the differences in precipitation patterns that impact the amount of water conserved by controlled drainage. As the record of data from the four study sites analyzed here continues to grow, differences in precipitation during the growing season when boards are in place should be tracked. The amount of conserved water should be related to a reduction in soil moisture deficits. Experimenting with different combination stress metrics can also lead to more effective soil moisture metrics. Following the same board management strategy across all sites and years studied can also help reduce noise.

Provided enough data, the analysis of crop yields with respect to soil moisture stress could be expanded to include other crops. Then the information available to farmers about controlled drainage would not simply point toward whether or not crop reductions will occur, but which crops would be best. Estimating the development of soybeans through growing degree days is not as common as with corn, but given the lack of time-sensitivity of the soil moisture metrics found in this study (metrics covering the late, early, and whole seasons worked as well as those covering single growth stages), even simpler divisions of the growing season may still be effective.

Finally, predicting the future effectiveness of controlled drainage given future climate variability is an important modeling question. More sporadic but intense rainfall could result in either increased excess soil moisture or increased drought stress, which may make controlled drainage could either more or less effective compared to free drainage.

4.2 Volumetric water content

The development and application of a single method for filling soil moisture data at all four field sites involved a thorough analysis of correlation between sensors that highlighted its spatial and temporal variability. The filling method could be further analyzed for effect on data quality—for example, root mean squared error as opposed to bias as the metric of the error. However, the raw volumetric water content data could also simply be used to characterize soil moisture. The relationship between mean soil moisture and variance is often studied (Vereecken 2008).

Chapter 2 concluded by stating that the filled soil moisture data was probably best used for analysis on a resolution of at least 1 day, but the raw volumetric water content measurements during periods when all data was recorded can still be used to study hydrologic processes. The data can be used to determine wetting front velocity, antecedent moisture conditions, time required for soil to saturate, and to detect preferential flow during rainfall events. This type of analysis has been done in other field studies using non-sequential response of soil moisture sensors as evidence for preferential flow (Hardie et al. 2012; Lin and Zhou 2008). The practical implication of a change in the wetting characteristics of a field is the potential for rapid transport of agro-chemicals via preferential flow. Bauters (2000) and Hardie (2012) concluded that higher antecedent moisture conditions resulted in reduced preferential flow, which could mean that fields with controlled drainage plots exhibit preferential flow less than free-draining fields. Meanwhile, a more classical wetting front under higher antecedent moisture conditions may result in more rapid saturation and generation of surface runoff.

The first step in using soil moisture to analyze infiltration is to identify events when soil moisture sensors record a response and corroborate them with precipitation events. Quantities like time to saturation or sensor response order do require the selection of a definitive starting point, which may be challenging since soil moisture response and precipitation do not always coincide simply. However, once a methodology is clearly established, the size of the volumetric water content datasets at DPAC is large enough to analyze at least 75 precipitation/response events.

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APPENDIX

Table A.1 Water retention as volumetric water content and equivalent depth for each plot and soil layer at DPAC

Site: DPAC								
			0.05 bar		0.1 bar		15 bar	
Plot	Measured Layer	Represented Layer	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)
NE	0 - 10	0 - 15	0.34	51	0.33	49	0.18	26
	10 - 20	15 - 30	0.34	51	0.34	50	0.20	30
	20 - 40	30 - 50	0.38	76	0.37	75	0.26	53
	40-60	50 - 80	0.38	114	0.37	112	0.25	76
NW	0 - 10	0 - 15	0.33	50	0.32	47	0.16	24
	10 - 20	15 - 30	0.33	50	0.32	49	0.19	29
	20 - 40	30 - 50	0.39	78	0.39	77	0.27	54
	40-60	50 - 80	0.39	116	0.38	114	0.28	85
SE	0 - 10	0 - 15	0.39	59	0.38	57	0.24	36
	10 - 20	15 - 30	0.40	60	0.39	59	0.25	37
	20 - 40	30 - 50	0.40	81	0.40	79	0.25	50
	40-60	50 - 80	0.40	120	0.39	118	0.24	72
SW	0 - 10	0 - 15	0.38	57	0.38	57	0.24	36
	10 - 20	15 - 30	0.39	58	0.38	57	0.26	39
	20 - 40	30 - 50	0.39	79	0.39	77	0.27	55
	40-60	50 - 80	0.41	123	0.40	121	0.27	82

Table A.2 Water retention as volumetric water content and equivalent depth for each plot and soil layer at SERF

Site: SERF								
			0.05 bar		0.1 bar		15 bar	
Plot	Measured Layer	Represented Layer	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)
F2	0 - 10	0 - 15	0.43	65	0.42	63	0.12	19
	10 - 20	15 - 30	0.45	68	0.45	67	0.07	11
	20 - 40	30 - 50	0.44*	87	0.40*	79	0.21*	42
	40-60	50 -80	0.42*	127	0.39*	116	0.21*	63
D3	0 - 10	0 - 15	0.44	66	0.43	65	0.13	20
	10 - 20	15 - 30	0.47	71	0.47	71	0.09	14
	20 - 40	30 - 50	0.44*	88	0.40*	80	0.21*	42
	40-60	50 -80	0.43*	129	0.39*	117	0.21*	62
D4	0 - 10	0 - 15	0.44	66	0.43	65	0.12	18
	10 - 20	15 - 30	0.45	68	0.45	68	0.07	11
	20 - 40	30 - 50	0.43*	87	0.39*	79	0.21*	42
	40-60	50 -80	0.42*	126	0.38*	115	0.20*	60
F5	0 - 10	0 - 15	0.43	64	0.42	63	0.08	11
	10 - 20	15 - 30	0.47	70	0.44	67	0.13	20
	20 - 40	30 - 50	0.43*	87	0.39*	79	0.21*	42
	40-60	50 -80	0.43*	129	0.39*	118	0.20*	61

*values estimated with Rosetta

Table A.3 Water retention as volumetric water content and equivalent depth for each plot and soil layer at St. Johns

Site: St. Johns								
			0.05 bar		0.1 bar		15 bar	
Plot	Measured Layer	Represented Layer	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)
N1	0 - 10	0 - 15	0.41	62	0.40	61	0.29	43
	10 - 20	15 - 30	0.36	55	0.36	54	0.29	43
	20 - 40	30 - 50	0.41	81	0.40	80	0.31	63
	40-60	50 - 80	0.45	134	0.44	133	0.24	71
N2	0 - 10	0 - 15	0.40	60	0.39	58	0.28	42
	10 - 20	15 - 30	0.38	57	0.37	56	0.28	42
	20 - 40	30 - 50	0.40	81	0.40	79	0.30	60
	40-60	50 - 80	0.41	123	0.40	121	0.31	94
N3	0 - 10	0 - 15	0.40	60	0.39	58	0.25	38
	10 - 20	15 - 30	0.38	58	0.38	56	0.26	39
	20 - 40	30 - 50	0.37	75	0.37	73	0.27	54
	40-60	50 - 80	0.40	120	0.39	118	0.29	88
S1	0 - 10	0 - 15	0.39	59	0.38	57	0.24	36
	10 - 20	15 - 30	0.37	55	0.36	54	0.25	38
	20 - 40	30 - 50	0.38	76	0.38	75	0.26	52
	40-60	50 - 80	0.39	118	0.39	116	0.32	96
S2	0 - 10	0 - 15	0.41	61	0.40	60	0.27	41
	10 - 20	15 - 30	0.41	62	0.41	61	0.28	43
	20 - 40	30 - 50	0.41	83	0.41	82	0.29	58
	40-60	50 - 80	0.39	116	0.38	114	0.27	81
S3	0 - 10	0 - 15	0.37	55	0.36	54	0.23	35
	10 - 20	15 - 30	0.40	59	0.39	59	0.27	41
	20 - 40	30 - 50	0.40	79	0.39	78	0.27	54
	40-60	50 - 80	0.40	119	0.39	118	0.32	96

Table A.4 Water retention as volumetric water content and equivalent depth for each plot and soil layer at SWROC

Site: SWROC								
			0.05 bar		0.1 bar		15 bar	
Plot	Measured Layer	Represented Layer	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)	VWC	equiv. depth (mm)
BW	0 - 10	0 - 15	0.44	67	0.41	61	0.22	33
	10 - 20	15 - 30	0.45	68	0.41	61	0.19	29
	20 - 40	30 - 50	0.41	82	0.38	77	0.20	40
	40-60	50 - 80	0.44	131	0.41	124	0.18	54
BE	0 - 10	0 - 15	0.45	67	0.41	61	0.22	33
	10 - 20	15 - 30	0.45	67	0.42	63	0.19	29
	20 - 40	30 - 50	0.43	86	0.40	79	0.20	41
	40-60	50 - 80	0.43	129	0.41	122	0.17	50
GA	0 - 10	0 - 15	0.45	67	0.41	62	0.13	19
	10 - 20	15 - 30	0.42	63	0.43	65	0.11	17
	20 - 40	30 - 50	0.42	83	0.40	80	0.25*	50*
	40-60	50 - 80	0.46	138	0.43	129	0.28*	84*
GB	0 - 10	0 - 15	0.45	68	0.41	62	0.10	16
	10 - 20	15 - 30	0.43	64	0.40	61	0.12	18
	20 - 40	30 - 50	0.42	83	0.39	78	0.24*	49*
	40-60	50 - 80	0.43	130	0.40	119	0.25*	74*

*values estimated with Rosetta

Table A.5 Statistical results for all thresholds—time

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
1. 60% of field capacity 0 - 80 cm									
mean difference	--	--	--	0.08	0.16	--	--	0.11	0.05
test statistic (t test)	--	--	--	0.70	1.46	--	--	1.34	1.08
p-value (t test)	--	--	--	0.50	0.17	--	--	0.21	0.30
yield correlation coefficient	--	--	--	-0.35	-0.32	--	--	-0.36	-0.37
p-value (yield correlation)	--	--	--	0.08	0.11	--	--	0.07	0.06
2. 65% of field capacity									
mean difference	--	--	--	0.15	0.09	0.03	--	0.04	0.04
test statistic (t test)	--	--	--	1.31	0.54	0.26	--	0.33	0.65
p-value (t test)	--	--	--	0.22	0.60	0.80	--	0.75	0.53
yield correlation coefficient	--	--	--	-0.40	-0.40	**-0.65**	--	**-0.64**	**-0.58**
p-value (yield correlation)	--	--	--	0.04	0.04	0.00	--	0.00	0.00
3. 70% of field capacity 0 - 80 cm									
mean difference	--	--	--	0.10	0.09	0.10	--	0.09	0.03
test statistic (t test)	--	--	--	0.91	0.66	0.84	--	0.76	0.51
p-value (t test)	--	--	--	0.38	0.52	0.42	--	0.46	0.62
yield correlation coefficient	--	--	--	-0.42	-0.34	**-0.69**	--	**-0.66**	**-0.58**
p-value (yield correlation)	--	--	--	0.03	0.08	0.00	--	0.00	0.00
4. 75% of field capacity 0 - 80 cm									
mean difference	--	--	-0.02	0.09	-0.01	0.20	--	0.14	0.01
test statistic (t test)	--	--	-0.37	0.70	-0.09	1.71	--	1.46	0.17
p-value (t test)	--	--	0.72	0.50	0.93	0.12	--	0.17	0.87
yield correlation coefficient	--	--	-0.21	-0.35	-0.50	**-0.69**	--	**-0.70**	-0.44
p-value (yield correlation)	--	--	0.28	0.07	0.01	0.00	--	0.00	0.02
5. 80% of field capacity 0 - 80 cm									
mean difference	--	--	-0.08	-0.05	-0.01	0.30	--	0.22	0.05
test statistic (t test)	--	--	-0.78	-0.53	-0.29	2.88	--	2.53	0.54
p-value (t test)	--	--	0.45	0.60	0.78	0.01	--	0.03	0.60
yield correlation coefficient	--	--	-0.22	-0.37	**-0.65**	**-0.56**	--	**-0.63**	-0.32
p-value (yield correlation)	--	--	0.27	0.06	0.00	0.00	--	0.00	0.11
6. 70% of field capacity 0 - 30 cm									
mean difference	--	--	-0.21	-0.11	0.10	0.02	--	0.03	-0.11
test statistic (t test)	--	--	-1.39	-0.81	0.66	0.17	--	0.24	-0.91
p-value (t test)	--	--	0.19	0.43	0.52	0.87	--	0.82	0.38
yield correlation coefficient	--	--	-0.09	-0.36	-0.47	-0.33	--	-0.39	-0.15
p-value (yield correlation)	--	--	0.64	0.07	0.01	0.09	--	0.05	0.47
7. 70% of field capacity 40 - 60 cm									
mean difference	--	--	--	0.18	0.18	0.25	--	0.23	0.11
test statistic (t test)	--	--	--	2.52	1.78	2.51	--	2.47	2.63
p-value (t test)	--	--	--	0.03	0.10	0.03	--	0.03	0.02
yield correlation coefficient	--	--	--	-0.35	-0.37	-0.40	--	-0.41	-0.38
p-value (yield correlation)	--	--	--	0.07	0.06	0.04	--	0.03	0.05

Table A.5 continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
8. 45% of plant available water 0 - 80 cm									
mean difference	--	--	0.07	0.08	0.02	0.30	--	0.24	0.16
test statistic (t test)	--	--	1.78	0.89	0.16	1.88	--	1.56	2.01
p-value (t test)	--	--	0.10	0.39	0.88	0.09	--	0.15	0.07
yield correlation coefficient	--	--	-0.18	-0.36	-0.34	-0.37	--	-0.40	-0.27
p-value (yield correlation)	--	--	0.36	0.06	0.08	0.06	--	0.04	0.18
9. 50% of plant available water 0 - 80 cm									
mean difference	-0.05	--	0.09	0.06	0.08	0.26	--	0.22	0.12
test statistic (t test)	-0.31	--	1.21	0.61	0.55	1.78	--	1.55	1.46
p-value (t test)	0.76	--	0.25	0.56	0.59	0.10	--	0.15	0.17
yield coefficient	-0.03	--	-0.11	-0.38	-0.35	-0.41	--	-0.43	-0.18
p-value (yield correlation)	0.89	--	0.59	0.05	0.08	0.03	--	0.03	0.36
10. 55% of plant available water 0 - 80 cm									
mean difference	-0.14	--	0.05	0.04	0.07	0.15	--	0.14	0.05
test statistic (t test)	-0.89	--	0.53	0.32	0.50	1.12	--	1.06	0.58
p-value (t test)	0.39	--	0.61	0.76	0.62	0.28	--	0.31	0.58
yield correlation coefficient	-0.04	--	-0.08	-0.36	-0.36	-0.46	--	-0.47	-0.12
p-value (yield correlation)	0.85	--	0.71	0.07	0.06	0.02	--	0.01	0.54
11. 60% of plant available water 0 - 80 cm									
mean difference	--	--	0.04	-0.01	-0.03	0.07	--	0.05	-0.01
test statistic (t test)	--	--	0.36	-0.08	-0.27	0.56	--	0.37	-0.14
p-value (t test)	--	--	0.73	0.94	0.79	0.59	--	0.72	0.89
yield correlation coefficient	--	--	-0.04	-0.34	-0.41	-0.47	--	-0.49	-0.07
p-value (yield correlation)	--	--	0.84	0.08	0.03	0.01	--	0.01	0.74
12. 50% of plant available water 40-60 cm									
mean difference	-0.02	--	0.15	0.09	0.01	0.27	0.11	0.20	0.14
test statistic (t test)	-0.18	--	1.65	1.15	0.06	2.57	1.33	1.83	1.96
p-value (t test)	0.86	--	0.13	0.27	0.96	0.03	0.21	0.09	0.08
yield correlation coefficient	-0.04	--	-0.15	-0.32	-0.35	**-0.56**	-0.03	-0.53	-0.30
p-value (yield correlation)	0.84	--	0.46	0.10	0.07	0.00	0.87	0.00	0.12
13. 90% of aeration threshold 0 - 30 cm									
mean difference	-0.08	-0.13	-0.13	-0.07	-0.06	-0.08	-0.12	-0.09	-0.10
test statistic (t test)	-1.04	-1.64	-1.53	-0.78	-1.04	-0.93	-1.56	-1.04	-1.52
p-value (t test)	0.32	0.13	0.15	0.45	0.32	0.37	0.15	0.32	0.16
yield coefficient	-0.33	-0.44	-0.12	0.24	0.29	0.15	-0.43	0.18	-0.11
p-value (yield correlation)	0.09	0.02	0.55	0.23	0.14	0.46	0.03	0.36	0.60
14. 95% of aeration threshold 0 - 30 cm									
mean difference	-0.02	-0.08	-0.10	-0.04	-0.02	-0.04	-0.06	-0.04	-0.06
test statistic (t test)	-0.74	-1.42	-1.51	-0.72	-0.73	-0.75	-1.34	-0.79	-1.31
p-value (t test)	0.47	0.18	0.16	0.49	0.48	0.47	0.21	0.44	0.22
yield coefficient	-0.44	-0.49	-0.20	0.29	0.26	0.10	-0.49	0.12	-0.17
p-value (yield correlation)	0.02	0.01	0.32	0.14	0.20	0.63	0.01	0.56	0.39

Table A.5 continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
15. 100% of aeration threshold 0 - 30 cm									
mean difference	-0.01	-0.05	-0.05	0.01	-0.01	-0.01	-0.04	-0.01	-0.02
test statistic (t test)	-1.17	-1.33	-1.10	0.66	-0.27	-0.59	-1.36	-0.55	-1.00
p-value (t test)	0.27	0.21	0.30	0.52	0.79	0.57	0.20	0.59	0.34
yield coefficient	-0.19	-0.43	-0.30	0.30	0.14	0.14	-0.42	0.14	-0.29
p-value (yield correlation)	0.35	0.03	0.13	0.13	0.48	0.49	0.03	0.49	0.14
16. 90% of aeration threshold 0 - 50 cm									
mean difference	-0.02	-0.05	-0.08	0.00	0.00	-0.01	-0.04	-0.01	-0.03
test statistic (t test)	-0.19	-1.12	-0.65	-0.01	0.02	-0.09	-0.76	-0.07	-0.32
p-value (t test)	0.85	0.29	0.53	0.99	0.99	0.93	0.46	0.95	0.76
yield coefficient	0.06	-0.50	0.05	0.44	0.41	0.40	-0.42	0.40	0.16
p-value (yield correlation)	0.76	0.01	0.79	0.02	0.04	0.04	0.03	0.04	0.43
17. 95% of aeration threshold 0 - 50 cm									
mean difference	-0.01	-0.04	-0.10	-0.03	-0.08	-0.03	-0.03	-0.04	-0.05
test statistic (t test)	-0.34	-1.25	-1.27	-0.31	-0.89	-0.85	-1.21	-0.86	-0.92
p-value (t test)	0.74	0.24	0.23	0.76	0.39	0.42	0.25	0.41	0.38
yield coefficient	0.03	**-0.60**	-0.03	0.44	0.32	0.32	**-0.60**	0.32	0.05
p-value (yield correlation)	0.90	0.00	0.87	0.02	0.10	0.11	0.00	0.11	0.81
18. 100% of aeration threshold 0 - 50 cm									
mean difference	0.00	-0.02	-0.04	-0.07	-0.03	0.00	-0.01	-0.01	-0.03
test statistic (t test)	0.21	-1.72	-0.97	-0.82	-0.87	-0.07	-1.53	-0.64	-0.98
p-value (t test)	0.83	0.11	0.35	0.43	0.40	0.95	0.15	0.53	0.35
yield coefficient	-0.34	**-0.60**	0.06	0.30	0.29	0.42	**-0.65**	0.35	0.04
p-value (yield correlation)	0.08	0.00	0.78	0.13	0.15	0.03	0.00	0.08	0.83
19. 90% of aeration threshold 0 - 80 cm									
mean difference	-0.18	-0.05	0.01	0.10	0.00	-0.01	-0.08	-0.01	0.00
test statistic (t test)	-1.66	-0.73	0.05	1.00	-0.03	-0.16	-1.20	-0.10	-0.08
p-value (t test)	0.13	0.48	0.96	0.34	0.97	0.88	0.26	0.92	0.94
yield coefficient	0.15	-0.28	0.10	0.43	0.52	0.43	-0.19	0.46	0.21
p-value (yield correlation)	0.46	0.15	0.61	0.03	0.01	0.03	0.34	0.01	0.29
20. 95% of aeration threshold 0 - 80 cm									
mean difference	-0.02	-0.06	-0.10	-0.06	-0.08	-0.02	-0.05	-0.03	-0.05
test statistic (t test)	-0.60	-1.84	-1.71	-0.67	-1.17	-0.84	-1.71	-0.98	-1.51
p-value (t test)	0.56	0.09	0.12	0.52	0.27	0.42	0.12	0.35	0.16
yield coefficient	-0.54	**-0.59**	-0.16	0.29	0.29	0.36	**-0.62**	0.32	-0.20
p-value (yield correlation)	0.00	0.00	0.42	0.15	0.14	0.06	0.00	0.10	0.32
21. 100% of aeration threshold, 0 - 20 cm									
mean difference	0.01	-0.02	-0.06	-0.06	-0.02	0.00	-0.01	0.00	-0.03
test statistic (t test)	1.71	-1.60	-1.55	-1.04	-0.82	-0.02	-0.99	-0.58	-1.39
p-value (t test)	0.11	0.14	0.15	0.32	0.43	0.99	0.34	0.57	0.19
yield coefficient	**-0.63**	**-0.65**	-0.29	0.34	0.29	0.37	**-0.66**	0.35	-0.32
p-value (yield correlation)	0.00	0.00	0.14	0.08	0.14	0.05	0.00	0.07	0.10

Table A.5 Continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
22. Deficit 5 + Excess 14									
mean difference	0.04	-0.06	-0.09	-0.04	-0.01	0.13	-0.03	0.09	0.00
test statistic (t test)	0.53	-0.87	-1.79	-0.83	-0.58	2.87	-0.51	2.48	-0.09
p-value (t test)	0.61	0.40	0.10	0.42	0.57	0.02	0.62	0.03	0.93
yield coefficient	-0.05	-0.16	-0.34	-0.31	**-0.61**	**-0.57**	-0.14	**-0.63**	-0.41
p-value (yield correlation)	0.82	0.42	0.08	0.11	0.00	0.00	0.47	0.00	0.03
23. Deficit 5 + Excess 17									
mean difference	0.04	-0.04	-0.09	-0.04	-0.04	0.13	-0.02	0.09	0.00
test statistic (t test)	0.56	-0.56	-1.51	-0.59	-0.93	2.75	-0.25	2.08	0.04
p-value (t test)	0.59	0.58	0.16	0.57	0.37	0.02	0.81	0.06	0.97
yield coefficient	0.03	-0.19	-0.26	-0.18	-0.53	-0.52	-0.14	**-0.58**	-0.34
p-value (yield correlation)	0.90	0.34	0.19	0.37	0.00	0.00	0.47	0.00	0.08
24. Deficit 5 + Excess 20									
mean difference	0.04	-0.05	-0.09	-0.05	-0.05	0.14	-0.03	0.10	0.00
test statistic (t test)	0.51	-0.71	-1.67	-0.86	-1.15	2.88	-0.38	2.34	-0.03
p-value (t test)	0.62	0.49	0.12	0.41	0.27	0.01	0.71	0.04	0.98
yield coefficient	-0.21	-0.27	-0.37	-0.28	**-0.57**	-0.54	-0.29	**-0.61**	-0.47
p-value (yield correlation)	0.29	0.17	0.06	0.15	0.00	0.00	0.15	0.00	0.01
25. Deficit 6 + Excess 14									
mean difference	-0.04	-0.16	-0.15	-0.08	0.04	-0.01	-0.13	0.00	-0.09
test statistic (t test)	-0.64	-2.11	-2.16	-1.17	0.60	-0.13	-1.98	-0.06	-1.52
p-value (t test)	0.54	0.06	0.05	0.26	0.56	0.90	0.07	0.96	0.16
yield coefficient	-0.07	0.04	-0.21	-0.30	-0.45	-0.32	0.02	-0.39	-0.23
p-value (yield correlation)	0.73	0.83	0.30	0.13	0.02	0.10	0.94	0.05	0.25
26. Deficit 6 + Excess 17									
mean difference	-0.03	-0.14	-0.15	-0.07	0.01	-0.01	-0.11	-0.01	-0.08
test statistic (t test)	-0.58	-1.89	-2.34	-1.34	0.20	-0.08	-1.79	-0.11	-1.69
p-value (t test)	0.57	0.09	0.04	0.21	0.84	0.94	0.10	0.92	0.12
yield coefficient	0.01	0.02	-0.12	-0.15	-0.35	-0.27	0.02	-0.32	-0.14
p-value (yield correlation)	0.96	0.92	0.54	0.47	0.08	0.17	0.92	0.11	0.49
27. Deficit 6 + Excess 20									
mean difference	-0.04	-0.15	-0.15	-0.09	0.01	0.00	-0.12	0.00	-0.08
test statistic (t test)	-0.67	-2.05	-2.29	-1.54	0.17	0.06	-1.92	0.01	-1.64
p-value (t test)	0.52	0.07	0.04	0.15	0.87	0.96	0.08	0.99	0.13
yield coefficient	-0.24	-0.06	-0.22	-0.25	-0.39	-0.30	-0.12	-0.35	-0.25
p-value (yield correlation)	0.22	0.76	0.26	0.20	0.04	0.13	0.55	0.08	0.22
28. Deficit 9 + Excess 14									
mean difference	-0.03	0.00	-0.01	0.01	0.03	0.11	-0.01	0.09	0.03
test statistic (t test)	-0.46	0.03	-0.19	0.22	0.45	1.62	-0.16	1.37	0.90
p-value (t test)	0.65	0.98	0.86	0.83	0.66	0.13	0.88	0.20	0.39
yield coefficient	-0.11	0.12	-0.22	-0.32	-0.30	-0.39	0.07	-0.40	-0.27
p-value (yield correlation)	0.60	0.56	0.26	0.11	0.12	0.04	0.73	0.04	0.17

Table A.5 Continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
29. Deficit 9 + Excess 17									
mean difference	-0.03	0.02	0.00	0.02	0.00	0.11	0.01	0.09	0.04
test statistic (t test)	-0.38	0.33	-0.08	0.23	-0.01	1.70	0.14	1.39	0.84
p-value (t test)	0.71	0.75	0.94	0.83	0.99	0.12	0.89	0.19	0.42
yield coefficient	-0.03	0.09	-0.13	-0.18	-0.20	-0.35	0.08	-0.35	-0.18
p-value (yield correlation)	0.90	0.67	0.52	0.36	0.31	0.07	0.70	0.07	0.38
30. Deficit 9 + Excess 20									
mean difference	-0.03	0.01	0.00	0.00	0.00	0.12	0.00	0.10	0.03
test statistic (t test)	-0.44	0.18	-0.10	0.04	-0.03	1.76	-0.01	1.45	0.80
p-value (t test)	0.67	0.86	0.92	0.97	0.98	0.11	0.99	0.17	0.44
yield coefficient	-0.29	-0.03	-0.24	-0.27	-0.24	-0.38	-0.12	-0.38	-0.32
p-value (yield correlation)	0.15	0.88	0.24	0.17	0.22	0.05	0.55	0.05	0.10
31. Deficit 12 + Excess 14									
mean difference	-0.02	0.04	0.02	0.03	0.00	0.11	0.02	0.08	0.04
test statistic (t test)	-0.32	0.88	0.52	0.56	-0.07	1.73	0.52	1.24	0.95
p-value (t test)	0.75	0.40	0.61	0.59	0.95	0.11	0.62	0.24	0.36
yield coefficient	-0.11	-0.30	-0.25	-0.26	-0.31	-0.47	-0.26	-0.45	-0.34
p-value (yield correlation)	0.57	0.12	0.20	0.20	0.12	0.01	0.19	0.02	0.08
32. Deficit 12 + Excess 17									
mean difference	-0.02	0.06	0.03	0.03	-0.03	0.12	0.04	0.08	0.05
test statistic (t test)	-0.26	1.39	0.43	0.48	-0.44	2.20	0.91	1.33	1.03
p-value (t test)	0.80	0.19	0.68	0.64	0.67	0.05	0.38	0.21	0.33
yield coefficient	-0.04	-0.37	-0.17	-0.12	-0.22	-0.51	-0.29	-0.46	-0.30
p-value (yield correlation)	0.85	0.06	0.41	0.55	0.27	0.01	0.14	0.02	0.13
33. Deficit 12 + Excess 20									
mean difference	-0.02	0.05	0.03	0.02	-0.04	0.13	0.03	0.08	0.04
test statistic (t test)	-0.33	1.18	0.49	0.29	-0.48	2.44	0.72	1.52	1.04
p-value (t test)	0.75	0.26	0.64	0.78	0.64	0.03	0.49	0.16	0.32
yield coefficient	-0.30	-0.44	-0.26	-0.20	-0.25	-0.53	-0.43	-0.49	-0.42
p-value (yield correlation)	0.12	0.02	0.18	0.31	0.20	0.00	0.02	0.01	0.03

Table A.6 Statistical results for all thresholds—magnitude

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
1. 60% of field capacity 0 - 80 cm									
mean difference	--	--	0.35	6.89	6.66	15.53	--	22.16	29.38
test statistic (t test)	--	--	0.69	1.54	1.23	1.08	--	1.13	1.30
p-value (t test)	--	--	0.50	0.15	0.24	0.30	--	0.28	0.22
yield coefficient	--	--	-0.10	-0.31	-0.30	-0.25	--	-0.27	-0.30
p-value (yield correlation)	--	--	0.62	0.11	0.13	0.20	--	0.17	0.13
2. 65% of field capacity 0 - 80 cm									
mean difference	--	--	0.17	11.32	9.32	18.24	--	27.53	38.99
test statistic (t test)	--	--	0.07	1.42	1.23	1.00	--	1.08	1.22
p-value (t test)	--	--	0.95	0.18	0.24	0.34	--	0.30	0.25
yield coefficient	--	--	-0.13	-0.34	-0.34	-0.36	--	-0.37	-0.39
p-value (yield correlation)	--	--	0.52	0.08	0.08	0.06	--	0.06	0.05
3. 70% of field capacity 0 - 80 cm									
mean difference	--	--	0.93	15.65	10.29	21.14	--	31.41	46.93
test statistic (t test)	--	--	0.20	1.36	1.00	0.93	--	0.97	1.08
p-value (t test)	--	--	0.84	0.20	0.34	0.37	--	0.35	0.30
yield coefficient	--	--	-0.17	-0.37	-0.37	-0.49	--	-0.47	-0.47
p-value (yield correlation)	--	--	0.38	0.06	0.06	0.01	--	0.01	0.01
4. 75% of field capacity 0 - 80 cm									
mean difference	-3.33	--	0.25	19.26	11.27	28.40	--	39.64	50.81
test statistic (t test)	-1.12	--	0.04	1.24	0.88	1.14	--	1.07	0.96
p-value (t test)	0.29	--	0.97	0.24	0.40	0.28	--	0.31	0.36
yield coefficient	-0.06	--	-0.20	-0.38	-0.40	-0.58	--	-0.55	-0.51
p-value (yield correlation)	0.78	--	0.32	0.05	0.04	0.00	--	0.00	0.01
5. 80% of field capacity 0 - 80 cm									
mean difference	-3.47	--	-2.05	19.27	10.53	44.53	-14.90	55.02	57.30
test statistic (t test)	-0.61	--	-0.23	1.01	0.77	1.71	-0.97	1.40	0.92
p-value (t test)	0.55	--	0.82	0.33	0.46	0.12	0.35	0.19	0.38
yield coefficient	-0.08	--	-0.22	-0.37	-0.45	-0.62	0.00	-0.59	-0.51
p-value (yield correlation)	0.70	--	0.27	0.06	0.02	0.00	1.00	0.00	0.01
6. 70% of field capacity 0 - 30 cm									
mean difference	-7.27	--	-14.28	-11.41	-4.72	-11.34	--	-16.04	-69.53
test statistic (t test)	-1.78	--	-1.83	-1.20	-0.90	-0.93	--	-0.94	-1.73
p-value (t test)	0.10	--	0.09	0.25	0.39	0.37	--	0.37	0.11
yield coefficient	-0.03	--	-0.07	-0.31	-0.41	-0.36	--	-0.38	-0.23
p-value (yield correlation)	0.89	--	0.73	0.12	0.03	0.07	--	0.05	0.25

Table A.6 continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
7. 70% of field capacity 40 - 60 cm									
mean difference	0.38	0.02	0.43	12.07	10.20	19.90	0.41	30.07	42.94
test statistic (t test)	1.00	1.00	0.15	1.90	2.18	1.69	1.00	1.89	2.11
p-value (t test)	0.34	0.34	0.89	0.08	0.05	0.12	0.34	0.09	0.06
yield coefficient	-0.11	-0.11	-0.14	-0.29	-0.33	-0.30	-0.11	-0.33	-0.36
p-value (yield correlation)	0.60	0.60	0.48	0.14	0.09	0.12	0.60	0.10	0.07
8. 45% of plant available water 0 - 80 cm									
mean difference	4.20	--	4.98	20.44	12.84	52.04	10.64	64.83	100.83
test statistic (t test)	1.63	--	0.98	1.83	1.40	2.46	1.79	2.18	2.40
p-value (t test)	0.13	--	0.35	0.09	0.19	0.03	0.10	0.05	0.04
yield coefficient	-0.14	--	-0.18	-0.23	-0.32	-0.35	-0.05	-0.37	-0.33
p-value (yield correlation)	0.49	--	0.36	0.25	0.10	0.07	0.82	0.06	0.10
9. 50% of plant available water 0 - 80 cm									
mean difference	4.34	--	6.06	21.63	12.95	58.81	--	71.71	112.12
test statistic (t test)	1.34	--	1.05	1.68	1.21	2.41	--	2.08	2.25
p-value (t test)	0.21	--	0.32	0.12	0.25	0.03	--	0.06	0.05
yield coefficient	-0.12	--	-0.18	-0.25	-0.35	-0.38	--	-0.40	-0.34
p-value (yield correlation)	0.54	--	0.36	0.20	0.08	0.05	--	0.04	0.08
10. 55% of plant available water 0 - 80 cm									
mean difference	2.58	--	6.85	22.44	13.34	63.77	--	77.05	117.72
test statistic (t test)	0.63	--	0.99	1.50	1.09	2.36	--	2.01	2.03
p-value (t test)	0.54	--	0.35	0.16	0.30	0.04	--	0.07	0.07
yield coefficient	-0.12	--	-0.18	-0.28	-0.37	-0.42	--	-0.43	-0.35
p-value (yield correlation)	0.56	--	0.37	0.16	0.06	0.03	--	0.03	0.07
11. 60% of plant available water 0 - 80 cm									
mean difference	0.53	--	6.85	22.58	13.13	65.91	6.33	78.99	114.66
test statistic (t test)	0.10	--	0.80	1.31	0.99	2.29	0.40	1.92	1.73
p-value (t test)	0.92	--	0.44	0.22	0.34	0.04	0.69	0.08	0.11
yield coefficient	-0.10	--	-0.17	-0.29	-0.39	-0.45	0.15	-0.46	-0.35
p-value (yield correlation)	0.62	--	0.39	0.14	0.04	0.02	0.46	0.02	0.07
12. 50% of plant available water 50 - 60 cm									
mean difference	2.96	6.56	4.37	18.47	11.45	50.36	9.51	61.76	94.05
test statistic (t test)	1.01	1.56	1.36	2.53	1.89	2.69	1.34	2.60	2.80
p-value (t test)	0.33	0.15	0.20	0.03	0.09	0.02	0.21	0.02	0.02
yield coefficient	-0.12	-0.06	-0.18	-0.23	-0.31	-0.29	-0.09	-0.31	-0.29
p-value (yield correlation)	0.56	0.75	0.37	0.24	0.12	0.14	0.66	0.12	0.15
13. 90% of aeration threshold 0 - 30 cm									
mean difference	-0.33	-3.94	-3.40	--	--	--	-4.25	--	-11.35
test statistic (t test)	-0.91	-1.54	-1.47	--	--	--	-1.48	--	-1.21
p-value (t test)	0.38	0.15	0.17	--	--	--	0.17	--	0.25
yield coefficient	-0.47	-0.47	-0.27	--	--	--	-0.47	--	-0.22
p-value (yield correlation)	0.01	0.01	0.17	--	--	--	0.01	--	0.28

Table A.6 continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
14. 95% of aeration threshold 0 - 30 cm									
mean difference	-0.11	-2.18	-1.66	--	--	--	-2.28	--	-4.55
test statistic (t test)	-0.95	-1.42	-1.25	--	--	--	-1.43	--	-0.98
p-value (t test)	0.36	0.18	0.24	--	--	--	0.18	--	0.35
yield coefficient	-0.40	-0.43	-0.28	--	--	--	-0.44	--	-0.27
p-value (yield correlation)	0.04	0.03	0.15	--	--	--	0.02	--	0.18
15. 100% of aeration threshold 0 - 30 cm									
mean difference	-0.06	-1.10	-0.52	--	--	--	-1.15	--	-1.28
test statistic (t test)	-1.22	-1.41	-1.04	--	--	--	-1.49	--	-0.74
p-value (t test)	0.25	0.19	0.32	--	--	--	0.17	--	0.48
yield coefficient	-0.09	-0.35	-0.19	--	--	--	-0.36	--	-0.24
p-value (yield correlation)	0.64	0.07	0.35	--	--	--	0.07	--	0.23
16. 90% of aeration threshold 0 - 50 cm									
mean difference	-0.10	-3.06	-5.23	--	--	--	-3.14	--	-13.27
test statistic (t test)	-0.17	-1.72	-1.01	--	--	--	-1.65	--	-0.75
p-value (t test)	0.87	0.11	0.33	--	--	--	0.13	--	0.47
yield coefficient	-0.22	-0.51	-0.04	--	--	--	-0.53	--	0.01
p-value (yield correlation)	0.28	0.01	0.84	--	--	--	0.00	--	0.95
17. 95% of aeration threshold 0 - 50 cm									
mean difference	0.10	-1.45	-2.66	--	--	--	-1.34	--	-7.96
test statistic (t test)	0.56	-1.98	-1.13	--	--	--	-1.81	--	-1.01
p-value (t test)	0.59	0.07	0.28	--	--	--	0.10	--	0.34
yield coefficient	-0.38	-0.46	-0.05	--	--	--	-0.47	--	-0.07
p-value (yield correlation)	0.05	0.02	0.81	--	--	--	0.01	--	0.72
18. 100% of aeration threshold 0 - 50 cm									
mean difference	-0.01	-0.54	-0.60	--	--	--	-0.54	--	-2.07
test statistic (t test)	-0.12	-2.23	-0.73	--	--	--	-2.05	--	-0.77
p-value (t test)	0.91	0.05	0.48	--	--	--	0.07	--	0.45
yield coefficient	-0.29	-0.34	0.00	--	--	--	-0.35	--	-0.10
p-value (yield correlation)	0.14	0.08	1.00	--	--	--	0.07	--	0.62
19. 90% of aeration threshold 0 - 80 cm									
mean difference	-1.08	-6.06	-6.89	--	--	--	-7.12	--	-21.43
test statistic (t test)	-0.73	-1.71	-1.28	--	--	--	-1.74	--	-1.22
p-value (t test)	0.48	0.11	0.23	--	--	--	0.11	--	0.25
yield coefficient	-0.45	-0.56	-0.20	--	--	--	-0.57	--	-0.20
p-value (yield correlation)	0.02	0.00	0.31	--	--	--	0.00	--	0.33
20. 95% of aeration threshold 0 - 80 cm									
mean difference	0.42	-3.19	-5.36	--	--	--	-2.75	--	-13.32
test statistic (t test)	0.75	-2.06	-1.65	--	--	--	-1.52	--	-1.54
p-value (t test)	0.47	0.06	0.13	--	--	--	0.16	--	0.15
yield coefficient	-0.71	-0.58	-0.27	--	--	--	-0.62	--	-0.35
p-value (yield correlation)	0.00	0.00	0.17	--	--	--	0.00	--	0.08

Table A.6 continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
21. 100% of aeration threshold 0 - 80 cm									
mean difference	0.27	-1.22	-1.03	--	--	--	-0.94	--	-2.75
test statistic (t test)	0.90	-1.57	-1.12	--	--	--	-1.10	--	-1.31
p-value (t test)	0.39	0.14	0.29	--	--	--	0.29	--	0.22
yield coefficient	-0.57	-0.53	-0.29	--	--	--	-0.55	--	-0.39
p-value (yield correlation)	0.00	0.00	0.14	--	--	--	0.00	--	0.04
22. 5 + 14									
mean difference	-3.58	-13.61	-3.71	19.33	10.77	43.61	-17.18	54.35	52.75
test statistic (t test)	-0.63	-1.37	-0.41	1.01	0.79	1.68	-1.13	1.39	0.86
p-value (t test)	0.54	0.20	0.69	0.33	0.44	0.12	0.28	0.19	0.41
yield coefficient	-0.09	-0.09	-0.28	-0.37	-0.45	-0.62	-0.09	-0.59	-0.54
p-value (yield correlation)	0.67	0.67	0.16	0.06	0.02	0.00	0.66	0.00	0.00
23. 5 + 17									
mean difference	-3.37	-12.88	-4.71	16.46	9.86	44.03	-16.23	53.86	49.34
test statistic (t test)	-0.60	-1.29	-0.51	0.84	0.72	1.69	-1.07	1.37	0.79
p-value (t test)	0.56	0.22	0.62	0.42	0.49	0.12	0.31	0.20	0.45
yield coefficient	-0.09	-0.18	-0.24	-0.34	-0.44	-0.62	-0.16	-0.59	-0.54
p-value (yield correlation)	0.65	0.38	0.22	0.08	0.02	0.00	0.44	0.00	0.00
24. 5 + 20									
mean difference	-3.06	-14.63	-7.41	15.15	9.65	44.29	-17.65	53.91	43.98
test statistic (t test)	-0.57	-1.50	-0.79	0.76	0.70	1.70	-1.21	1.37	0.69
p-value (t test)	0.58	0.16	0.44	0.46	0.50	0.12	0.25	0.20	0.50
yield coefficient	-0.24	-0.43	-0.39	-0.34	-0.44	-0.62	-0.40	-0.59	-0.62
p-value (yield correlation)	0.23	0.03	0.04	0.09	0.02	0.00	0.04	0.00	0.00
25. 6 + 14									
mean difference	-7.38	-22.79	-15.93	-11.36	-4.48	-12.25	-30.14	-16.72	-74.08
test statistic (t test)	-1.80	-2.25	-2.09	-1.20	-0.87	-1.00	-2.18	-0.99	-1.88
p-value (t test)	0.10	0.05	0.06	0.26	0.40	0.34	0.05	0.35	0.09
yield coefficient	-0.04	-0.01	-0.13	-0.30	-0.41	-0.35	-0.02	-0.38	-0.26
p-value (yield correlation)	0.86	0.97	0.53	0.13	0.03	0.07	0.93	0.05	0.20
26. 6 + 17									
mean difference	-7.17	-22.06	-16.94	-14.22	-5.39	-11.83	-29.19	-17.21	-77.48
test statistic (t test)	-1.79	-2.18	-2.29	-1.46	-1.09	-0.99	-2.13	-1.05	-2.04
p-value (t test)	0.10	0.05	0.04	0.17	0.30	0.34	0.06	0.32	0.07
yield coefficient	-0.04	-0.08	-0.09	-0.24	-0.38	-0.34	-0.07	-0.36	-0.24
p-value (yield correlation)	0.84	0.68	0.67	0.24	0.05	0.08	0.72	0.06	0.23
27. 6 + 20									
mean difference	-6.85	-23.80	-19.64	-15.53	-5.60	-11.57	-30.61	-17.15	-82.85
test statistic (t test)	-1.85	-2.43	-2.72	-1.57	-1.12	-0.96	-2.34	-1.04	-2.21
p-value (t test)	0.09	0.03	0.02	0.14	0.29	0.36	0.04	0.32	0.05
yield coefficient	-0.20	-0.31	-0.26	-0.22	-0.39	-0.34	-0.30	-0.37	-0.33
p-value (yield correlation)	0.32	0.11	0.19	0.27	0.04	0.08	0.13	0.06	0.10

Table A.6 continued

	Plant - VE	VE - V6	V6 - V16	V16 - R3	R3 - R5	R5 - R6	Early Season	Late Season	Whole Season
28. 9 + 14									
mean difference	4.23	6.29	4.40	21.68	13.20	57.89	10.51	71.04	107.57
test statistic (t test)	1.31	1.21	0.75	1.68	1.25	2.39	1.31	2.08	2.21
p-value (t test)	0.22	0.25	0.47	0.12	0.24	0.04	0.22	0.06	0.05
yield coefficient	-0.14	-0.14	-0.24	-0.25	-0.34	-0.38	-0.15	-0.39	-0.37
p-value (yield correlation)	0.49	0.50	0.23	0.21	0.08	0.05	0.46	0.04	0.06
29. 9 + 17									
mean difference	4.44	7.02	3.40	18.82	12.29	58.31	11.46	70.55	104.17
test statistic (t test)	1.38	1.32	0.53	1.36	1.15	2.41	1.40	2.06	2.06
p-value (t test)	0.20	0.21	0.61	0.20	0.27	0.03	0.19	0.06	0.06
yield coefficient	-0.15	-0.27	-0.20	-0.21	-0.33	-0.37	-0.26	-0.38	-0.37
p-value (yield correlation)	0.46	0.18	0.31	0.29	0.10	0.06	0.19	0.05	0.06
30. 9 + 20									
mean difference	4.75	5.28	0.70	17.51	12.08	58.57	10.04	70.60	98.80
test statistic (t test)	1.49	0.96	0.10	1.23	1.13	2.41	1.21	2.06	1.92
p-value (t test)	0.16	0.36	0.92	0.24	0.28	0.03	0.25	0.06	0.08
yield coefficient	-0.40	-0.52	-0.35	-0.20	-0.33	-0.37	-0.55	-0.39	-0.48
p-value (yield correlation)	0.04	0.01	0.08	0.31	0.09	0.06	0.00	0.05	0.01
31. 12 + 14									
mean difference	2.85	4.38	2.72	18.53	11.69	49.44	7.23	61.09	89.50
test statistic (t test)	0.97	0.98	0.88	2.54	1.90	2.63	0.99	2.54	2.64
p-value (t test)	0.35	0.35	0.40	0.03	0.08	0.02	0.34	0.03	0.02
yield coefficient	-0.13	-0.31	-0.26	-0.23	-0.29	-0.28	-0.26	-0.30	-0.32
p-value (yield correlation)	0.51	0.11	0.19	0.26	0.14	0.15	0.19	0.13	0.11
32. 12 + 17									
mean difference	3.06	5.11	1.71	15.67	10.78	49.86	8.17	60.59	86.10
test statistic (t test)	1.06	1.15	0.41	1.79	1.69	2.65	1.12	2.49	2.37
p-value (t test)	0.31	0.27	0.69	0.10	0.12	0.02	0.29	0.03	0.04
yield coefficient	-0.15	-0.41	-0.20	-0.16	-0.27	-0.28	-0.37	-0.29	-0.31
p-value (yield correlation)	0.47	0.03	0.32	0.41	0.17	0.16	0.06	0.15	0.11
33. 12 + 20									
mean difference	3.38	3.37	-0.99	14.36	10.57	50.13	6.75	60.65	80.73
test statistic (t test)	1.19	0.71	-0.20	1.54	1.69	2.67	0.90	2.52	2.17
p-value (t test)	0.26	0.49	0.84	0.15	0.12	0.02	0.39	0.03	0.05
yield coefficient	-0.43	-0.59	-0.36	-0.15	-0.28	-0.28	-0.61	-0.29	-0.45
p-value (yield correlation)	0.03	0.00	0.06	0.45	0.15	0.15	0.00	0.14	0.02