METHODS OF DELINEATING IRRIGATION MANAGEMENT ZONES FOR VARIABLE RATE IRRIGATION

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By

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ABSTRACT

Uniform rate irrigation on variable soil landscapes can cause spatial differences in plant available water, which leads to inconsistent crop yields as well as the inefficient use of water resources and irrigation infrastructure. Variable rate irrigation has the potential to increase water use efficiency and reduce spatial variability in plant available water by customizing irrigation applications across variable soil landscapes. Variable rate irrigation is implemented by delineating a field into management zones with relatively homogeneous available water holding capacity. These have traditionally been delineated using soil apparent electrical conductivity (ECa) mapping; however, concerns with interference from soil salinity and laborious data acquisition has created a demand for new ways of identifying spatial variability in available water-holding capacity (AWC). One emerging approach for this is based on interactions of plant stress response to soil moisture conditions inferred using remote sensing techniques. This thesis introduced and field-tested two methods of delineating irrigation management zones that utilize remote sensing indices to measure plant response during a drydown scenario. The indices examined were apparent canopy temperature and normalized difference vegetation index (NDVI). The traditional (ECa) and emerging (apparent canopy temperature and NDVI) zone delineation methods were compared by testing the ability of these methods to identify spatial variability in AWC between 48 sample locations in a 16-ha irrigated field in Outlook, Saskatchewan. Available water holding capacity was quantified at the 48-sampling locations by determining the water retention characteristic of soil horizons that differ in texture using the pressure plate method. Soil apparent electrical conductivity (ECa) was acquired via EM38-Mk2 survey on bare soil. Apparent canopy temperature and NDVI remote sensing data were acquired via unmanned aerial vehicle (UAV) during early and late stages of a drydown scenario on an established wheat crop. As the field dried, spatial variability in plant available water became

apparent between areas in the field with low and high AWC, which helped to develop a relationship between the plant response methods and AWC.

The apparent canopy temperature method was found to outperform the traditional zone delineation methods under both early and late drydown conditions, whereas the NDVI method was only able to outperform ECa under late drydown conditions. This is a substantial limitation for NDVI because the late drydown conditions caused crop damage in areas of the field with low AWC. The ECa method was found to accurately identify spatial variability in AWC at the field site; however, this method performed poorly in salinity affected soils. Apparent canopy temperature has the potential to be a suitable replacement for traditional zone delineation methods, as this method was able to delineate accurate management zones under minor drydown conditions, which did not cause apparent crop damage in wheat. However, the utility of this method can be diminished by crop damage and error caused by variable cloud cover during data acquisition. The practical considerations and abilities of each method to identify spatial variability in AWC are key factors for determining the most practical method or combination of methods to utilize for delineating management zones for variable rate irrigation.

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LIST OF ABBREVIATIONS

AWC: Available water-holding capacity

CSIDC: Canada-Saskatchewan Irrigation Diversification Centre

ECa: Soil apparent electrical conductivity

FC: Field capacity

PAWC: Practical available water-holding capacity

$PAWC_{50}$: Practical available water-holding capacity from 0 – 50 cm

MAD: Management allowable depletion

NDVI: Normalized difference vegetation index

PWP: Permanent wilting point

UAV: Unmanned aerial vehicle

VRI: Variable rate irrigation

1 INTRODUCTION

1.1 Context

The spatial variability of plant available water is a common problem in agricultural fields and is particularly concerning in irrigated fields. This variability is primarily caused by interactions among soil water holding capacity, topography, crop evapotranspiration rate, and soil salinity. Irrigation scheduling using uniform rate irrigation is not always capable of accounting for highly variable soil landscapes, creating the potential for disparate areas of a field to have below or above ideal soil moisture status, leading to reduced crop yield and quality as well as inefficient use of irrigation water sources and infrastructure (Sadler et al., 2005). Variable rate irrigation (VRI) is a precision agriculture technology designed to maintain optimum soil moisture status in non-uniform fields by spatially varying the volume of irrigation applications, and has the potential to conserve water and increase crop yield and quality (Evans and King, 2012). Current research has shown that the realized benefits of VRI are highly variable because its success is dependent on several interacting factors, such as agronomic economics, range of crop moisture tolerance, degree of soil variability, and environmental conditions. However, the viability of VRI may increase with greater attention to water conservation during periods of drought and increased competition for water among environmental, recreational, municipal and industrial users (Sadler et al., 2005). Furthermore, VRI has been demonstrated to provide benefits other than increased water use efficacy, such as increasing harvestable area and decreasing crop disease by reducing the probability of soil saturation in depressions (Sadler et al., 2005). These added benefits could provide greater economic returns for moisture-sensitive high-value crops with high input costs (such as potatoes). Improving the methods used to implement VRI will make this technology more efficient and economical for irrigators to adopt.

Variable rate irrigation is commonly implemented by delineating a field into irrigation management zones based on spatial variability in available water-holding capacities (AWC) (Haghverdi et al., 2015). Irrigation schedules are then developed by treating each management zone as an individually irrigated area. This approach to irrigation has the potential to conserve water and support the maintenance of adequate plant available water in fields with variable soil types, while reducing the probability of runoff caused by irrigating soils in excess of their field capacity (FC). Irrigation management zones are delineated by utilizing indirect techniques to predict spatial variability in AWC, and have traditionally been delineated using soil apparent electrical conductivity (ECa) mapping (Hedley et al., 2010; Sui and Yan, 2017). More recently, methods which utilize remote sensing of plant response have been identified for their zone delineating potential. Normalized difference vegetation index (NDVI) and apparent canopy temperature are two remote sensing indices that can spatially relate crop response to soil moisture conditions. This thesis introduces a strategy for delineating management zones using these remote sensing-based plant response methods to identify spatial variability in AWC during a drydown scenario.

Plant response indices can be affected by several environmental factors, making data interpretation challenging; however, these indices have the potential to identify spatial variability in plant available water when the main variable affecting plant response is drought stress. By drying the soil to simulate a drought scenario, areas with low AWC would reach deficient levels of plant available water before areas with high AWC, and thereby induce a spatially variable drought-stress response driven by spatial variability in AWC. This thesis evaluates the ability of traditional (ECa) and emerging remote sensing-based plant response (NDVI and apparent canopy temperature) zone delineation methods to identify spatial variability in AWC, as well as the feasibility of these methods to be utilized in field-scale zone delineation operations.

1.2 Research objectives

The first objective of this research is to determine if the plant response zone delineation methods (NDVI and apparent canopy temperature) can identify spatial variability in AWC more accurately than the ECa method. The second objective of this research is to determine which of the methods (NDVI, apparent canopy temperature, or ECa) can delineate the field into accurate management zones. The third objective of this research is to identify the practical and technical considerations associated with delineating irrigation management zones using each method discussed.

1.3 Organization of thesis

This thesis is presented in the manuscript-style format, for a total of 6 chapters. The first two chapters provide a general introduction (Ch. 1) and review of relevant literature (Ch. 2). The next two chapters (Ch. 3 and Ch. 4) present the main body of the research in manuscript format. The first research objective, focused on identifying spatial variability in AWC, is addressed in Chapter 3: *Identifying Spatial Variability in Available Water-holding Capacity: Remote Sensing of Plant Response Under a Drydown Scenario* Versus *Soil Apparent Electrical Conductivity Mapping*. Chapter 4 addresses objectives two and three: *Methods of Delineating Irrigation Management Zone: Remote Sensing of Plant Response Under a Drydown Scenario* Versus *Soil Apparent Electrical Conductivity Mapping*. Chapter 5 summaries and synthesizes the two research chapters, suggests how they can be applied, and proposes how they could be improved upon. Chapter 6 provides a comprehensive reference list for the entire thesis.

2 LITERATURE REVIEW

2.1 Uniform rate irrigation on variable soil landscapes

Spatial variability of plant available water is a common crop production issue in both dry-land and irrigated agricultural fields. It is primarily caused by interactions among spatial variability in soil water holding capacity, topography, crop evapotranspiration rate, and soil salinity. Irrigation scheduling using uniform rate irrigation does not account for variable soil landscapes, creating the potential for disparate areas of a field to have below- or above-ideal soil moisture status, leading to reduced crop yield and quality (Sadler et al., 2005). Issues with uniform rate irrigation are often realized as surface or subsurface water redistribution into soil landscape depressions, caused by irrigating upper slope positions at rates exceeding the infiltration capacity or volumes that exceed field capacity (FC) of the soil. This water redistribution can lead to crop disease in landscape depressions and drought stress in upper slope positions, as well as increased likelihood of deep percolation and nutrient leaching in depressions (Sadler et al., 2005). Furthermore, prolonged saturation or ponding in landscape depressions commonly leads to increased soil salinity through evaporative salt concentration (Henry, 2003). Proper irrigation scheduling can reduce the probability of these issues; however, uniform rate irrigation is not always capable of maintaining spatially consistent crop water status when a field has highly variable soil texture or topography (Sadler et al., 2005).

2.2 Feasibility of variable rate irrigation

Variable rate irrigation (VRI) has the potential to increase water use efficiency and increase crop yield and quality (Evans and King, 2012). However, results have been highly variable because successful implementation of VRI is dependent on several interacting factors, including the degree of soil variability, annual climate variability and soil-crop interactions (Evans and King, 2012). Adoption rates of VRI have been low due to a lack of a clearly demonstrated benefit, high initial investment, and generally low commodity to water/pumping cost ratio (Sadler et al., 2005). Adoption of VRI may become more feasible with increased attention to water conservation during periods of drought and increased competition for water use among environmental, recreational, municipal and industrial users (Sadler et al., 2005). Implementation of VRI results in a 10 to 15 % water savings relative to uniform rate irrigation practices (Sadler et al., 2005). Furthermore, VRI has been demonstrated to provide benefits other than water savings, such as increasing harvestable area within a field and decreasing crop disease by reducing the probability of soil saturation in depressions (Sadler et al., 2005). These benefits provide a potential for greater economic returns when producing moisture-sensitive high-value crops with high input costs.

2.3 Delineating irrigation management zones

Precision agriculture technologies typically vary inputs by delineating a field into management zones with relatively homogeneous soil and landscape characteristics, so as to provide each zone with the precise inputs required to optimise the cost-benefit ratio between input costs and yield income (Schepers et al., 2004). Variable rate irrigation utilizes these same concepts with water/pumping costs as the main input cost with the added potential for improved yield and yield quality as a result of reducing spatial variability in plant available water (Evans and King, 2012). Irrigation management zones are delineated with the purpose of reducing spatial variability in plant available water in variable soils landscapes. Common sources of spatial variability in plant available water are relatively static soil and field properties, including salt concentration, soil texture, topography, rocky outcrops, water ways and roads (Evans et al., 2013). It can be difficult to account for all variables that lead to plant available water variability and therefore irrigation management zones are commonly initially delineated based on spatial variability of available water holding capacity (AWC) (Haghverdi et al., 2015). Available water holding capacity is the amount of water a soil can retain between field capacity (FC) and permanent wilting point (PWP), and is closely related to soil clay content. Each zone is then individually managed with a separate irrigation schedule. The water balance approach is a common irrigation scheduling technique that can be adapted to VRI; it aims to maintain soil moisture status between FC and a predetermined management allowable depletion (MAD) value, which is typically set at 50 – 70 % of plant available water to reduce crop water stress and maximize yield (Andales et al., 2011). Managing irrigation zones in this manner has the potential to support the maintenance of adequate plant available water in fields with variable soil types, while reducing the probability of irrigating soils above field capacity which in turn reduces topographical water redistribution caused by saturating higher elevation soils. Static management zones based on just spatial variability in AWC are often inadequate for optimal irrigation management (Evans et al., 2013). However, spatial variability in AWC is a key variable that can be a strong base for delineating irrigation management zones in fields that exhibit spatial variability in soil texture (Haghverdi et al., 2015).

2.4 Methods of identifying spatial variability in AWC

Soil apparent electrical conductivity (ECa) surveys are common utilized to delineating irrigation management zones by estimate spatial variability in soil texture, from which variability in AWC is inferred (Hedley et al., 2010). Yield maps are also utilized to for this purpose, but can produce varying results due to the complex and multiple drivers of yield variability (Haghverdi et al., 2015). The use of yield maps to delineate management zones requires knowledge of the factors that gave rise to spatial variation in crop patterns (Long, 1998).

ECa measurements are primarily influenced by soil salinity, water content and clay content. Additionally, cation exchange capacity, bulk density, organic matter, and several other soil physical and chemical properties can affect soil ECa (Corwin and Lesch, 2005). Due to the number of influencing factors, this method is only capable of measuring variability in AWC if the other factors affecting ECa measurements exhibit minor variability or if they can be reliably estimated (Corwin and Lesch, 2005). This limitation can introduce several potential sources of error in measuring spatial variability in AWC using ECa, as soil moisture and salinity are often variable in irrigated fields. Soil salinity can cause variation in ECa of up to 65 – 70 % (Sudduth et al., 2001); this could introduce enough error to make this method ineffective for measuring variability in AWC in salt-affected fields. An additional deficiency of this method is that it requires a time-consuming and intrusive instrument survey that cannot be completed during the growing season. An alternative method that is more convenient and less prone to soil salinity and moisture interference is required to identify spatial variability AWC for delineating irrigation management zones.

An emerging approach to delineating VRI management zones is to utilize remote sensing metrics to measure plant response to spatially variable soil moisture conditions (Haghverdi et al., 2015). Data from these remote sensing indices can be acquired via satellite or unmanned aerial vehicle (UAV), and include normalized difference vegetation index (NDVI) and thermal-imaging-derived apparent canopy temperature. Plant response methods collect spatial data on crop response to soil moisture conditions, rather than measuring every factor affecting soil moisture variability. This method could provide diverse utility for delineating irrigation management zones, as it can be used to monitor spatial and temporal variability in soil moisture conditions to continuously refine management zones (Haghverdi et al., 2015). However, remote sensing methods are not infallible and can be affected by several factors, such as flooding, salinity and crop disease or pests (Jones et al., 2009). For this reason, plant response methods are likely to have the greatest potential to identify spatial variability in AWC when spatial differences in plant avialable water are large, e.g. during a prolonged drying phase or the early stages of a drought.

Normalized difference vegetation index (NDVI) is a measure of plant health, which utilizes a relationship between plant reflectance of red and near-infrared wavelengths, whereby healthy plants reflect more near-infrared and absorb more red energy than bare soil or less healthy plants (Tucker, 1979). Normalized difference vegetation index (NDVI) has the potential to be used for management zone delineation because this metric is closely related to photosynthetic activity in plants, which can be affected by soil moisture conditions (Tucker, 1977).

Canopy temperature has been shown to be inversely correlated to plant available water, whereby healthy well-watered plants display open stomata and high transpiration rates, resulting in cool leaf surfaces due to the rates of evaporation (Jackson et al., 1981; Jones et al., 2002). When a plant has limited access to soil moisture, stomata close, which decreases evaporative cooling and causes increased canopy temperature (Jones et al., 2002). The evaporative cooling effect of plant transpiration results in a strong correlation between canopy temperature and stem water potential, which in turn is strongly correlated soil water potential in the root zone (Jones et al., 2002). However, an exact expression for the relationship is lacking, largely due to the dynamic nature of root growth and differences in the ability of different plant species to conserve water through stomatal closure (Jones et al., 2002). The ability of canopy temperature to identify spatial variability in AWC may be limited by other factors that may affect apparent canopy temperature, including intermittent cloud cover, broken leaf stems caused by high winds, and low atmospheric demand following precipitation events (Colaizzi et al., 2003). Canopy temperature measurements can most accurately identify variability in plant access to moisture under conditions that favour high stomatal conductance; these conditions occur on warm days when the sun is in the highest position, humidity is moderate to low, and there is sufficient wind speed to drive a vapour flux (Jackson et al., 1981; Jones et al., 2002). These variables can be limiting, but the ability of thermal imaging of canopy temperature to be measured using a UAV allows the operator to choose the best days and times to perform UAV flights.

While ECa maps are commonly used to delineate irrigation management zones, there is little research on how soil salinity can affect the accuracy of this practice, even though the strong affect of salinity on ECa measurements is well documented (Corwin and Lesch, 2005). Apparent canopy temperature and NDVI measurements have been found to share a relationship to soil moisture conditions under specific environmental conditions; however, there is limited research applying these relationships to delineate static management zones.

3 IDENTIFYING SPATIAL VARIABILITY IN AVAILABLE WATER HOLDING CAPACITY: REMOTE SENSING OF PLANT RESPONSE UNDER A DRYDOWN SCENARIO VERSUS SOIL APPARENT ELECTRICAL CONDUCTIVITY MAPPING

3.1 Preface

Utilizing indirect techniques to predict spatial variability in AWC is a practical approach for delineating irrigation management zones. Many studies have utilized remote sensing metrics for measuring relationships between plant response and soil variability factors, but none have examined these relationships in a drydown scenario to identify a relationship between apparent canopy temperature or NDVI and available water holding capacity. AWC was estimated at 48 sampling locations within the field site based on a laboratory-derived relationship between soil texture and water retention. Traditional and emerging zone delineation methods were evaluated on their ability to identify AWC at the 48 sampling locations. These included two plant response methods (apparent canopy temperature and NDVI) under drydown conditions, as well as a traditional zone delineation method (soil apparent electrical conductivity). The zone delineation methods that can accurately identify spatial variability in AWC will be recommended as potentially useful tools for delineating irrigation management zones.

3.2 Abstract

Variable rate irrigation (VRI) is a precision agriculture technology that spatially varies irrigation applications to increase water use efficiency and reduce spatial variability in plant available water on variable soil landscapes. Irrigation applications are varied based on unique water requirements of individual management zones that are typically delineated based on variability in available water-holding capacity (AWC). Irrigation management zones have traditionally been delineated using soil apparent electrical conductivity (ECa) mapping to estimate spatial variability in soil texture, from which variability in AWC is inferred; however, concerns with interference from soil salinity and laborious data acquisition has piqued interest in utilizing remote sensing techniques to identify spatial variability in AWC. This project evaluated the ability of two remote sensing-based plant response indices (apparent canopy temperature and NDVI) to identify spatial variability in AWC during a drydown scenario. Apparent canopy temperature (r^2 = 0.649; RMSE = 8.85 mm) was found to have a strong relationship with AWC under early drydown conditions relative to NDVI (r^2 = 0.521; RMSE = 10.33 mm). Late drydown conditions established a stronger relationship between both plant response methods and AWC but caused severe crop damage in low-AWC areas of the field. The ability of the ECa method to identifying spatial variability in AWC was comparable to the remote sensing plant response methods. The ability of apparent canopy temperature to identify variability AWC under minor drydown conditions that do not cause crop damage makes this method a suitable candidate to replace and/or utilize in conjunction with traditional methods.

3.3 Introduction

Variable rate irrigation (VRI) is implemented by delineating a field into management zones based on variability in available water-holding capacity (AWC) (Haghverdi et al., 2015). The accuracy of these management zones is the foundation to a successful VRI water management strategy. Irrigation management zones are commonly delineated using soil apparent electrical conductivity (ECa) to estimate spatial variability in soil texture, from which variability in AWC is inferred (Hedley et al., 2010). Soil apparent electrical conductivity measurements are influenced by soil salinity, water content, and clay content, which can confound interpretations and increase uncertainty in using ECa to indicate spatial variability in AWC (Corwin and Lesch, 2005). Yield maps are also utilized to delineate irrigation management zones, but produce varying results due to the complex and multiple drivers of yield variability (Haghverdi et al., 2015). Recently, there has been a growing interest in an emerging approach to delineating VRI management zones that utilizes remote sensing metrics to measure plant responses to soil moisture conditions (Haghverdi et al., 2015), such as normalized difference vegetation index (NDVI) and apparent canopy temperature. Normalized difference vegetation index is a measure of plant health, which utilizes a relationship between plant reflectance of red (0.62 – 0.70 µm) and near-infrared (0.70 – 2.5 µm) wavelengths, whereby healthy plants reflect more near-infrared and absorb more red energy than bare soil or less healthy plants (Tucker, 1979). Normalized difference vegetation index has the potential to be utilized for management zone delineation because this metric is closely related to photosynthetic activity in plants, which can be affected by moisture conditions (Tucker, 1977). The temperature of the plant canopy, measured using thermal sensing, is also closely related to plant access to soil moisture because as soil moisture decreases, soil matric potential increases, causing a decreased rate of stomatal conductance in leaves; this results in a decrease in the evaporative cooling effect of transpiration (Jackson et al., 1981; Jones et al., 2002). As a result of this relationship, areas with low soil moisture have higher apparent canopy temperatures.

This chapter proposes a method for estimating spatial variability in AWC, whereby plant response is measured during a drydown scenario, in which the field is purposefully dried following an irrigation application to cause a crop drought stress response in area with AWC. During a drydown scenario, plants in areas with low AWC will exhibit a negative response due to a deficiency in plant available water before areas with higher AWC; remote sensing indices should theoretically be able to measure this spatially variable plant response, which would enable these plant response methods to identify spatial variability in AWC. Apparent canopy temperature and NDVI measurements can indirectly measure interactions between spatial variability in AWC and plant response due to variables such as low soil fertility in sandy soil that causes decreased canopy density (Brady and Weil, 1998), low stomatal conductance due to areas with low AWC being susceptible to low plant available water (Jackson et al., 1981; Jones et al., 2002; Osakabe et al., 2014), and potential for leaf desiccation in areas with low AWC (Tucker, 1977; Paltridge and Barber, 1988). The influence of these variables will theoretically compound over the duration of the drydown scenario. Stunted growth due to low soil fertility in sandy soils will likely be occurring prior to commencement of the drydown scenario and influence measurements from the plant response methods throughout the growing season. Variability in stomatal conductance between areas with low and high AWC is likely to manifest a spatially variable plant response as plant available water decreases below management allowable depletion (MAD) more rapidly in areas of the field with lower AWC. Variability in leaf desiccation between areas with low and high AWC is not likely to be present until the drydown scenario has progressed to a level of severity where near-permanent wilting point (PWP) plant available water is present in areas with lower AWC.

The rate at which an area of a field will fall below MAD conditions in a drydown scenario will be a function of its AWC and crop evapotranspiration rate. Currently, the level of drydown required to induce a plant response to spatial variability in AWC is not known, and must be determined in order to validate this method. If the level of drydown required to delineate accurate irrigation management zones also causes crop damage, the feasibility of the plant response drydown method is diminished. Testing the plant response drydown concept in this research will help identify if this is a feasible approach to use in the process of delineating irrigation management zones.

The purpose of this study is to evaluate the ability of traditional and emerging irrigation zone delineation methods to identity spatial variability in AWC. Methods that can consistently and accurately identify spatial variability in AWC will be recommended to be utilized in delineating management zone for variable rate irrigation. The objectives of this study are to: (1) characterize spatial variability in AWC, topography and soil salinity at the field site and assess how these factors affect spatial variability of plant available water, (2) evaluate the ability of the plant response methods (NDVI and thermal imaging of apparent canopy temperature) to identify spatial variability in AWC during a drydown scenario, (3) evaluate the ability of the traditional zone delineation methods (ECa and crop yield) to identify spatial variability in AWC, and (4) compare the plant response methods to the traditional ECa method.

3.4 Methods

3.4.1 Field site

The field site is a 16-ha (40 acre) area within a 64 ha field irrigated with a center pivot system in Outlook, Saskatchewan (51.468562 °N, -107.009675 °E), at the Canada-Saskatchewan Irrigation Diversification Centre (CSIDC). The field is formally referred to as the CSIDC Off-Station Field. The mean annual precipitation is 348.6 mm (Government of Canada, 2019) and typically requires supplemental irrigation to meet crop water demand. The physiographic region of the field site is on the Outlook Plain sub-section of the South Saskatchewan River Plain (Ellis et al. 1970). This area consists of glacial-fluvial and lacustrine plains, and local rolling dunes. The soils are classified as loamy Chernozemic soils on sandy glacio-lacustrine parent material. The dominant soil texture is >45% sand and >15% clay, with the inclusion of an aeolian sandy surface layer that ranges in thickness from 10 – 83 cm (Eilers, 1997). The sand was transported by wind from sand dunes directly south of the field site (Ellis et al. 1970) and was deposited over a completely intact loamy soil profile (Stushnoff and Acton 1987). The low water holding capacity of this variable sand layer is presumed to be the dominant source of soil moisture variability at the field site.

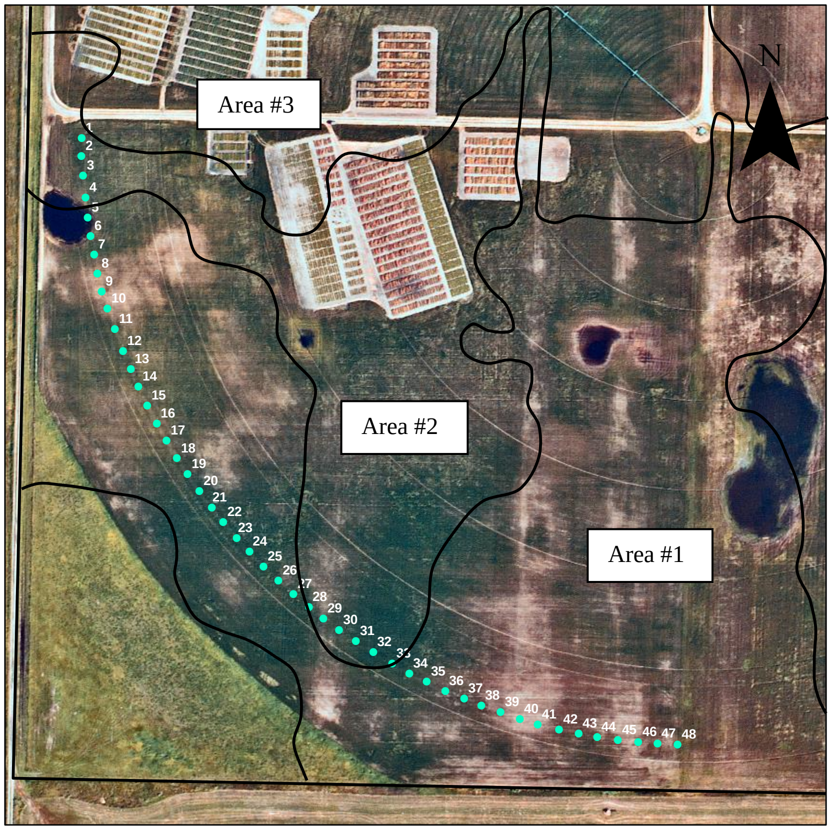

Fig. 3.1: Aerial image of the field site (Aug 9, 2011) overlain with detailed soil survey polygons and the location of the 48-sampling location radial transect. Area No. 1: loamy Bradwell type soil overlain by wind-blown sands that are 17 to 57 cm thick.; Area No. 2: loamy Bradwell type soil overlain by wind-blown sands that are 8 to 19 cm thick.; Area No. 3: loamy Bradwell type soil with absence of wind-blown sandy veneer (Eilers, 1997).

3.4.2 Agronomic and irrigation management

The field was cropped with canola in 2017 and spring wheat in 2018. Remote sensing of canola resulted in a poor relationship between remote sensing indices and AWC at all stages of the 2017 growing season due to spectral inference from the flowering crop; therefore, the dataset will not be included in further analysis, but is included in Appendix A. Spring wheat was grown in the 2018 field season as it facilitates remote sensing of plant response due to lasting green photoactive leaves that do not become blocked by large flowers (Basnyat et al., 2004). The wheat crop was seeded on May 31st, 2018. Ammonium phosphate (11:51:0) was side banded and urea

(46:0:0) was broadcast at a spatially uniform rate of 67 kg ha^{-1} and 112 kg ha^{-1}, respectively. The field was sprayed with a broadleaf herbicide following crop emergence to terminate any volunteer canola from the previous field season and promote a weed-free and consistent wheat field. Irrigation treatments were applied using a 7-span Valmont centre pivot irrigation system (Valmont. Nebraska, USA) equipped with 69 kPa (10 psi) pressure regulators and Nelson rotator sprinklers (Nelson Irrigation Corporation, Washington, USA) mounted on drop tubes. During the germination, tillering, and stem extension growth stages, adequate plant available water was maintained in the rooting zone by irrigation or rainfall to promote spatially consistent seed germination and crop establishment. Linear patches of poor germination occurred due to wheat being seeded into thick linear swaths of canola trash. These patches were very visible early in the growing season but appeared to mostly fill in as the crop progressed. Once the crop was well established and in the heading growth stage, the field was purposely exposed to a drydown scenario by ceasing irrigation applications to determine if the plant response methods could identify spatial variability in AWC as plant available water decreased in the field. During the drydown scenario from July 5 to July 21, the field received no water inputs, however sites 46 to 48 received an accidental irrigation treatment on July 18 before the remainder of the field was irrigated on July 21.

3.4.3 Soil sampling and site selection

Sampling locations were chosen using the Judgement Sampling Technique, which utilizes soil landscape information to aid in the selection of sampling locations that are representative of variability within a field (Pennock, 2004). This technique was employed using NDVI data, soil survey data, and observations from field scouting to select the location of a 48-sampling location radial transect, equally spaced (9 m) along the 7th pivot tower tire track (376 m from the pivot point), to capture a wide range of thicknesses in the aeolian sand layer (Eilers, 1997). The transect points were mapped using ArcGIS and then located in the field using a Trimble Catalyst Global Navigation Satellite System (Trimble Inc. California, USA). The 48 sampling locations were cored using a hydraulic punch and classified based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998). Thickness, classification, depth, and texture (hand texturing) were recorded for each soil horizon. Samples were collected in fixed increments (0 – 10 cm, 10 – 30 cm and 30 – 50 cm) and analysed for soil conductivity using the methods outlined in Miller and Curtin (2008) at a 1:2 soil to deionized water fixed ratio extraction.

3.4.4 Determination of soil water retention characteristics

Practical plant available water-holding capacity (PAWC) from 0 – 50 cm ($PAWC_{50}$) was adopted as the soil water retention metric for this study; it is defined as the volumetric water holding capacity between -33 kPa (FC) and -500 kPa from 0 – 50 cm. The $PAWC_{50}$ is a comparable metric to AWC but uses a -500 kPa matric pressure in place of the -1,500 kPa (permanent wilting point) value as the low end of available soil moisture. Using a pressure of -500 kPa results in a water-holding metric that has approximately 20% less available water than the traditional pressure of -1,500 kPa for the soil types represented at the field site (Fig. 3.2). The $PAWC_{50}$ metric was chosen for this application because it holds the practical advantage that it can be more easily and reliably measured in the lab. The depth range of 0 – 50 cm was chosen because this depth range contains 66 –100 % of total root length in spring wheat during the majority of the growing season (Entz et al., 1992).

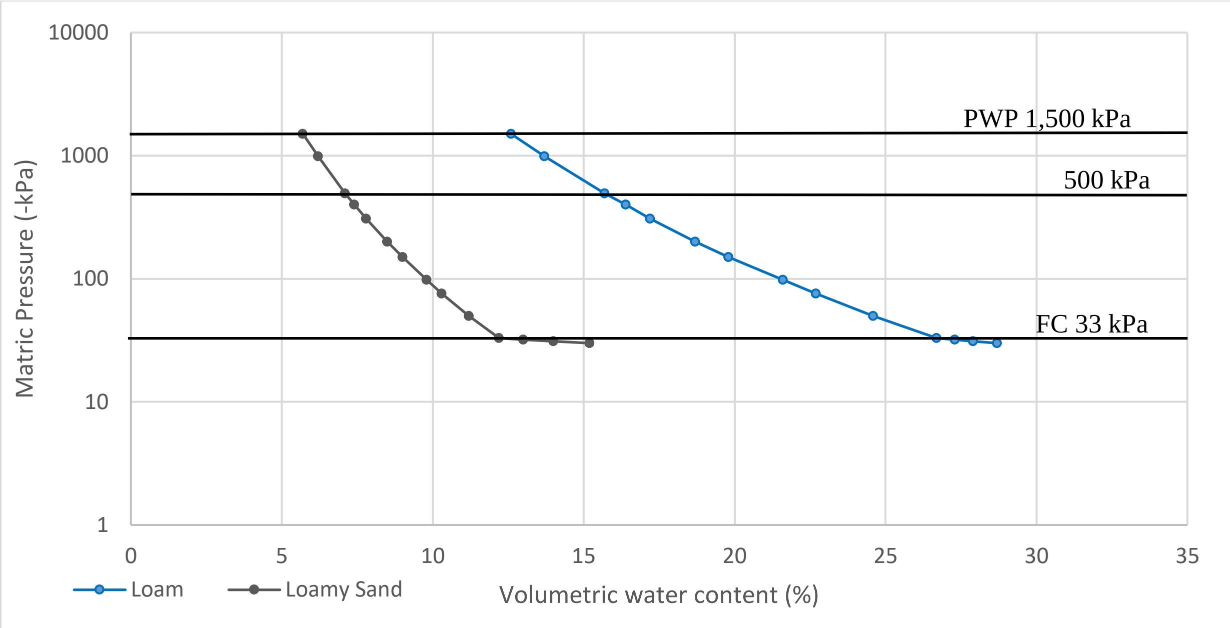

Fig. 3.2 Estimated soil water retention at matric pressures of -1500 and -500 kPa for loamy sand and loam textured soils.

Note: Matric pressure values obtained using pedotransfer function from (Saxton and Rawls, 2006).

Practical available water-holding capacity from 0 – 50 cm ($PAWC_{50}$) was quantified at the 48 sampling locations (2018) by analyzing water retention characteristics of soil horizons from ten soil cores that were collected in the fall of 2017. The ten 2017 sampling locations were selected to be representative of soil variability at the field site using a combination of Landsat8 derived NDVI data from the 2016 growing season, aerial imagery, and practical knowledge gained through field scouting. At these 10 locations, soil profile samples were collected using a hydraulic coring unit and then each visible soil horizon was sub-sampled to determine the soil texture and water retention characteristics. The samples were prepared for analysis by drying at 105°C for 24 h and sieving to 2 mm. Soil texture was measured using the hydrometer method (Ashworth et al., 2001) with density readings at 40 seconds and 6 hours to calculate sand % and clay %, respectively.

The samples were then grouped based on horizon and texture class. Six horizon and three texture classes were found within these samples, resulting in 6 horizon/texture groups. A clay layer was present at some sites but was not included in the analysis due to this layer being found at depth > 1 m. Practical plant available water holding capacity was quantified for each soil horizon/textural class by measuring soil water retention using the pressure plate extractor method outlined in Dane and Hopmans (2002) at pressures of 10 kPa and 500 kPa. After confirming that the water retention characteristics were consistent within each soil horizon/texture group, the mean PAWC of each group was calculated and then assigned to a matching soil horizon/textural group at each of the 48 sampling locations (Fig. 3.3). Because soil horizons/texture groups present exhibited consistent water retention characteristics throughout, this presented an efficient technique to quantify $PAWC_{50}$ at each of the 48 sampling locations.

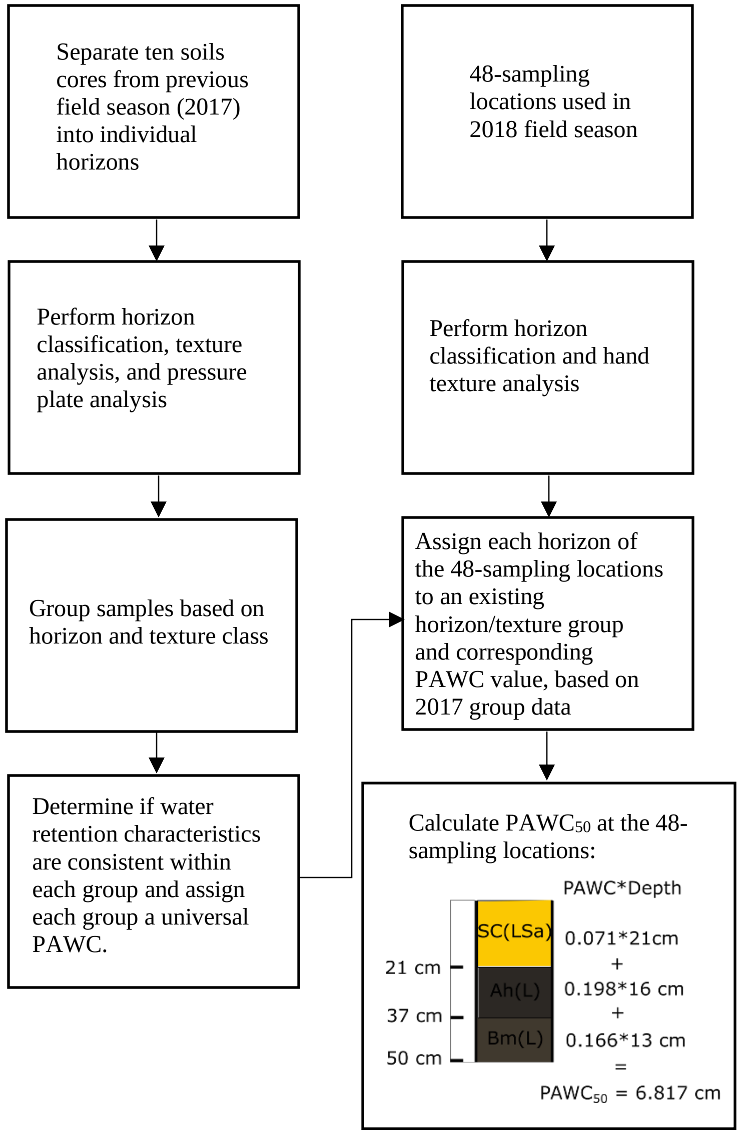

Fig. 3.3 Workflow diagram of the methodologies used to quantify practical available water-holding capacity from 0 – 50 cm ($PAWC_{50}$)at the 48 sampling locations.

3.4.5 Soil apparent electrical conductivity survey

Apparent electrical conductivity surveys were performed at the field site in September of 2017 with 12-m spacing between rows and 2-m spacing along rows using the EM38-MK2 (Geonics Limited, Mississauga, Ontario). This ECa survey data was interpolated in ArcMap (ESRI, California, USA) using the Inverse Distance Weighting (IDW) tool (Power, 2; Search Radius, Fixed; Distance, 14 m; Minimum Number of Points, 5). The ECa data for each of the 48 sampling locations were then extracted using the "Extract Values to Points" tool in ArcMap.

3.4.6 Crop yield

Yield samples were harvested from 1 m^2 area at the 48 sampling locations once the wheat had completely ripened. Samples where dried, threshed, weighed, and analyzed for grain moisture content. Crop yield was calculated by normalizing the grain moisture contents to 10 % moisture by weight. This data was used to determine if crop yield was related to $PAWC_{50}$ rather than using combine yield mapping technologies because there was no access to this type of equipment for this project.

3.4.7 UAV remote sensing

Remote sensing data was gathered by a DJI Inspire 1 ver.2 UAV (DJI, Shanzhen, China). The High-Precision NDVI multispectral sensor (Sentera, Minnesota, USA) was hard-wired and mounted to the bottom of the UAV. This sensor measures reflected light in the red (625 nm) and near-infrared (850 nm) bands, which was then used to calculate NDVI. This sensor produces a 0.5-m resolution .tiff raster image when flown at a 91-m altitude. A Zenmuse XT (336 x 256) thermal camera (FLIR Systems, Oregon, USA) was mounted to the UAV via gimbal to collect thermal images to determine crop apparent canopy temperatures. Flights were performed using

DJI Base Station automated flight software (DJI, Shenzhen, China) set to 1) 89% frontlap/sidelap, 91 m altitude, and 2.3 m s^{-1} speed for the thermal sensor and 2) 70% frontlap/sidelap, 91 m altitude, and 9 m s^{-1} speed for the NDVI camera. Once the .tiff raster images were acquired, they were stitched into a mosaic image using Pix4Dmapper (Pix4D, S.A. Lausanne, Switzerland). The UAV remote sensing data was acquired on July 5, 10, 12, and 19 during the drydown scenario; however, data was only presented from flights on July 12 and July 19 because of a failure to process/stitch thermal images from other flight dates. A 90% frontlap/sidelap and camera resolution of at least 640x480 is recommended when stitching images from thermal cameras (Pix4D). The failure to consistently stitch thermal data is attributed to the resolution of the thermal camera used in this study. In ArcMap, the July 12 and July 18 remote sensing data was re-sampled and averaged to a 2 m resolution using the "Resample" tool to average the high-resolution UAV data over the sampling points; the remote sensing index values were then determined for the 48 sampling locations using the "Extract Values to Points" tool.

3.4.8 Soil moisture monitoring

Continuous soil moisture status was monitored at four of the 48 sampling locations using an EM50 data logger (Meter Group, Washington, USA), equipped with a GS3 Ruggedized Soil Moisture, Temperature, and Electrical Conductivity Sensor (Meter Group, Washington, USA) placed at 20- and 40-cm depths, and tipping bucket precipitation gauges. The continuously monitored sites were chosen using a categorized random technique, wherein locations were randomly selected from categories defined by texture class and thickness of the aeolian layer. Soil moisture sensors were placed by digging a 30-cm by 60-cm trench to 50-cm depth and inserting the sensors into undisturbed soil at 20- and 40-cm depths. The trenches were then filled by packing in all the previously removed soil. Stomatal conductance, leaf area index, spring soil nutrient content and soil pH at 0 – 10 cm, 10 – 30 cm and 30 - 50 cm increments were collected in the spring as ancillary data. Soil moisture was also monitored weekly during the field season at each of the 48 sampling locations with the CPN 503DR Hydroprobe neutron probe (CPN International Inc., California, USA) at 20-cm increments to a depth of 110 cm. Due to the complicated nature of this soil moisture data, it was only used to determine which sampling locations were prone to soil saturation in the 30 – 50 cm increment for ECa data analysis. This neutron probe data is presented in Appendix B.

3.5 Results and discussion

3.5.1 Soil landscape and water variability

3.5.1.1 Quantifying $PAWC_{50}$ at the 48 sampling locations

Based on the 2017 field sampling, the soil horizon/texture groups used to characterize the spatial distribution of PAWC are: Ap sandy loam (Ap(SaL)), Surface C loamy sand (SC(LSa)), Ah loam (Ah(L)), and B loam (Bm(L)). The surface horizon/texture group at nearly every sample location are the SC(LSa) or AP(SaL) groups and are thickest within Area #1 and thin within Area #2 at the field sites (Fig. 3.1). Below these sandy horizons throughout the entire field are the Ah(L) and Bm(L) horizon/texture groups. The SC(LSa) horizon/texture group has the lowest PAWC due to a large percentage of aeolian sand (Fig. 3.4). The Ap(SaL) horizon/texture group has a lower percentage of aeolian sand and an elevated PAWC relative to the SC(LSa) group (Fig. 3.4). The Ah(L) and Bm(L) horizon/texture groups have a much lower percentage of sand resulting in much high PAWC relative to the SC(LSa) and Ap(SaL) groups (Fig. 3.4). The PAWC value for each horizon/texture group was calculated by subtracting the mean FC by the 500 kPa water retention values (Fig. 3.4). Each horizon of the 48-sampling locations (Fig. 3.5) was assigned an existing horizon/texture group and corresponding PAWC value (Fig. 3.4). Practical available water-holding capacity from 0 – 50 cm ($PAWC_{50}$) was then calculated at the 48 samples locations using the calculation illustrated in Fig. 3.3.

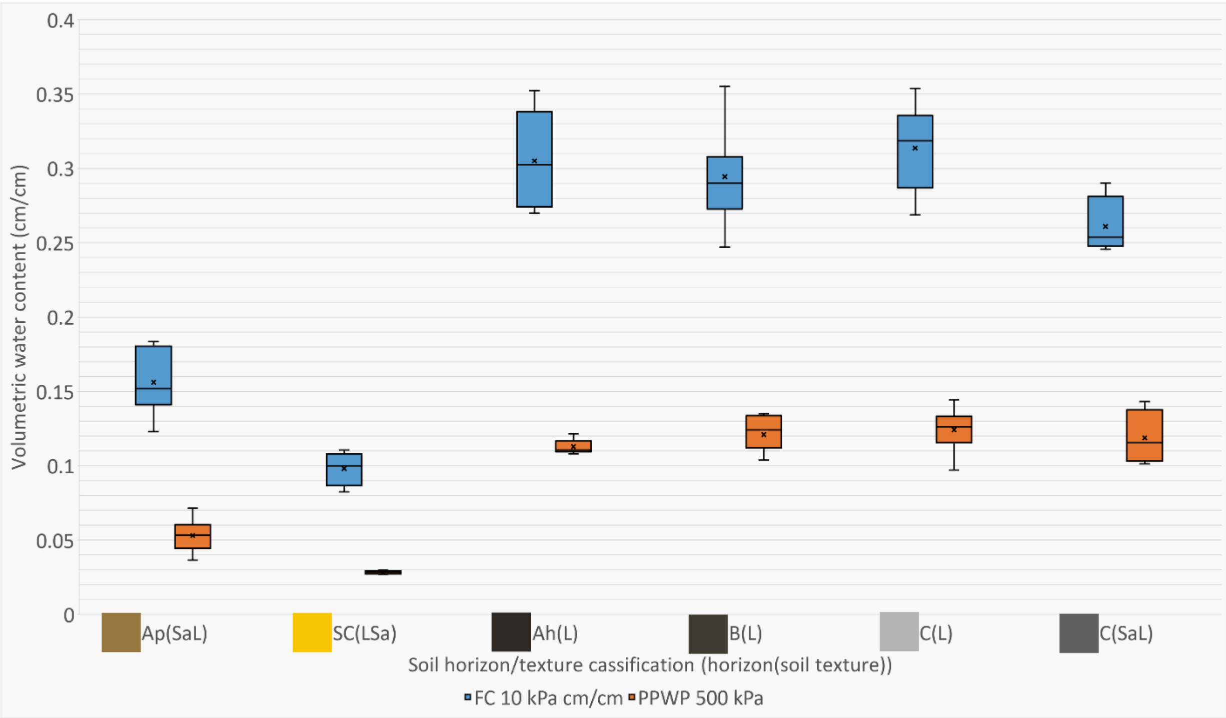

Fig. 3.4 Soil water content values at field capacity (FC) and 500 kPa matric potential separated by the soil horizon/texture groups found at the field site.

Note: **The soil horizon/texture groups are: Ap sandy loam (Ap(SaL)), Surface C loamy sand (SC(LSa)), Ah loam (Ah(L)), and B loam (Bm(L)). The color associated with each color group can be cross-referenced to Fig. 3.5.**

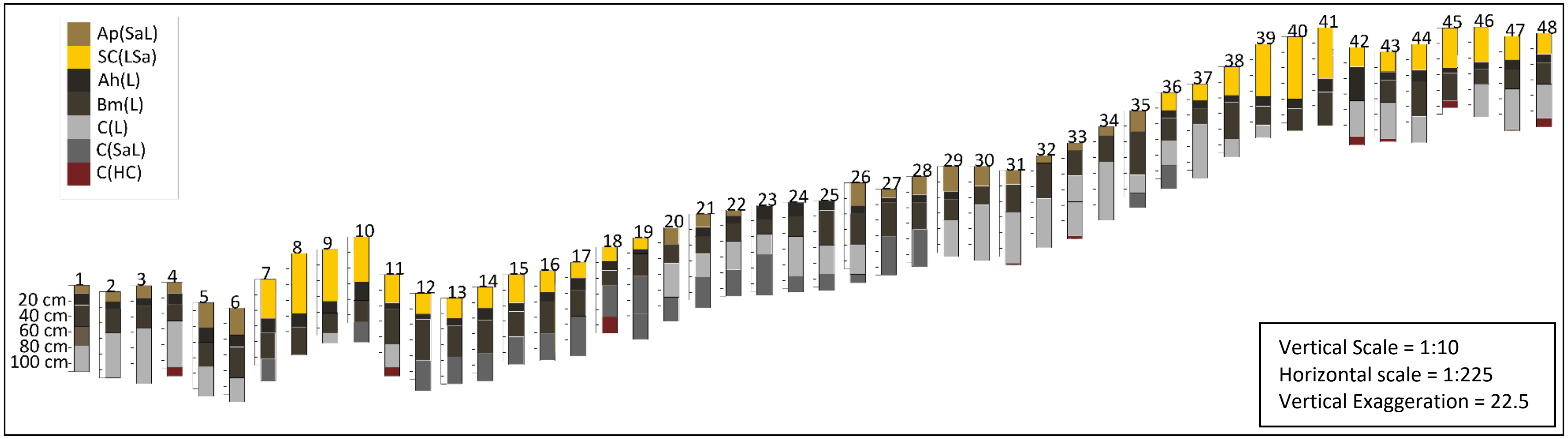

Fig. 3.5 Cross-section of each soil profile from the 48-sampling location transect.

Note: **The vertical exaggeration of 22.5 makes topography appear much more pronounced than it is. Soil texture classifications: Sandy loam (SaL); loamy sand (LSa); loam (L); heavy clay (HC).**

3.5.1.2 Soil moisture variability factors at the field site

The 48-sampling locations have a $PAWC_{50}$ range of 36 to 88 mm, largely due to the variable thickness of the SC(LSa) and Ap(SaL) horizons. The surface topography has a slope range from 0 to 3.1% between sampling locations (Fig. 3.6) and is dominated by slopes less than 2.2%, with the majority of slopes being less than 1% (Fig. 3.6). This landscape has a low risk of surface runoff; however, topographic variations do influence movement of water into landscape depressions when upper slope soils are wetted beyond field capacity. The SC(LSa) and Ap(SaL) horizons have a low risk of surface runoff due to high infiltration capacity but are particularly susceptible to saturation and lateral subsurface flow due to the low field capacity on these sandy horizons. Soil salinity at the majority of sampling locations is minor, but sites 1 through 4 are within a soil conductivity range of 2 to 4 mS m^{-1} within 0 – 50 cm depths, which poses a risk of having a noticeable effect on crop growth and soil water potentials (Fig. 3.6) (Miller and Curtin, 2008).

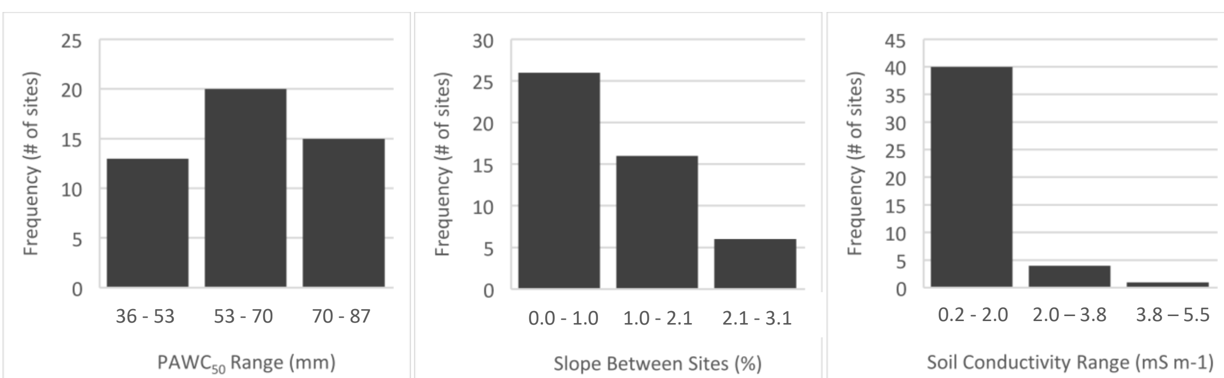

Fig. 3.6 Histograms of soil moisture variability factors from the 48-sampling locations at the field site. Left: practical plant available water-hold capacity from 0 - 50 cm ($PAWC_{50}$). Middle: slope % between sampling locations. Right: soil conductivity.

3.5.1.3 Modal soil sampling locations and soil moisture tendencies

The intricacies of soil moisture variability among 48-sampling locations can be difficult to assess; therefore, four sampling locations were chosen to represent modal soil moisture variability groups in this landscape (Table 3.1). The sampling locations that have a thick SC(LSa) horizon have the lowest $PAWC_{50}$ and are represented by $Site_{sand}$ (Site 46). Sampling locations with the thickest SC(LSa) horizons are located on sand ridges at sites 8 – 10 and 39 – 41within Area #1 (Fig. 3.1; Fig. 3.5). As the distance from the sand ridges increases, the surface horizon gradually transitions to a thin Ap(SaL) or SC(LSa) horizon, resulting in sampling locations with high $PAWC_{50}$ located in Area #1 and #2 from sites 18 – 34; these sites are represented by $Site_{loam}$ (Site 33). The areas in the field with moderately thin Ap(SaL) or SC(LSa) horizons and moderate $PAWC_{50}$ values are not represented by a model site due to the absence of a soil moisture logger in these areas. Sites 6, 12, 13, and 42 are prone to soil saturation throughout the entire soil column due to a perched water table in these areas caused by runoff from adjacent interflow prone aeolian sand. These sampling locations have moderately low $PAWC_{50}$ due to a moderately thick SC(LSa) horizon and are represented by $Site_{sat}$ (Site 42). Sites 1, 2, 3, and 4 have minor soil salinity due to evaporative salt concentration caused by a perched water table at sites 1 through 6. These sampling locations have high PAWC due to a predominantly loam textured soil and are represented by $Site_{saline}$ (Site 4). Site 24 also had high soil salinity; however, the cause of salinity at this site was not clear. The sampling locations that are not prone to saturation or affected by salinity make up the majority of sampling locations and are relatively evenly distributed between sites with low and high $PAWC_{50}$ (Fig. 3.7). The four modal sites represent the broad range of soil moisture tendencies that occur at the field site and investigating how these sites responded to environmental conditions in the 2018 field season will help explain the findings from the zone delineation methods being evaluated in this study.

Table 3.1 Soil data logger site information.

Site	Modal site	$PAWC_{50}$ (mm)	Aeolian horizon	landscape position	defining feature
46	$Site_{sand}$	42	45 cm SC(LSa)	Shoulder	Low $PAWC_{50}$; drought-prone
33	$Site_{loam}$	78	10 cm Ap(SaL)	Level	high $PAWC_{50}$; vigorous growth
42	$Site_{sat}$	63	28 cm SC(LSa)	Depression	Low $PAWC_{50}$; saturation prone
3	$Site_{saline}$	76	10 cm Ap(SaL)	Level	high $PAWC_{50}$; minor soil salinity

Note: practical plant available water from 0 – 50 cm ($PAWC_{50}$), sand thickness, aeolian/surface horizon, landscape position, and defining features.

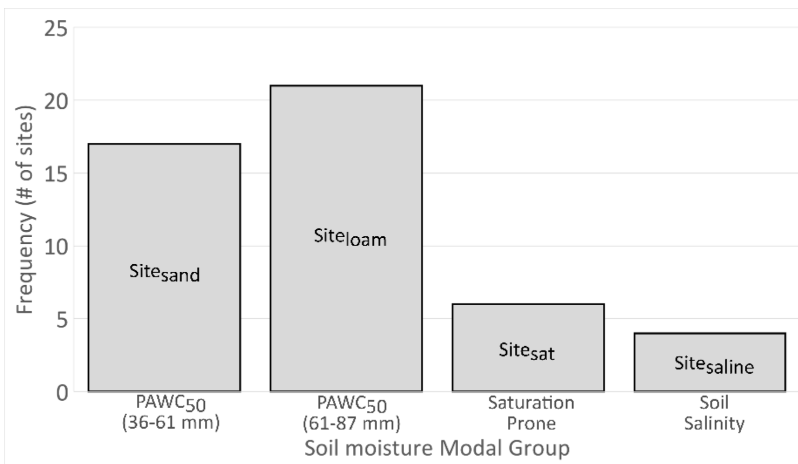

Fig. 3.7 sampling location distribution among the four modal soil moisture groups.

Fig. 3.8 illustrates the disparity in plant available water among the four modal sampling locations from data collected by in situ soil moisture sensor data logger stations. During the early growing season, soil moisture was high at all modal sampling locations until the drydown scenario began on following July 5 and soil moisture decrease at the field site. $Site_{sand}$ and $Site_{sat}$ have similar field capacity values at the 20 cm depth; however, plant available water decreased at a higher rate at $Site_{sand}$. $Site_{sat}$ is in a poorly drained depression and was saturated at the beginning of the drydown scenario, whereas $Site_{sand}$ is well-drained and had no additional soil water storage beyond FC. Plant available at $Site_{loam}$ decreased at a much slower rate relative to $Site_{sand}$ due to the high $PAWC_{50}$ at this site. $Site_{saline}$ has a conductivity of 2.1 mS m^{-1} from 0 – 50 cm and exhibits persistent soil saturation at a 20 cm depth (Fig. 3.8). The reason for this persistent situation is unknown but may be related to the effect that soil conductivity has on osmotic potential because the site is not in a depression nor does it exhibit severely stunted crop growth.

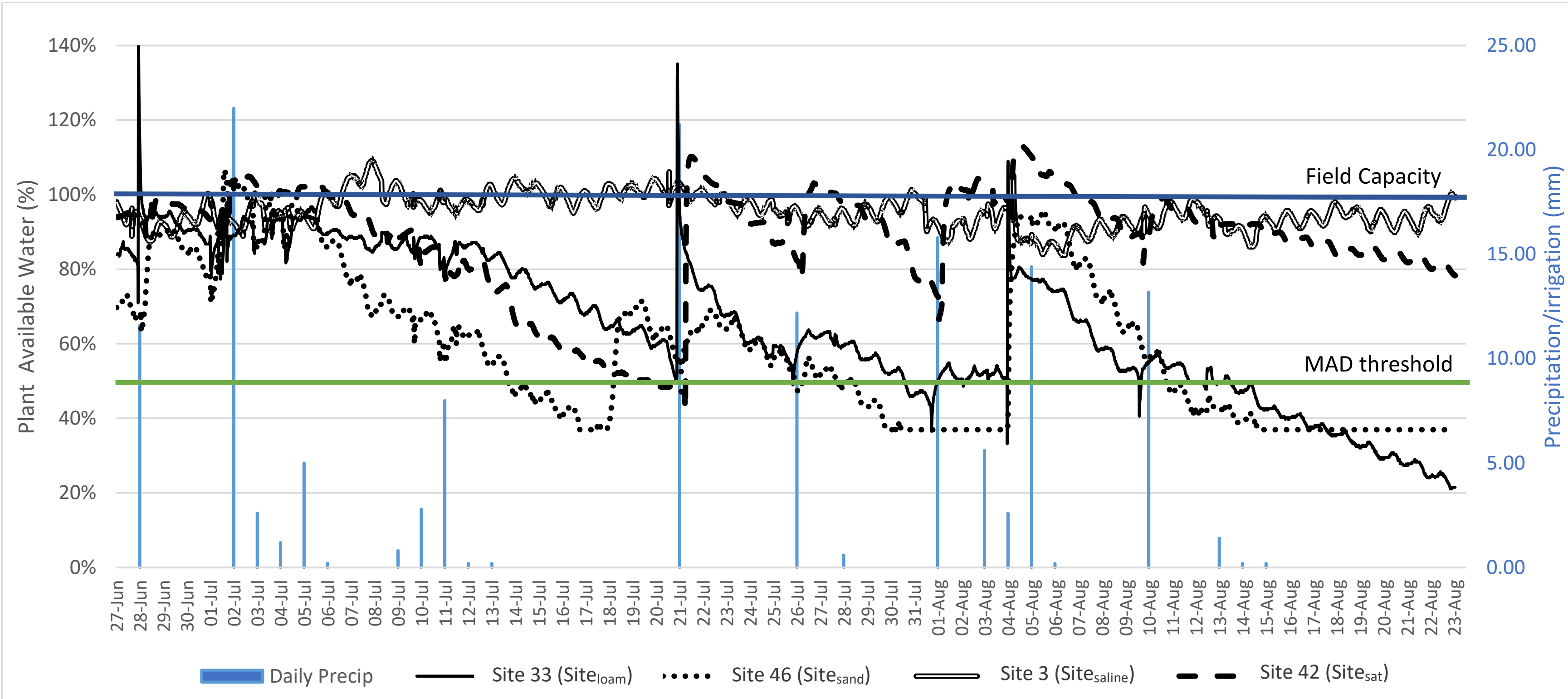

Fig. 3.8 Plant available water (20 cm depth) of the four representative modal sampling locations and daily precipitation/irrigation.

Note: Management allowable depletion (MAD) set to 50 % of plant available water. Plant available water calculation: plant available water = (field capacity – permanent wilting point) / (volumetric water content – permanent wilting point). Field capacity was set as the stabilized soil sensor reading follow a data spike from irrigation or perception. Permanent wilting point was set as the -500 kPa value assigned to the corresponding soil type (fig. 3.4)

3.5.2 Apparent canopy temperature and NDVI method

The drydown scenario began on July 5th with soil moisture near field capacity (FC) at all 48 sampling locations and continued until July 18. During this period there were minimal water inputs and soil moisture continuously decreased through evapotranspiration. During the drydown scenario, apparent canopy temperature and NDVI data were collected on July 12 and 18 (Fig. 3.9). Under early drydown conditions, apparent canopy temperature (r^2 = 0.649; RMSE = 8.85 mm) was found to more accurately identify variability in $PAWC_{50}$ relative to NDVI (r2 = 0.521; RMSE = 10.33 mm) (Fig. 3.9). Under late drydown conditions, apparent canopy temperature (r^2 = 0.742; RMSE = 7.59 mm) was still more accurate at measuring spatial variability in $PAWC_{50}$ relative to NDVI (r^2 = 0.700, RMSE = 8.17 mm). However, the relationship between NDVI (r^2 = +0.179; RMSE = -2.16 mm) and $PAWC_{50}$ strengthened more than that of the relationship between apparent canopy temperature (r^2 = +0.093; RMSE = -1.27 mm) and $PAWC_{50}$ under late drydown conditions.

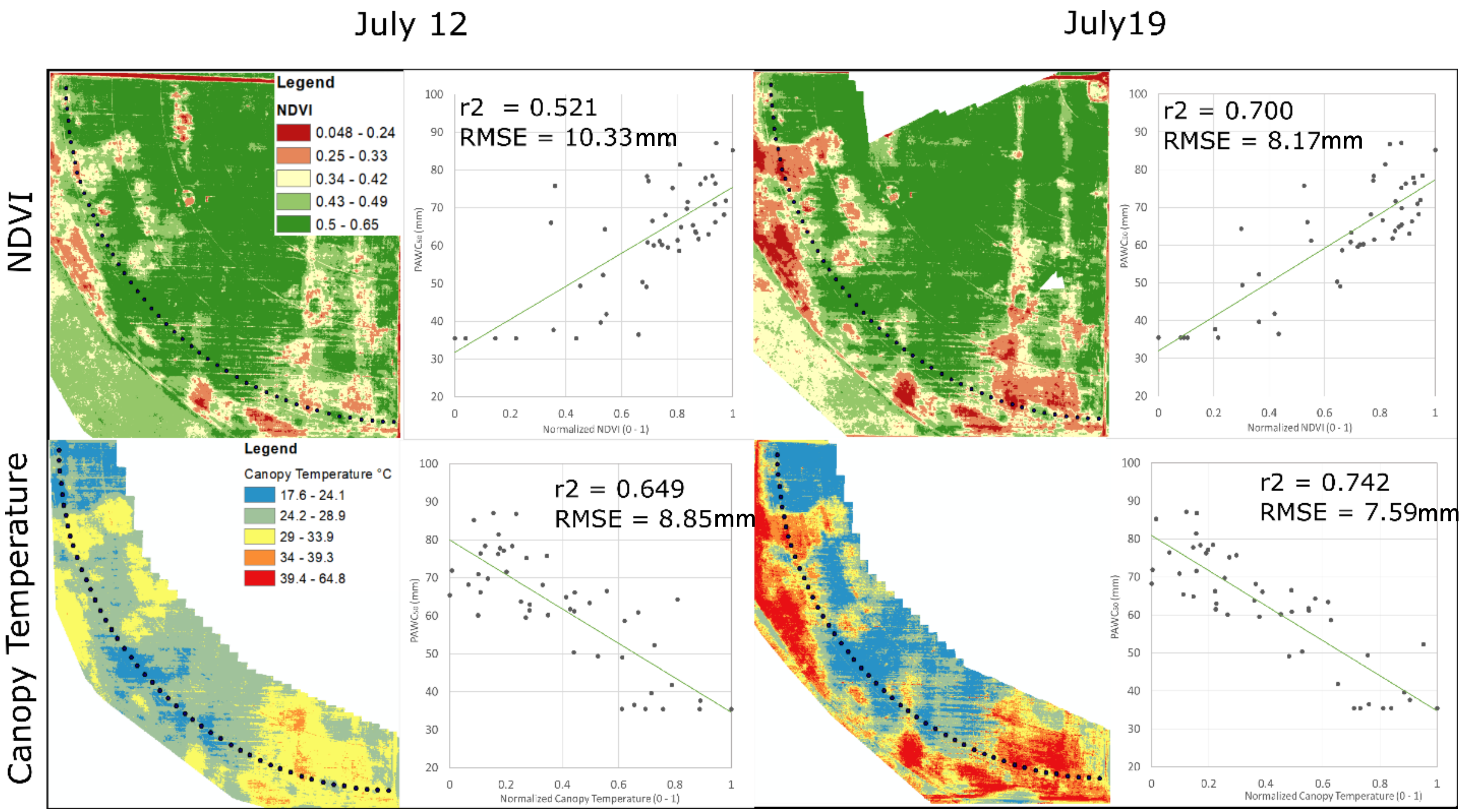

Fig. 3.9 Remote sensing data (NDVI and apparent canopy temperature) and corresponding linear regressions with practical plant available water ($PAWC_{50}$) from early drydown (July 12) and late drydown (July 19).

The soil moisture conditions at $Site_{loam}$ and $Site_{sand}$ (Table 3.1) were chosen to illustrate how plant available water varies spatially between sites with low ($Site_{sand}$) and high ($Site_{loam}$) $PAWC_{50}$ during the drydown scenario and how spatiotemporal variation in plant available water affects the results from the plant response drydown experiment (Fig. 3.10). July 12 is considered early drydown because at this timepoint, soil moisture status was within an adequate range for healthy plant growth at both low ($Site_{sand}$) and high ($Site_{loam}$) $PAWC_{50}$ sites (Fig. 3.10); however, matric potential increased to -400 kPa at $Site_{sand}$ and only -65 kPa at $Site_{loam}$. July 18 is considered late drydown because sites with low $PAWC_{50}$ ($Site_{sand}$) had reached very low plant available water and the sites with high $PAWC_{50}$ ($Site_{loam}$) had maintained adequate plant available water for healthy plant growth above the MAD threshold (Fig. 3.10).

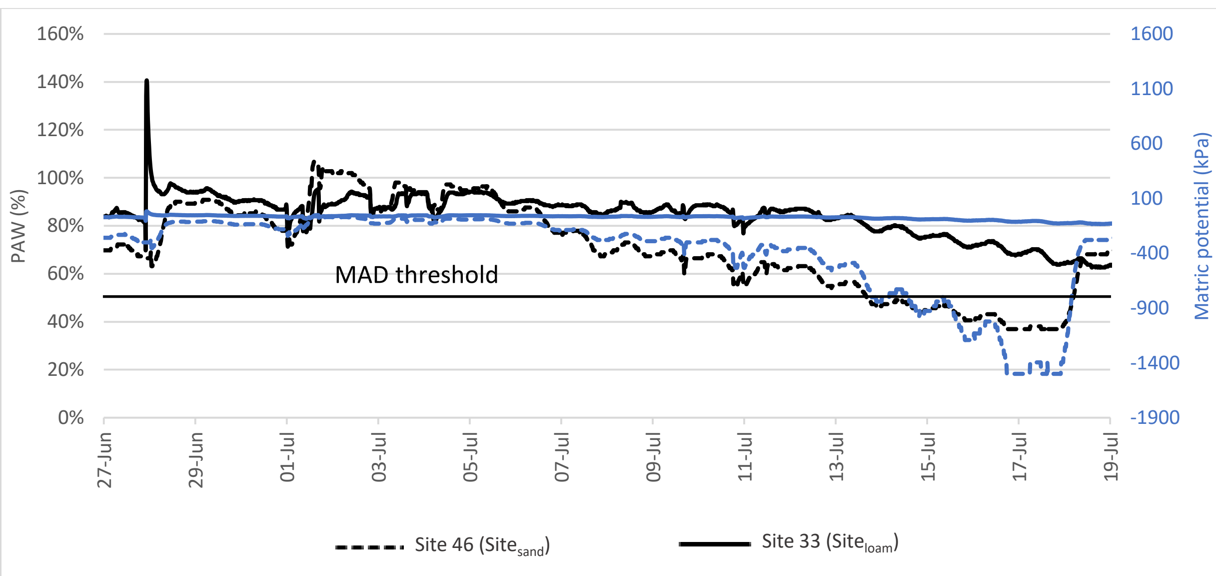

Fig. 3.10 Data logger time series of plant available water and soil matric potential.

Note: **Management allowable depletion (MAD) threshold set to 50 % of PAW. Matric pressure values obtained using pedotransfer function (Saxton and Rawls, 2006). Plant available water calculate as in Fig. 3.8.**

Interactions between spatial variability in $PAWC_{50}$ and plant response can influence remote sensing measurements through three primary mechanisms. The first mechanism is that areas with sandy soils and low $PAWC_{50}$ are known to have generally poor soil characteristics, which can cause plant growth to become stunted (Brady and Weil, 1998). Stunted plants lead to increased exposure to bare soil, causing an increase in apparent canopy temperature due to the influence of the higher temperature of exposed soil relative to leaves. Stunted plant growth also reduces NDVI values due to the high absorbance of near-infrared radiation by soil. The second mechanism influencing remote sensing measurements is the susceptibility of soils with low $PAWC_{50}$ to low plant available water and increased matric potential, leading to low stomatal conductance. This low stomatal conductance decreases the evaporative cooling effect and results in increased apparent canopy temperatures (Jackson et al., 1981; Jones et al., 2002). Deceased stomatal conductance also limits CO_2 uptake in leaves, which leads to stunted photosynthetic activity in plants thereby lowering NDVI values (Osakabe et al., 2014). The third mechanism influencing remote sensing measurements is that plants in areas with low $PAWC_{50}$ can be sensitive to severe drought conditions, which can cause leaf desiccation, and permanent crop damage (Tucker, 1977; Paltridge and Barber, 1988). Partial or whole leaf desiccation increases apparent canopy temperatures because cured leaves do not transpire. Partial or whole leaf desiccation also decreases NDVI values as leaf desiccation halts photosynthetic activity (Tucker, 1977; Paltridge and Barber, 1988). These three mechanisms all result in increased apparent canopy temperature and lower NDVI values in areas with low $PAWC_{50}$, which allows apparent canopy temperature and NDVI measurements to identify spatial variability in $PAWC_{50}$ by differentiating between areas with low and high $PAWC_{50}$, under drydown conditions.

In the present study, the first mechanism causes variable crop growth prior to the drydown scenario, as the influence of this mechanism is not dependent on soil moisture conditions and therefore affected crop growth throughout the growing season. Under early drydown conditions, the crop is also influenced by the second mechanism, as areas with low $PAWC_{50}$ exhibit an increased soil matric potential which results in decreased stomatal conductance. Apparent canopy temperature may produce a more sensitive response to decreased stomatal conductance, relative to NDVI because apparent canopy temperature exhibits a stronger relationship to $PAWC_{50}$ under early drydown conditions. These findings are consistent with existing research which shows a strong correlation between apparent canopy temperature and stem water potential, which in turn is strongly correlated to soil water potential in the root zone (Jackson et al., 1981; Jones et al., 2002). However, the relationship between NDVI and stomatal conductance is complex and dependent on specific plant species characteristics (Ceccato et al., 2001). Under late drydown conditions the crop is influenced by the first and second mechanisms, as well as the third mechanism because areas with low $PAWC_{50}$ exhibited an increased soil matric potential to near PWP levels, which caused leaf desiccation; whereas, areas with high $PAWC_{50}$ maintained a relatively low soil matric potential (Fig. 3.10). The respective relationships between apparent canopy temperature and NDVI with $PAWC_{50}$ were strengthened under late drydown conditions, this is likely due to the addition of mechanism three (leaf desiccation), which markedly lowered NDVI values and increased apparent canopy temperatures in areas with low $PAWC_{50}$. Unlike early drydown, the strength of the relationship between NDVI and $PAWC_{50}$ in late drydown was comparable to that of apparent canopy temperature and $PAWC_{50}$, because leaf desiccation is a more sensitive plant response indicator for NDVI measurement due to loss of chlorophyll, relative to stomatal conductance. The apparent canopy temperature method was able to accurately identify areas with low $PAWC_{50}$ under early drydown conditions due to the reduced stomatal conductance in these areas; therefore, continuing drydown conditions to the point of leaf desiccation in low $PAWC_{50}$ areas was not necessary for this method.

Although both methods work well for measuring variability in $PAWC_{50}$ under drought conditions, the apparent canopy temperature method may be better suited to delineate irrigation management zones because it exhibits a stronger relationship to $PAWC_{50}$ under early drydown conditions, and therefore water can be applied before yield loss. The NDVI method may only yield reliable results under crop-damaging drought conditions, due to the need for leaf desiccation. Despite this strong relationship between both of the plant response methods and $PAWC_{50}$, the transferability of these results should be considered with caution. In particular, spatial variability in the thickness of the surface aeolian sand layer was the dominant source of plant available water variability at the field site; consequently, these methods may have different results on different types of variable soil landscapes. Furthermore, crop selection can be an influential variable as certain crop species, such as canola (Appendix A), have phenological traits (such as large flowers) that can interfere with the ability of the plant response metrics to measure variability in $PAWC_{50.}$ Lastly, environmental factors such as crop-damaging weather, excessive rainfall, and pests or crop disease may stifle the performance of these plant response methods (Jones et al., 2009); none of which occurred in this experiment.

3.5.3 Soil apparent electrical conductivity method

The relationship between ECa and $PAWC_{50}$ (r^2 = 0.63, RMSE = 9.12 mm) was comparable to that of NDVI and apparent canopy temperature remote sensing methods (Fig. 3.11b). When sampling locations that exhibit soil salinity were removed from the regression, the relationship between ECa and $PAWC_{50}$ strengthened (r^2 = 0.72, RMSE = 8.07 mm) (Fig. 3.11c) and this relationship strengthened further following the removal of sites that exhibit both persistent soil saturation from 30 – 50 cm and/or soil salinity (r^2 = 0.85, RMSE = 6.18 mm) (Fig. 3.11d). The increase in r^2 and RMSE values indicate that spatial variability in both soil salinity and soil water content weaken the relationship between ECa and $PAWC_{50}$. The difficulties experienced when using ECa to measure spatial variability in $PAWC_{50}$ in the presence of variable soil salinity and water content is consistent with findings in the literature, which suggest that soil salinity and soil water content must have only minor variability, or be able to be estimated reliably, in order to use ECa measurements to indirectly measure soil water retention (Sudduth et al., 2001; Corwin and Lesch, 2005).

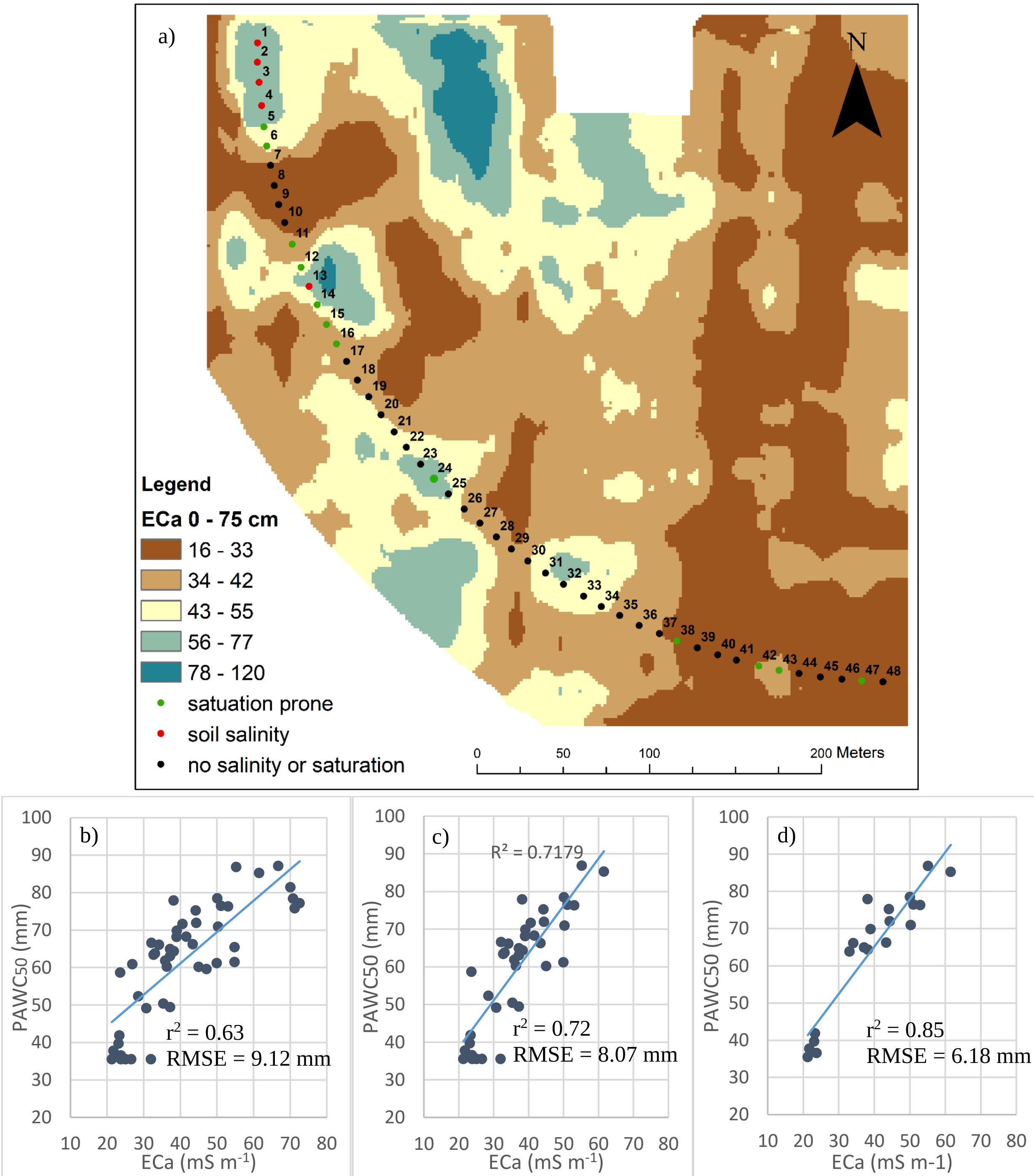

Fig. 3.11 a) Interpolated soil apparent electrical conductivity (ECa) map and scatter plots of ECa versus $PAWC_{50}$. b) all 48 sampling locations; c) sites with salinity > 2 mS cm^{-1} removed; d) sites with salinity > 2 mS cm^{-1} and persistent soil saturation in the 30 – 50 cm range removed.

Soil salinity only marginally reduced the strength of the relationship between ECa and $PAWC_{50}$ because soil salinity above 2 mS m^{-1} was only present at 5 of the 48 sampling locations. A larger spatial extent of soil salinity may inflict further interference on the relationship between ECa and $PAWC_{50}$ because soil salinity can inflate soil ECa values, making it difficult to distinguish areas with soil salinity from areas with high $PAWC_{50}$. For instance, site 13 and site 25 both have an ECa of 55 mS m^{-1}, but very different soil characteristics. Site 13 has a lower $PAWC_{50}$ (62 mm) than site 25 (87 mm), but a soil conductivity of 1.5 mS cm^{-1} resulted in an inflated ECa value at site 13. Predictable high soil salinity (for example, localized to a low-lying area) may cause less of an issue for ECa to measure variability in $PAWC_{50}$ because it would be easier to identify these areas on an ECa map due to the very high ECa values of severely saline soils (Corwin and Lesch, 2005).

Spatial variability in soil moisture at the field site weakens the relationship between ECa and $PAWC_{50}$ to a similar degree as soil salinity (Fig. 3.11b, Fig. 3.11c); however, soil moisture variability is much more widespread than soil salinity. Soil water content variability alone is unlikely to negate the feasibility of delineating irrigation management zones with ECa maps, as the relationship between ECa and $PAWC_{50}$ maintains a strong relationship ($r^2 = 0.71$, RMSE = 8.16 mm) when both low moisture and saturation prone sites are included in the regression (Fig. 3.11b, Fig. 3.11c). Soil apparent electrical conductivity can have a strong relationship to $PAWC_{50}$ and therefore be a useful metric for delineating irrigation management zones; however, the dynamic soil factors that influence ECa measurements should be thoroughly understood when using ECa maps to delineate irrigation management zones.

3.5.4 Yield versus PAWC

The relationship between crop yield and $PAWC_{50}$ ($r^2 = 0.621$; RMSE = 9.19 mm), is comparable to the ECa survey and the plant response methods (Fig. 3.12). Yield data is highly dependent on dynamic environmental conditions and phenological crop traits (Long, 1998), which has led to varied results when utilizing yield data to delineate irrigation management zones (Haghverdi et al., 2015). For this reason, generating conclusions from results using this method should be approached with caution. The strong relationship between yield and $PAWC_{50}$ produced by this research may have been inflated due to the influence of crop drought stress caused by low plant available water in areas of the field with low $PAWC_{50}$ during the drydown scenario. Therefore, yield data may be more useful for measuring variability in $PAWC_{50}$ in growing seasons where drought is known to have negatively affected yields. A drought response of this nature may regularly occur on dry-land agricultural fields; therefore, historical dry-land yield data from drought years may be useful for delineating irrigation management zones. The yield data used in this analysis were acquired from hand harvest crop samples at each of the 48 sampling location, therefore actual yield mapping technologies may provide different results.

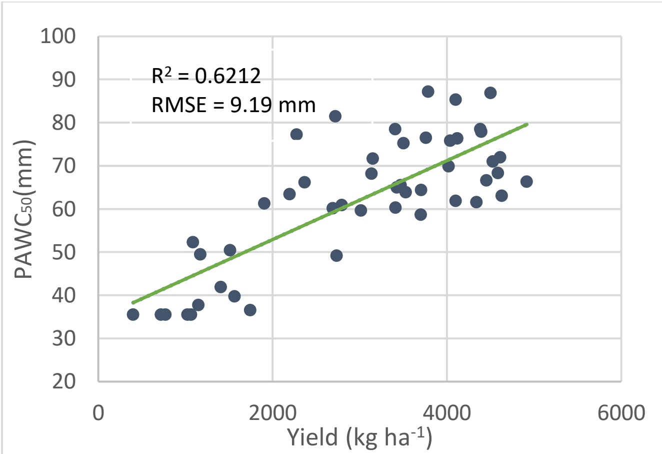

Fig. 3.12 Linear regression of yield versus $PAWC_{50}$ from the 48 sampling locations. Yield data calculated from hand sampled 1 m^2 plots.

3.6 Conclusion

This study evaluated multiple methods of identifying spatial variability in $PAWC_{50}$ for the application of delineating irrigation management zones for variable rate irrigation. Two plant response methods (NDVI and apparent canopy temperature) were utilized to indirectly measure spatial variability in $PAWC_{50}$ by measuring plant response during early and late drydown conditions. Apparent canopy temperature can more accurately identify spatial variability in $PAWC_{50}$ relative to NDVI under early conditions. The NDVI method showed a marginal relationship to $PAWC_{50}$ under early drydown conditions and a stronger relationship under late drydown conditions; however, the late drydown conditions caused crop damage. Soil apparent electrical conductivity (ECa) mapping was also utilized to measure spatial variability in $PAWC_{50}$. The ability of the ECa method to identifying spatial variability in $PAWC_{50}$ was comparable to the remote sensing plant response methods; however, there are significant concerns with using this method in the presence of soil salinity and to a lesser degree in the presence of soil moisture variability. The crop yield was found to share a moderately strong relationship to spatial variability in $PAWC_{50}$; however, this could have been partly related to the crop damage that occurred during late drydown conditions.

The strong relationship between apparent canopy temperature and $PAWC_{50}$ under early drydown conditions makes this method a suitable candidate to replace and/or utilize in conjunction with traditional methods. The results from NDVI were not as promising due to this method working best under crop-damaging late drydown conditions. The transferability of the plant response methods may vary on fields with different expressions of soil moisture variability and different plant species with phenological traits (such as large flowers) that can interfere with remote sensing plant response metrics. Furthermore, crop growth patterns can be affected by several factors such as soil salinity, environmental conditions, and crop diseases or pests. The dynamic factors that can influence ECa and remote sensing plant response measurements can lead to weak relationships to $PAWC_{50}$; therefore, these factors should be thoroughly understood when using any of these methods to delineate irrigation management zones.

4 METHODS OF DELINEATING IRRIGATION MANAGEMENT ZONES: REMOTE SENSING OF PLANT RESPONSE UNDER A DRYDOWN SCENARIO VERSUS SOIL APPARENT ELECTRICAL CONDUCTIVITY MAPPING

4.1 Preface

The research in this chapter evaluates the ability of the methods studied in Chapter 3 to delineate accurate irrigation management zones. The discussed methods are NDVI and apparent canopy temperature, both measured during a drydown scenario, as well as static ECa mapping. The research in Chapter 3 provided conclusions as to which methods can best identify spatial variability in $PAWC_{50}$, whereas this chapter evaluates their ability to delineate management zones with the narrowest range and most homogeneous distribution of $PAWC_{50}$. The chapter also evaluates the ability of lower resolution satellite-based NDVI data to identify spatial variability in $PAWC_{50}$. If these lower resolution data sources could be utilized to delineate management zones, the NDVI method would be much more accessible than the apparent canopy temperature method. The practical and technical considerations associated with each zone delineation technique are identified and discussed in this chapter. A table of the advantages and disadvantages of each method is provided to summarize the practical considerations associated with each method and their capability to delineate accurate irrigation management zones.

4.2 Abstract

Variable rate irrigation (VRI) is commonly administered by delineating a field into management zones based on variability in available water-holding capacity (AWC) (Haghverdi et al., 2015). The accuracy of these management zones is the foundation to a successful VRI development. Management zones have traditionally been delineated using soil apparent electrical conductivity (ECa); however, inconsistencies with this method and laborious data acquisition has increased interest in utilizing remote sensing techniques to delineate irrigation management zones. This research evaluated the ability of the traditional ECa method and two remote sensing-based plant response indices (apparent canopy temperature and NDVI) under drydown conditions to delineate irrigation management zones with the narrowest range and most homogeneous distribution of practical available water-holding capacity from 0 – 50 cm ($PAWC_{50}$). NDVI data was acquired via unmanned aerial vehicle (UAV), Sentinel satellite, and Landsat8 satellite, to determine how resolution affected the ability of NDVI to identify spatial variability in $PAWC_{50}$, where apparent canopy temperature could only be acquired via UAV. The apparent canopy temperature method was the most reliable, as it could accurately delineate zones with homogeneous $PAWC_{50}$ under early and late drydown conditions. The NDVI method performed best under late drydown conditions and produced zones with poor homogeneity under early drydown conditions. The ECa method was able to delineate relatively homogenous management zones. Performance between NDVI remote sensing platforms indicates that higher spatial resolution data can delineate more homogenous management zones. This research weighed the applied performance and the practical considerations associated with the discussed methods to determine the potential feasibility of each method to delineate management zones on a production field scale.

4.3 Introduction

Variable rate irrigation (VRI) is implemented by spatially varying irrigation applications between predetermined management zones. Delineating irrigation management zones with relatively homogeneous practical available water holding capacity from 0 – 50 cm ($PAWC_{50}$) within zones can decrease the potential for runoff caused by irrigating soils above volumes that exceed field capacity. Management zones used to administer VRI have traditionally been delineated using soil apparent electrical conductivity (ECa) mapping to estimate spatial variability in soil texture, from which variability in $PAWC_{50}$ is inferred (Haghverdi et al., 2015); however, concerns with interference of other soil factors and laborious data acquisition has increased interest in utilizing remote sensing techniques to delineate irrigation management zones. Both plant response (apparent canopy temperature and normalized difference vegetation index (NDVI) under drydown conditions) and traditional (soil apparent electrical conductivity) zone delineation methods have been demonstrated to identify spatial variability in $PAWC_{50}$ (Chapter 3); the apparent canopy temperature method was found to have the strongest relationship to $PAWC_{50}$. The results from the NDVI method were not as promising due to this method working best under crop-damaging drydown conditions; however, data for this method can be acquired from satellite-based sensors which would be seamless relative to UAV remote sensing data acquisition.

The accuracy of a delineated management zone is dependent on the heterogeneity of the soil characteristics within each zone (Schepers et al., 2004). The most accurate methods will develop management zones with the narrowest range and most homogeneous distribution of available water holding capacity. Management zones with relatively homogeneous available water-holding capacity (AWC) have the potential to sustain spatially consistent optimum plant available water in fields with variable soil types. This is accomplished by reducing the runoff associated with exceeding field capacity, and by irrigating areas with low AWC more frequently with lower volume applications. Each of the methods discussed has unique logistical and technical challenges that will affect their feasibility related to delineating irrigation management zones at a production field scale. Examining the applied zone delineation performance of both plant response and traditional zone delineation methods, as well as their practical considerations, will help determine which zone delineation methods are best suited to individual irrigation projects.

The purpose of this chapter is to evaluate the zones delineated by the plant response and traditional zone delineation methods, and to assess practical considerations associated with each method. The specific objectives of this chapter are to: (1) Evaluate the ability of the plant response and traditional zone delineation methods to delineate accurate management zones with homogeneous available water holding capacity (2) determine if the resolution of satellite-derived NDVI data affects the performance of this method (3) identify the logistical and technical challenges associated with the plant response and traditional zone delineation methods, and (4) to outline strengths and weaknesses of each zone delineation method.

4.4 Methods

The site characteristics, agronomic management, experimental design and remote sensing approaches are summarized below; more details can be found in Section 3.2.

4.4.1 Field site

The field site (thoroughly described in Section 3.4.1) is a 16-hectare (40 acres) area within a 64-ha field irrigated with a center pivot system in Outlook, Saskatchewan. The soil profile of the site includes an aeolian sandy surface layer that ranges in thickness from 10 – 83 cm (Eilers, 1997).

4.4.2 Agronomic and irrigation management

Water and soil nutrition were managed to facilitate consistent crop germination and establishment (thoroughly described in Section 3.4.2). Spring wheat was grown during the 2018 field season as it facilitates remote sensing of plant response due to lasting green photoactive leaves that do not become blocked by large flowers (Basnyat et al., 2004). Once the crop was in the heading growth stage, the field was purposely exposed to a drydown scenario from July 5 to July 21 by ceasing irrigation applications. The purpose of the drydown scenario was to determine if the plant response methods could identify spatial variability in $PAWC_{50}$ as plant available water decreased in the field.

4.4.3 Soil sampling and site selection

Judgement sampling (Pennock, 2004) was employed to select 48 sampling locations along a radial transect (Fig. 3.5) with the purpose of capturing the variability in the thickness of the aeolian sand layer (thoroughly described in Section 3.4.3).

4.4.4 Determination of soil water retention characteristics

Practical plant available water-holding capacity from 0 – 50 cm ($PAWC_{50}$) was adapted as the soil water retention metric for this study and is the volumetric water holding capacity volume between matric pressures of -33 kPa (FC) and -500 kPa from 0 – 50 cm. The $PAWC_{50}$ metric was estimated for the 48 sampling locations by assigning laboratory-measured water retention characteristics from a smaller subset of 10 soil cores to the 48 locations based on their common soil horizon and texture characteristics (thoroughly described in Section 3.4.4 and 3.5.1.1).

4.4.5 Soil apparent electrical conductivity survey

The ECa survey (thoroughly described in Section 3.4.5) was performed at the field site during September of 2017 using the EM38-MK2 with a 12-m spacing between rows and 2-m spacing along rows (Geonics Limited, Mississauga, Ontario). This ECa survey data was interpolated in ArcMap (ESRI, California, USA) using Inverse Distance Weighting (IDW) and was then extracted for each sampling location.

4.4.6 UAV remote sensing

Remote sensing data were collected (thoroughly described in Section 3.4.7) with a High-Precision NDVI multispectral sensor (Sentera, Minnesota, USA) and a Zenmuse XT (336 x 256) thermal camera (FLIR Systems, Oregon, USA), which were mounted to a DJI Inspire 2 UAV (DJI, Shenzhen, China) and processed using Pix4Dmapper (Pix4D, S.A. Lausanne, Switzerland). The UAV remote sensing data were acquired weekly during the growing season, starting at early crop establishment through to crop maturation.

4.4.7 Satellite data

Landsat-8 (U.S. Geological Survey, Virginia, USA) and Sentinel-2 Constellation (European Space Agency, Paris, France) satellite-based remote sensing data were acquired for the 2018 field season (through http://earthexplorer.usgs.gov/). Satellite data was collected for the 2018 growing seasons. Data from Landsat-8, Band 4 (red, 0.630 – 0.680 um) and Band 5 (near-infrared, (0.845 – 0.885 um) were used to calculate NDVI in ArcMap. Landsat-8 has a 10-day return period and Bands 4 and 5 have a 30-m resolution. Data from Sentinel-2, Band 4 (red, 0.650 – 680 um) and Band 8 (near-infrared, 0.7845 – 0.8995 um) were used to calculate NDVI in

ArcMap. The Sentinel-2 satellite constellation has a five-day return period, and band 4 and 8 have a 10-m resolution.

4.4.8 Delineating irrigation management zones and statistical analysis

Management zones were delineated by applying a clustering classification technique in ArcMap (ESRI, California, USA) to evaluate which methods produce zones with the most homogenous $PAWC_{50}$ values within each zone and a significantly different $PAWC_{50}$ between zones. This evaluation was accomplished by first using the "Iso-cluster" tool on the zone delineation method data to delineate the field into 2 and 3 categories (zones) (Fig. 4.1). The sampling locations were assigned a zone value (zone a, b, or c) so the statistical analysis could be performed on $PAWC_{50}$ values within and between zones. A Tukey's Honestly Significant Difference test (Tukey Test) was then performed on each of the model outputs to determine which method produced zones with significantly different $PAWC_{50}$. The homogeneity of the zones was compared using the average zone range (AZR) which was calculated by determining the interquartile range of $PAWC_{50}$ from the sampling locations that fell within each zone and then calculating the average range between the zones for each zone delineation output.

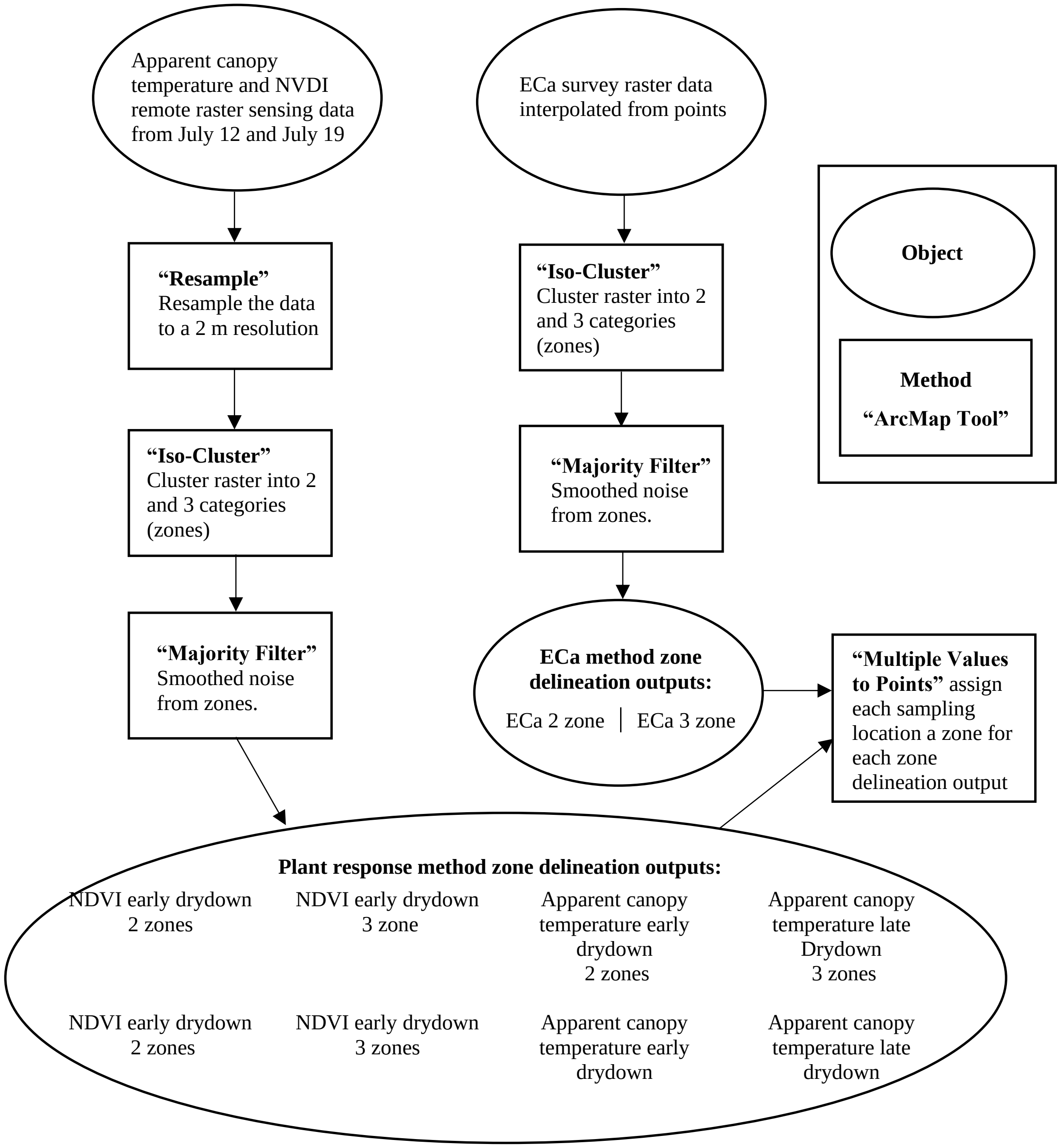

Fig. 4.1 Workflow diagram of the zone delineation procedure performed using ArcMap.

4.5 Results

4.5.1 Delineating irrigation management zones

4.5.1.1 NDVI versus apparent canopy temperature versus ECa

The zone delineation methods were tested for their ability to delineate management zones with homogeneous $PAWC_{50}$, while retaining significantly different $PAWC_{50}$ between each zone (Fig. 4.1). All the tested methods could delineate the field into two management zones with significantly different $PAWC_{50}$ values; however, delineating the field into just two zones resulted in zones having poor homogeneity (AZR of 18 to 19 mm for all methods) (Fig. 4.2). The NDVI method was unable to delineate the field into more than two significantly different management zones under early drydown conditions; however, under late drydown conditions, the NDVI method was able to delineate the field into three significantly different zones with improved homogeneity (AZR = 9.3 mm) (Fig. 4.2). The apparent canopy temperature method was also able to delineate three management zones with significantly different $PAWC_{50}$ under both the early (AZR = 11.3 mm) and late (AZR = 9.3 mm) drydown conditions (Fig. 4.3). Similarly, the ECa method was able to delineate the field into three zones with significantly different $PAWC_{50}$; however, the homogeneity of these zones (AZR = 16 mm) was much lower than three-zone results for either of the two plant response methods (Fig. 4.2).

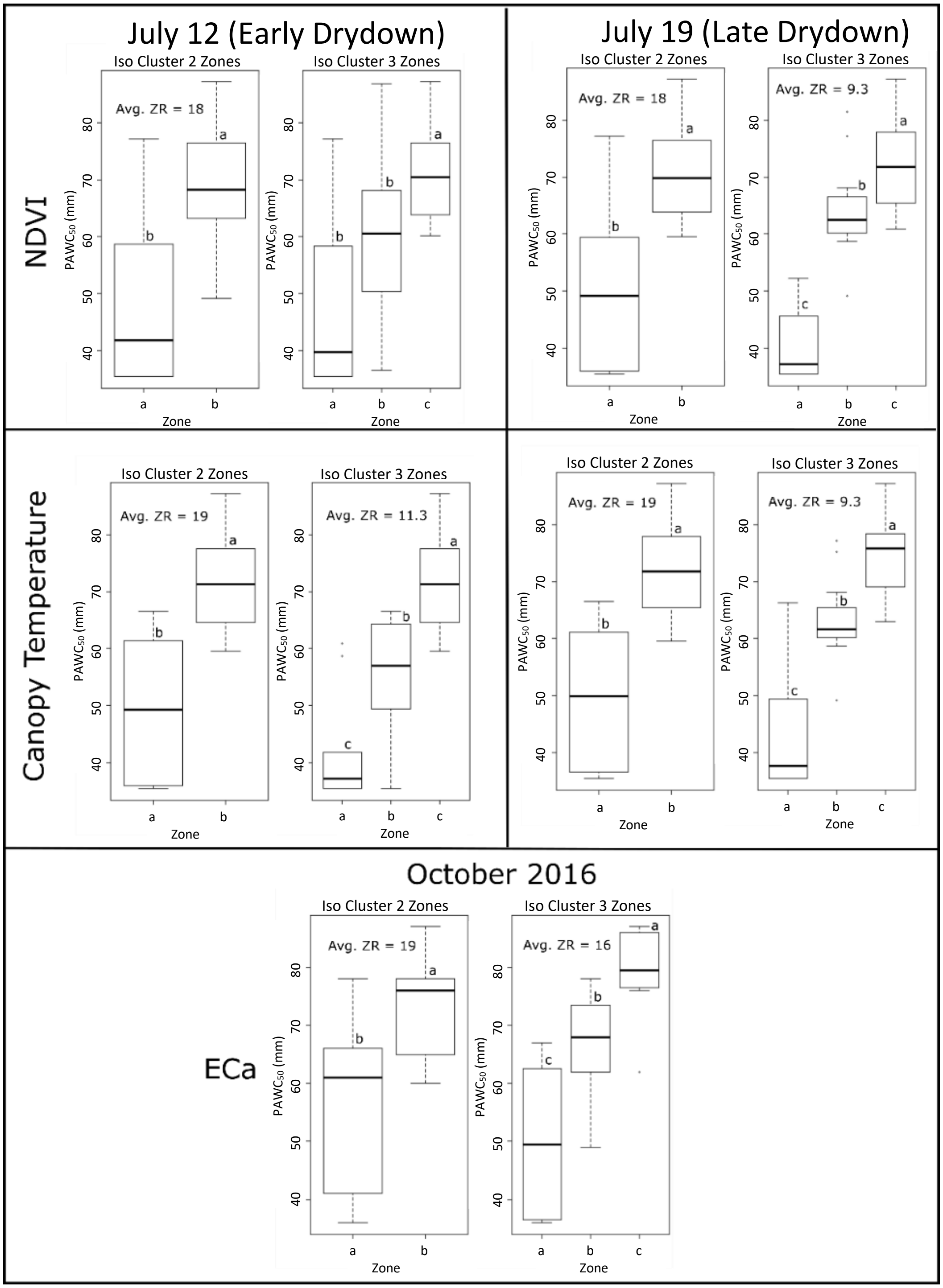

Fig. 4.2 Comparison of zone practial available water holding capacity from 0 – 50 cm ($PAWC_{50}$) homogeneity between methods.

Note: **Lower case letters indicate significant differences (95% confidence interval) as determined by a Tukey's Honestly Significant Difference Test. The average zone range (AZR) is the average interquartile range of each zone.**

4.5.1.2 NDVI platforms: Landsat8 versus Sentinel-2 versus UAV

The NDVI plant response method can utilize data acquired via Landsat8 Satellite, Sentinel-2 Satellite, or through UAV flights. These remote sensing platforms have different spatial and temporal resolutions that affect the ability of each to delineate management zones with accurate $PAWC_{50}$. The Landsat8 platform was only able to delineate the field into two significantly different management zones with the lowest zone homogeneity of all NDVI platforms (AZR = 18.5 mm) (Fig. 4.3b). The Sentinel-2 platform was able to delineate three significantly different management zones with increased zone homogeneity (AZR = 15 mm), relative to Landsat8 (Fig. 4.3b). The UAV platform was able to delineate the most homogeneous management zones (AZR = 8.3 mm), relative to both satellite platforms (Fig. 4.3b). Only one time-point was used to compare the resolution of these data source due to a lack of data from similar dates as a result of the different return periods of the satellite platforms and failure to acquire data due to cloud cover.

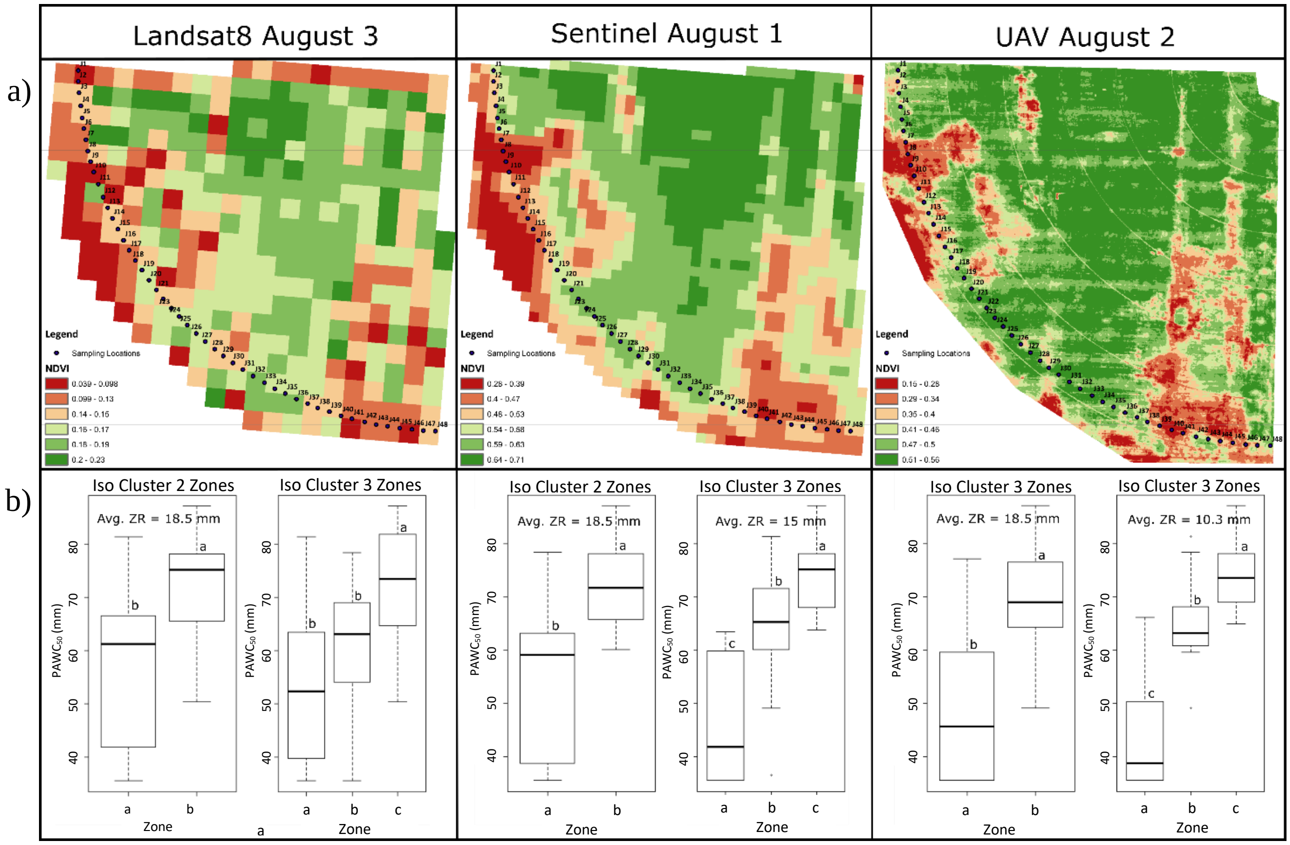

Fig. 4.3 a) NDVI Raster data visual repsentation and b) comparison of zone practical available water holding capacity from 0 – 50 cm ($PAWC_{50}$) homogeneity between Landsat8 satellite (30 m resolution), Sentinel-2 satellite (10 m resolution), and the UAV (0.5 m resolution).

Note: Lower case letters indicate significant differences (95% confidence interval) as determined by a Tukey's Honestly Significant Difference Test. The average zone range (AZR) is the average interquartile range of each zone.

4.6 Discussion

4.6.1 Practical considerations: NDVI

4.6.1.1 NDVI: Early versus late drydown

The NDVI method can delineate more homogeneous management zones under late drydown conditions relative to early drydown conditions; however, Chapter 3 found that the late drydown conditions caused permanent crop damage, which is a major disadvantage of this method. Early drydown NDVI may still be feasible, as the level of management zone homogeneity required to successfully implement VRI is not well understood. Implementing VRI by irrigating management zones that were delineated using the NDVI method under early drydown conditions may still lead to spatial variability in plant available water because of the wide range in plant available water within zones (AZR = 19 mm). However, management zones with an AZR of 19 mm would be a great improvement over uniform rate irrigation in this field, which has a range in $PAWC_{50}$ of 52 mm.

4.6.1.2 NDVI: Remote sensing platforms

A major benefit of the NDVI method is that the required remote sensing data can be acquired from open-source satellite platforms (Landsat8 and Sentinel-2). Temporal frequency is an important factor that affects the feasibility of utilizing data from these platforms. Sentinel-2 (5-day return period) had 7 data acquisition failures due to cloud cover out of 15 passes during the field season and Landsat8 (10-day return period) had 3 data acquisition failures due to cloud cover out of 5 passes during the growing season. The higher spatial and temporal resolution of the Sentinel-2 Satellite allows for the delineation of more accurate zones and a better chance of acquiring data, relative to Landsat8. The UAV remote sensing platform can delineate more accurate management zones than the satellite platform and has much more flexibility in temporal resolution, as the UAV platform allows for data acquisition on any day that has suitable flying conditions. However, the satellite platforms are available as open-source data through online government portals, whereas the UAV method requires a UAV with specialized sensors, skilled labour to collect and process data, and compliance with legal regulations that can restrict potential flight areas and flight altitudes.

4.6.2 Practical considerations: Apparent canopy temperature

The apparent canopy temperature method can reliably delineate accurate management zones under early and late drydown conditions; however, this method has multiple practical considerations that affect its feasibility at a field scale. Collecting and processing thermal images is less user-friendly and more expensive relative to NDVI, as thermal imaging requires more time to cover the same area as NDVI due to the image 90% overlap required to stitch low-resolution thermal imagery from a UAV platform (Pix4D). Furthermore, thermal bands that are available via satellites are not capable of delineating intra-field management zones due to their low resolution. The longer flight times associated with UAV based thermal imaging leads to a greater probability of encountering variable cloud cover, which causes interference in apparent canopy temperature readings as shaded crop canopies exhibit cooler temperatures than sunlit crop canopies (Jackson et al., 1981). Apparent canopy temperature data fluctuates by a large magnitude if environmental conditions change from sunlit to cloud cover during a UAV remote sensing flight, whereas the NDVI data does not exhibit these large fluctuations (Fig. 4.4). Variable cloud cover interference was mostly avoided in this study as UAV flights were limited to the 48 sampling locations, rather than covering the entire area of a standard 130-acre irrigation pivot.

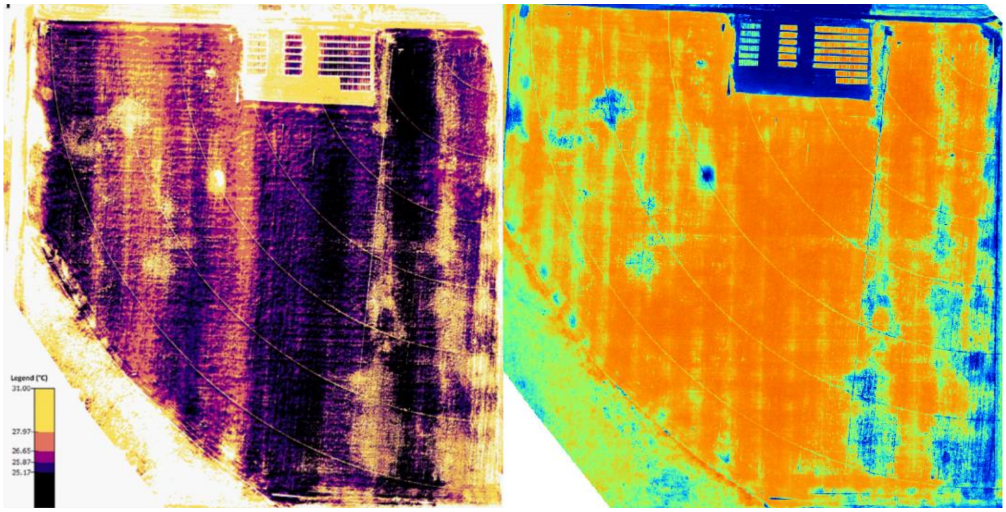

Fig. 4.4 Apparent canopy temperature (left) and NDVI (right) collected simultaneously from the canola field on July 5, 2017, during in-flight variable cloud cover.

4.6.3 Practical considerations: ECa

The ECa method was able to delineate management zones with moderately homogeneous $PAWC_{50}$, however, Chapter 3 indicated that this method can have severe limitations when soil salinity is present and moderate limitations when soil moisture is highly variable. In addition to these limitations, there are multiple practical considerations that affect the feasibility of using this method to delineate irrigation management zones. The main deficiencies of the ECa method are the time-consuming instrument survey that requires dragging an instrument on a non-metal sledge through a field with a 12 m pass width; therefore, it is recommended that ECa surveys are not performed during the growing season due to the potential for crop damage. Variability in soil temperature and frost can also interfere with the measurement from an ECa survey, further reducing the suitable timeframe for ECa surveys to be completed (Sudduth et al., 2001).

It is challenging to determine the degree of interference that soil salinity causes in the relationship between ECa and $PAWC_{50}$ because soil salinity is difficult to reliably predict; therefore, it is important to complete a salinity analysis of physical soil samples to determine the degree of salinity interference. Interpretation of ECa data for delineating irrigation management zones requires a comprehensive understanding of the dynamic effects that soil landscapes and soil salinity have on the instruments used to measure soil ECa.

4.7 Conclusion

This study evaluated the ability of two plant response methods (NDVI and apparent canopy temperature) under drydown conditions and the traditional ECa method to delineate unique management zones that exhibit homogeneous within-zone $PAWC_{50}$. The apparent canopy temperature method was able to delineate accurate irrigation management zones under early (AZR = 11.3 mm) and late (AZR = 9.3 mm) drydown conditions. NDVI method performed best under late drydown conditions (AZR = 9.3 mm) but provided poor results under early drydown conditions (AZR = 18 mm). The ECa method was able to delineate relatively homogenous management zones (AZR = 16 mm) in the near absence of soil salinity, but it is suspected that this method would provide poor results in fields with a greater extent of soil salinity. The Landsat8 satellite platform was found to have too low of resolution to delineate accurate management zones. The Sentinel-2 satellite platform was utilized to delineated more homogenous management zones relative to Landsat8 but did not outperform the UAV platform; however, the Sentinel-2 platform data is more accessible than the UAV platform as the data can be acquired through open source government portals. The zone delineation methods evaluated in this study each have unique practical considerations that affect their feasibility to delineate accurate irrigation management zones. The practical considerations and varying abilities of each method to delineate accurate management zones has been summarized in Table 4.1 to aid in choosing a method that is compatible with unique variable rate irrigation/crop production projects.

Table 4.1 Advantages and disadvantage of zone delineation methods and remote sensing data collection platforms.

Zone delineation method	Advantages	Disadvantages
NDVI	Great results under late drought conditions; both UAV and satellite data can be used	Fair results under early drought conditions; potential to damage crop during drydown scenario
Apparent canopy temperature imagery UAV	Can delineate accurate management zone under early and late drydown conditions	Satellite thermal band resolution is too low; longer flight times due to 90% image overlap; more sensitive to errors caused by variable cloud cover
Remote sensing Platforms		
- UAV	Sampling dates can be chosen by the user; high spatial resolution; new sensors and software being developed for agriculture industry; can collect high-resolution RGB images of the field, which can aid in the interpretation of other data sources	Flights are time-consuming and require skilled labour; sensors and stitching programs can be expensive; must comply with NAV CANADA regulations
- Satellite	Sentinel-2 and Landsat8 data are free to use if you follow the user conditions; historic data can be utilized	Cloud cover can block data acquisition; subject to predetermined pass dates and spatial resolution of bands
- *Sentinel-2*	Good spatial (10 m) and temporal (5 days) resolution	Data only goes back to 2016
- *Landsat8*	Similar data to other Landsat satellites, which have a data archive going back to the 1970s	Low spatial (30 m) and temporal (10 days) resolution
Soil apparent electrical conductivity	Good results at the field site which exhibited soil moisture variability and minor soil salinity Reliable method for measuring spatial variability in soil salinity, which can be used in precision remediation of salt-affected soils	Requires and time-consuming instrument survey; very sensitive to salinity and moisture variability error
Yield	Able to identify spatial variability in AWC; however, these results may have been influenced by the drydown scenario	Unreliable due to variability in environmental conditions and other crop growth factors between growing season

5 SYNTHESIS AND CONCLUSION

Uniform rate irrigation on highly variable soil landscapes does not account for spatial differences in available water-holding capacity, which leads to reduced crop yield and quality, as well as an inefficient use of irrigation water sources and irrigation infrastructure (Sadler et al., 2005). Variable rate irrigation (VRI) can minimize differences in plant available water by spatially varying irrigation applications based on specific crop needs (Evans and King, 2012). However, studies on VRI have failed to consistently show a positive cost-benefit ratio due to the complex interactions that affect the realized benefits, including annual climate variability, degree and nature of soil variability, soil-crop interaction, and crop economics (Evans and King, 2012). Variable rate irrigation has potential to become more appealing with increased contention among environmental, recreational, municipal and industrial users, as water becomes more scarce, especially under drought conditions (Sadler et al., 2005). Variable rate irrigation is commonly implemented by delineating a field into management zones with relatively homogenous available water-holding capacity (AWC) (Haghverdi et al., 2015). Methods that can identify spatial variability in AWC are critical for delineating irrigation management zones. This has traditionally been accomplished using soil apparent electrical conductivity (ECa) mapping techniques (Hedley et al., 2009), or yield maps (Haghverdi et al., 2015). An emerging approach to delineating irrigation management zones utilizes relationships between plant response and soil moisture conditions by measuring this plant response with remote sensing techniques (Haghverdi et al., 2015). The study described in Chapter 3 of this thesis introduced a method of delineating irrigation management zones which measures plant response to soil moisture conditions under a drydown scenario. The purpose of the drydown scenario was to increase variability in plant available water between areas of the field with low and high AWC, which would cause a spatially variable plant response and establish a relationship between the plant response remote sensing indices and AWC. Two remote sensing-based plant response delineation methods (apparent canopy temperature and NDVI) were evaluated under drydown conditions and were compared to two traditional delineation methods (ECa and yield). These methods were evaluated by their ability to identify spatial variability in practical available water-holding capacity from 0 – 50 cm ($PAWC_{50}$) at 48-sampling locations in the field site. Chapter 4 expanded the evaluation of these same methods by evaluating their ability to delineate accurate management zones and explored the practical considerations associated with each method.

5.1 Summary of findings

An aeolian sand layer of variable thickness was found to be the dominant source of spatial soil moisture variability at the studied field site. This soil layer had a large effect on the $PAWC_{50}$ of the soil at any given location due to its low water retention characteristics. Areas with a thick aeolian sand layer were found to be prone to drought stress between irrigation applications, yet these areas were easily saturated by an irrigation event which led to saturation conditions in landscape depressions. The practice of uniform rate irrigation on this variable soil landscape led to a high degree of spatial variability in plant available water, making it an ideal field to implement variable rate irrigation and test zone delineation methods.

The apparent canopy temperature plant response method exhibited the strongest relationship to $PAWC_{50}$ under both early (r^2 = 0.649; RMSE = 8.85 mm) and late (r^2 = 0.742; RMSE = 7.59 mm) drydown conditions, whereas the NDVI plant response method exhibited a marginal relationship to $PAWC_{50}$ under early drydown conditions (r^2 = 0.521; RMSE = 10.33 mm) and a stronger relationship under late drydown conditions (r^2 = 0.742; RMSE = 7.59 mm). This was attributed to the apparent canopy temperature data being sensitive to small variabilities in the evaporative cooling effect of stomatal conductance caused by a small degree of variability in plant available water between sites with high and low $PAWC_{50}$ under early drydown conditions. The NDVI plant response method was found to require a high degree of drydown, in order to accurately identify spatial variability in $PAWC_{50}$, resulting in leaf desiccation caused by very low plant available water in areas with low $PAWC_{50}$. The permanent crop damage required to accomplish this was found to be a negative attribute of this method. The traditional ECa method was able to identify spatial variability in $PAWC_{50}$ (r^2 = 0.63, RMSE = 9.12 mm); however, it was challenging to determine whether ECa measurements were affected by soil salinity or $PAWC_{50}$ associated with higher clay content. The crop yield was found to exhibit a moderately strong relationship to spatial variability in $PAWC_{50}$ (r^2 = 0.615); however, this favourable result is likely due to the crop damage that occurred during late drydown conditions.

The results from the applied zone delineation study (Chapter 4) supported the results from Chapter 3, where the zone delineation methods that could best identify spatial variability in $PAWC_{50}$ could also delineate management zones with the most homogenous distribution in $PAWC_{50}$. The homogeneity of the zones for each method was compared using the average zone range (AZR), which is the average range in $PAWC_{50}$ of each zones that a method delineates. The apparent canopy temperature method was able to delineate accurate irrigation management zones under early (AZR = 11.3 mm) and late (AZR = 9.3 mm) drydown conditions. The NDVI method performed best under late drydown conditions (AZR = 9.3 mm) but provided poor results under early drydown conditions (AZR = 18 mm). The ECa method was able to delineate relatively homogenous management zones (AZR = 16 mm). The zones with the lowest AZR values exhibited the highest level of homogeneity; however, it is not clear what level of homogeneity is required to reduce variability in plant available water for optimum water use efficiency and crop production conditions. Production of higher value crops may require more accurate irrigation management zones as risk of monetary losses due to spatial soil moisture variability will be much higher. Furthermore, crop species will vary in their tolerance to drought stress, soil saturation stress, and disease pressure caused by prolonged soil saturation.

The zone delineation methods that were tested in this thesis have varying abilities and unique practical considerations. The apparent canopy temperature method provides the most promising results for delineating irrigation management zones; however, this method was also found to have technical challenges due to longer flight times and the potential for cloud cover inference. The NDVI method has a limited ability to delineate irrigation management zones under early drydown conditions and improves greatly under late drydown conditions. The zones delineated from the NDVI data acquired from Landsat8 and Sentinel-2 Satellites exhibited less homogeneous management zones relative to the UAV platform due to the lower resolution of the satellite bands. The accessibility of 10 m resolution Sentinel-2 data is an important advantage for the NDVI plant response method. Existing satellite-based NDVI data has a large potential to be utilized for delineating irrigation management zones by acquiring this data from time points of known past droughts; however, the Sentinel data only goes back to 2016, where Landsat8 data goes back to the 1970s. The ECa method was able to delineate relatively accurate irrigation management zones; the main deficiencies of this method are the time-consuming instrument survey that can cause crop damage, as well as the potential for interference in the regression between ECa and $PAWC_{50}$ caused by spatial variability in soil salinity and to a lesser extent soil water content (Corwin and Lesch, 2005). However, the influence that soil salinity has on ECa measurements makes ECa mapping a reliable method for measuring spatial variability in soil salinity, which is invaluable information when remediating and irrigating saline soils (Corwin and Lesch, 2005).

Field investigations, analysis of physical soil samples, and insight from producers into sources of spatial variability in soil moisture can be valuable information to aid in selecting the appropriate data sets for delineating accurate irrigation management zones (Haghverdi et al., 2015). There are myriad unique soil landscapes and agricultural production scenarios that may benefit from variable rate irrigation; therefore, it is critical that the intricacies that lead to soil water variability in irrigated fields and how that will affect individual crop production projects are well understood when delineating irrigation management zones for the implementation of VRI.

5.2 Suggested method improvements and further research direction

From the experience gained while evaluating these zone delineation methods, several areas for potential improvement were noted.

(1) The field on which the drydown plant response method was tested exhibited poor wheat germination in a linear pattern where the seeds were germinated into thick beds of canola trash from the previous field season. This could have been avoided by harrowing the field; therefore, this method could be improved upon by providing greater focus on establishing a consistent crop.

(2) The low-resolution thermal camera that was used in this study lead to long flight durations and difficulties processing/stitching images. A higher resolution camera would decrease flight times and increase the probability of being able to complete a flight of a common 65-ha (130 acre) irrigation pivot without having intermittent cloud interference.

Another way to decrease thermal flight times would be to fly at a higher altitude. In this study there was a flight limit of 100 m due to legal restrictions; therefore, it would be advantageous to acquire a flight licence with a higher altitude restriction. Increasing flight altitude would also decrease resolution, which is unlikely decrease the performance of this method up to a resolution of a couple of meters.

(3) The strong drydown conditions that were required for the NDVI plant response method is a serious concern for this method; however, this drydown could potentially take place later in the growing season closer to when the crop reaches its maximum yield potential. This may be difficult to time because beginning the drydown too early creates a potential for reduced yields and beginning the drydown too late creates a potential for maturation/turning leaves to interfere with the relationship between the plant response methods and $PAWC_{50}$. The suboptimal field conditions and instrument parameters that were experienced in the trialling of the drydown plant response methods is a testament to the resiliency of this method; however, more research is required to determine how consistent this method will be under different environmental conditions.

(4) The ability of the NDVI method to identify spatial variability in $PAWC_{50}$ under late drydown conditions creates an opportunity to apply this method to present and historic Sentinel-2 NDVI data during drought periods, as this satellite platform was found to have adequate resolution for delineating intra-field management zones. Further research could explore utilizing this approach to delineate management zones in dry-land agricultural fields for a multitude of precision agriculture applications.

Spatial variability in the thickness of the surface aeolian sand layer was the dominant source of spatial variability in plant available water at the field site; consequently, these methods may provide different results on field with different expressions of variable soil landscapes. Further investigation into testing this drydown method on fields with a different type of soil moisture variability would help determine the resiliency of this method. Spatial variability caused by the intersection of different soil types or greater topographic influence on spatial variability in plant available water would be ideal candidates for further research. Testing the drydown method on other crop types would also help to progress this concept. Other crops that have a low potential for flower interference such as other cereal grains, beans and peas would be good candidates for further crop selection trails with the plant response method.

There are outstanding questions in the literature around the realized benefit of variable rate irrigation. More field-scale research may help provide insight into the interactions between environmental factors, degree of soil landscape variability, and unique crop production scenarios, and how these interactions affect potential for VRI to increased water use efficiency and improve crop yield and quality. There is currently very little research regarding estimating the potential benefits of VRI, with these three interacting factors in mind. A better understanding of these factors would help determine the interacting variables that would make VRI a worthwhile technology to adopt.

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APPENDIX A: NDVI REMOTE SENSING DATA COMPARISON AT DIFFERENT CROP GROWTH STAGE OF CANOLA AND WHEAT

APPENDIX A-1: NDVI plant response method in a canola field

The Normalized Difference Vegetation index (NDVI) plant response method completed in 2017 produce poor results, as NDVI exhibited a weak relationship to practical available water-holding capacity ($PAWC_{50}$) (Fig. A.1c). The cause for the poor result is likely due to interference in spectral reflectance of leaves by the canola flowers.

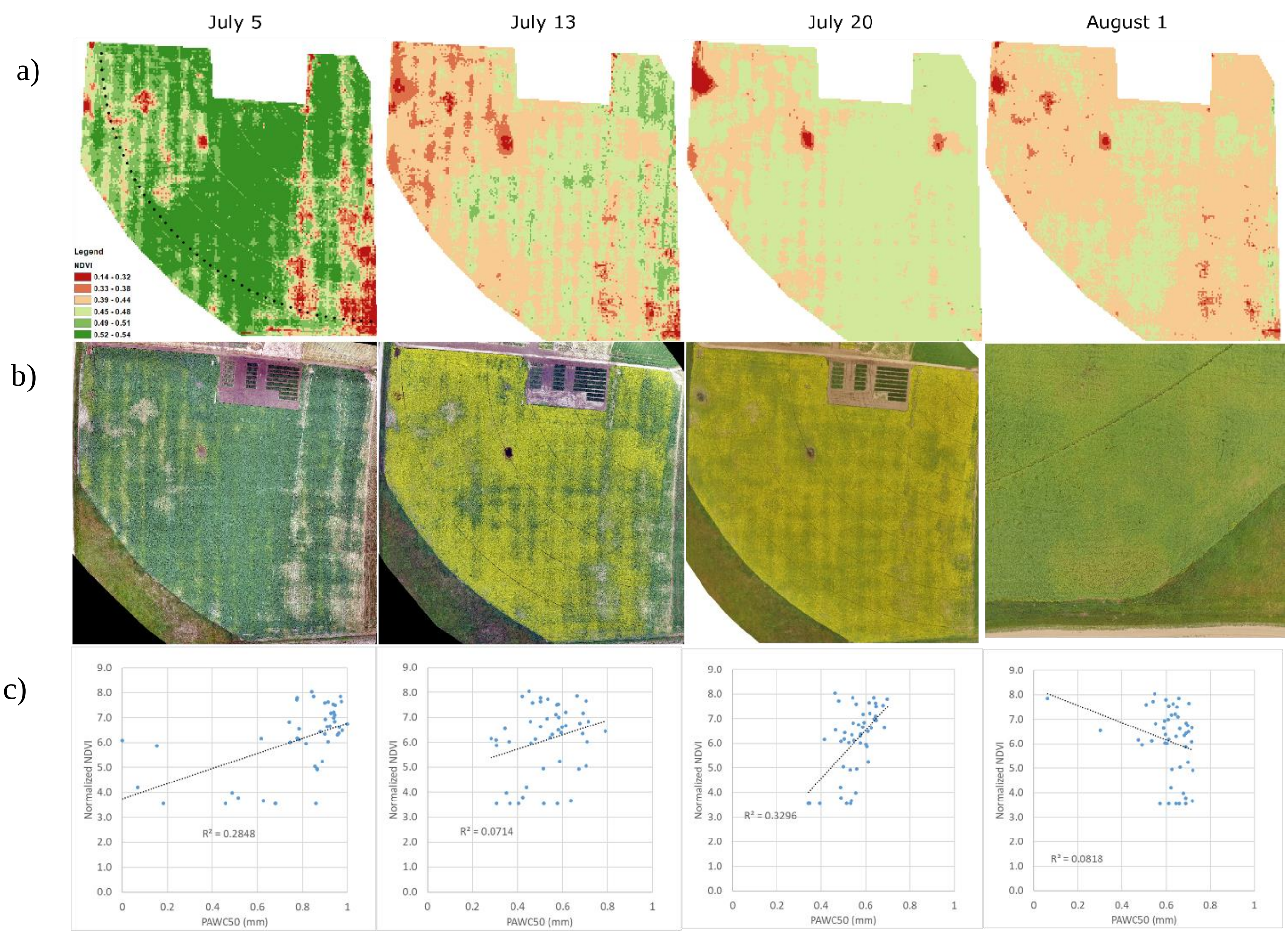

Fig. A.1 Remote sensing plant response method (NDVI) at the field site (canola) in 2017. a) Normalized difference index (NDVI), b) RGB Orth mosaic (August 1: single image), c) linear regression of $PAWC_{50}$ versus Normalized NDVI.

Appendix A-2: Timing of remote sensing data in a wheat field

The timing of plant response methods can have a large impact on their ability to identify spatial variability in $PAWC_{50}$ because crops have different leaf area index during the growing season as they transition through the life cycle. This growth progression can bring about biological changes that can affect the ability of remote sensing methods to measure plant responses to changing moisture conditions. NDVI has a stronger relationship to $PAWC_{50}$ when the wheat crop fills in (July12 , $r^2 = 0.51$; RMSE = 10.3 mm) relative to early dates (June 27; $r^2 = 0.36$; RMSE =16.2 mm), and later dates when the crop had ripened (Aug 23; $r^2 = 0.10$; RMSE =14.1 mm); indicating that NDVI plant response data provides the best results from a mature photoactive crop canopy (Fig. A.2c).

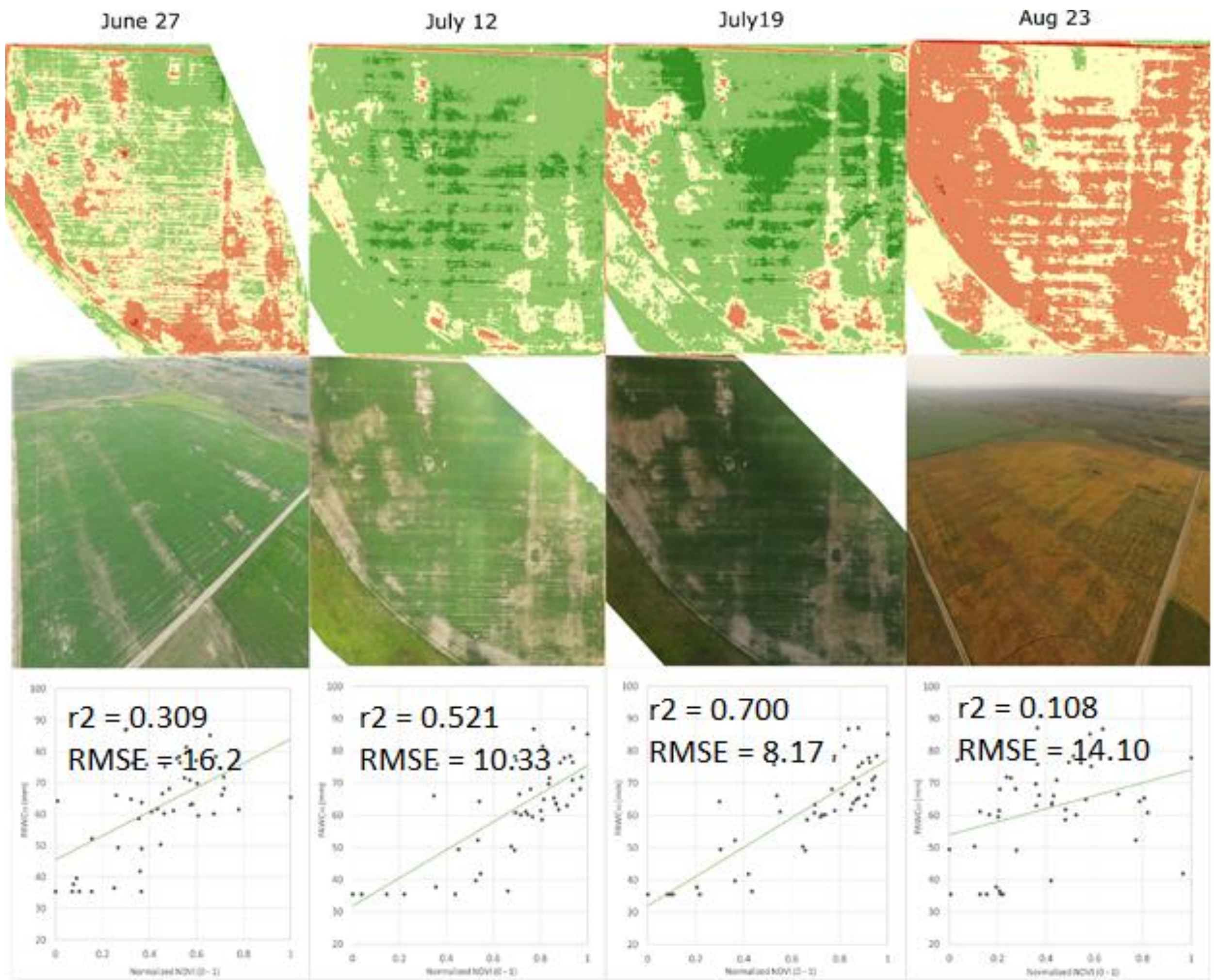

Fig. A.2 Remote sensing plant response method at the field sites (wheat) in 2018. a) Normalized difference index (NDVI), b) RGB Orth mosaic (June 27 and August 23: single image), c) linear regression of $PAWC_{50}$ versus Normalized NDVI.

In the early growing season, germination was stunted due to thick linear layers of canola trash, which contributed to a fragmented crop cover that is apparent in the June 27 remote sensing data (Fig. A.2a). These spots appeared to have been mostly filled in by the crop on July 12 images (Fig. A.2a). Early growing season NDVI data may have provided better results under more consistent germination conditions. A poor relationship between NDVI and $PAWC_{50}$ was observed on August 23 because the wheat field was partially matured and ceasing photosynthetic activity. Mature wheat leaves have low chlorophyll content, which diminishes the relationship between NDVI and $PAWC_{50}$ due to changing red and NIR reflectance interactions of the ripened leaves (Tucker, 1979). The best times to utilize the NDVI plant response method to delineate management zones is when the crop is in the peak growing season when the crop is filled in and photosynthetic activity is high. This method has less potential to be utilized during the early growing season as well as once the crop has ripened.

APPENDIX B: SAMPLING LOCATION TRANSECT SOIL CLASSIFICATION SURVEY

Table B.1 Basic profile descriptions using the Canadian System of Soil Classification for the 48-sampling locations at the field site.

Sampling Location	Horizon	Depth	Hand Texture	Colour (moist)	Effervescence (0-3)	Slope Position
1	Ap	0-10	Lsa	10YR 3/2	0	Level
	Ah	10-26	SaL	10YR 2/2	1	
	Bmk	26-53	SaL	10YR 4/3	3	
	ICk	53-78	CL	10YR 5/2	3	
	IICk	78-110+	Sa	10YR 4/2	3	
2	Ap	0-13	Lsa	10YR 4/2	0	Level
	Ah	13-22	SaL	10YR 3/2	1	
	Bm	22-53	SaL	10YR 4/1	2	
	Ck	53 - ?	LSa	10YR 5/2	3	
3	Apk	0-16	LSa	10YR 3/2	1	Level
	Ahk	16-27	SaCL	10YR 2/1	1	
	Bmk	27-55	SaCL	10YR 4/3	2	
	Ck	55-126+	SaCL	10YR 5/2	3	
4	Ap	0-14	SaL	10YR 3/2	0.5	Backslope
	Ahk	14-29	SaCL	10YR 2/2	1	
	Bmk	29-50	SaCL	10YR 4/3	3	
	Ck	50-110	SaL	10YR 4/2	3	
	Ck	110-120+	C	10YR 4/2	3	
5	Ap	0-32	Sa	10YR 3/2	0	Depression
	Ah	32-42	CL	10YR 3/1	0	
	Bm	42-74	SaCL	10YR 3/2	1	
	Ck	74-120+	SaL	10YR 4/2	3	
6	Ap	0-20	SaL	10YR 3/2	0	Backslope
	C	20-35	Sa	10YR 4/2	0	
	Abk	35-50	SaCL	10YR 2/2	2	
	Bmbk	50-90	CL	10YR 3/3	2	
	Ck	90-120	CL	10YR 4/3	3	
7	C	0-51	Sa	10YR 4/3	0	Backslope
	Ahb	51-69	CL-SaCL	10YR 2/1	1	
	Bmkb	69-103	CL	10YR 4/3	2	
	ICkb	103-130+	CL	10YR 5/2	3	
8	C	0-77	Sa	10YR 4/3	0	
	Abk	77-95	CL-SaCL	10YR 2/1	1	
	Bmbk	95-130	CL-SaCL	10YR 3/3	1	

(Continued on next page)

Table B.1 - continued

Sampling Location	horizon	depth	Hand Texture	colour (moist)	Effervescence (0-3)	Slope Position
9	C	0-67	Sa	10YR 4/3	0	Level
	Ahbk	67-82	SaCL	10YR 2/1	1	
	Bmbk	82-108	SaCL	10YR 3/3	2	
	Ck	108-120	SaCL	10YR 4/3	3	
10	C	0-58	Sa	10YR 5/3	0.5	
	Ahk	58-82	CL	10YR 2/1	1	
	Bmkb	82-110	CL	10YR 3/3	2	
	Ckb	110-135+	CL	10YR 4/3	3	
11	C	0-36	Sa	10YR 4/3	0	Level
	Abk	36-45	CL	10YR 3/2	1	
	Bmk	45-90	CL	10YR 4/3	2	
	ICkb	90-120	SaCL	10YR 5/3	3	
	IICkb	120-130+	SaCL	10YR 5/2	3+	
12	C	0-27	Sa	10YR 4/3	0	Level
	Ahb	27-34	CL	10YR 2/2	1	
	Bmbk	34-87	CL	10YR 3/3	2	
	Ck	87-125	CL-C	10YR 5/3	3	
13	C	0-26	Sa	10YR 4/3	0	Level
	Abhk	26-36	CL	10YR 2/1	1	
	Bmkb	36-76	CL	10YR 3/3	2	
	Ckb	76-110+	SaCL	10YR 4/2	3	
14	Ap	0-28	Sa	10YR 3/2	0	
	Ah	28-43	CL	10YR 3/1	1	
	Bmk	43-85	CL	10YR 3/2	2	
	Ck	120+	CL	10YR 4/2	3	
15	C	0-36	Sa	10YR 4/3	0	Level
	Abhk	36-48	CL	10YR 2/2	1	
	Bmkb	48-80	CL	10YR 4/3	1	
	Cbk	80-115+	SaCL	10YR 5/3	3	
16	C	0-28	Sa	10YR 4/3	0	Level
	Ahb	28-40	CL-SiCL	10YR 2/2	0.2	
	Bmbk	40-81	CL	10YR 3/3	1	
	Ck	81-115+	SaCL	10YR 4/3	2	
17	C	0-21	SA	10YR 4/3	0	Level
	Ahbk	21-37	CL	10YR 2/1	1	
	Bmkb	37-70	CL	10YR 3/3	1	
	Ckb	70-120+	SaCL-SaC	10YR 5/3	2	

(Continued on next page)

Table B.1 - continued

Sampling Location	horizon	depth	Hand Texture	colour (moist)	Effervescence (0-3)	Slope Position
18	C	0-19	Sa	10YR 4/3	0	Level
	Ahkb	19-30	CL-SiCL	10YR 3/2	0.5	
	Bmbk	30-50	CL-SiCL	10YR 3/3	1	
	ICkb	50-90	SaL	10YR 4/3	2	
	IICkb	90-?	C	10YR 4/2	2	
19	C	0-15	Sa	10YR 4/3	0	Backslope
	Ahbk	15-21	SaCL	10YR 3/2	0.5	
	Bmkb	21-50	CL	10YR 3/3	2	
	ICk	50-98	SaCL	10YR 4/3	3	
	IICk	98-130+	SaC	10YR 4/3	3	
20	Ap	0-22	SaL	10YR 3/2	0	Level
	Bmk	22-56	SaCL	10YR 4/3	1	
	ICk	56-100	LSa	10YR 5/3	2.5	
	IICk	100-120	SaC	10YR 4/2	2	
21	Ap	0-17	SaL	10YR 3/2	0	Level
	Ahkb	17-29	CL	10YR 2/2	1	
	Bmk	29-51	CL	10YR 4/4	2	
	ICkb	51-82	LSa	10YR 4/3	3	
	IICkb	82-120+	C	10YR 4/2	3	
22	Ap	0-8	LsSa	10YR 3/2	0	Level
	Ahbk	8-17	Sa	10YR 3/2	0.5	
	Bmkb	17-40	SaC	10YR 3/3	1	
	ICkb	40-77	SaL	10YR 4/3	2	
	IICkb	77-110	SaC	10YR 4/2	2	
23	Ahp	0-18	SaL	10YR 3/2	0	Level
	Bmk	18-37	CL	10YR 3/3	1	
	ICk	37-63	SaL	10YR 4/3	2	
	IICk	63-115	C	10YR 3/2	2	
24	Ap	0-18	SaL	10YR 3/2	0	Level
	Bm	18-44	SaCL	10YR 3/3	1	
	ICk	44-95	SaL	10YR 4/2	2	
	IICk	95-115+	SaC	10YR 3/2	2	
25	Ap	0-12	SaL	10YR 3/2	0	Level
	B	12-57	SaCL	10YR 3/3	1	
	ICk	57-94	SaL	10YR 4/3	2	
	IICk	94-115	SaC	10YR 4/2	2	

(Continued on next page)

Table B.1 - continued

Sampling Location	horizon	depth	Hand Texture	colour (moist)	Effervescence (0-3)	Slope Position
26	Ap	0-30	LSa	10YR 4/3	0	Level
	Ah	30-40	CL	10YR 3/1	0	
	Bm	40-80	CL	10YR 4/3	2	
	Ick	80-118	SaL	10YR 4/3	3	
	IICk	118-128	SaC	10YR 4/2	3	
27	Ap	0-11	LSa	10YR 3/2		Level
	Ah	11-18	SaCL	10YR 2/1		
	Bm	18-61	CL-C	10YR 4/2		
	C	61-110+	SaCL	10YR 4/3		
28	Cp	0-23	LSa	10YR 4/2	0	Backslope
	Ahb	23-34	CL	10YR 2/1	1	
	Bmk	34-68	SaCL	10YR 3/2	2	
	C	68-115	SaL	10YR 4/2	0	
29	C	0-32	Lca	10YR 4/2	0	Level
	Ahb	32-43	CL	10YR 3/2	1	
	Bmbk	43-70	CL	10YR 4/3	3	
	C	70-115	SaL	10YR 4/2	0	
30	Ap	0-25	SaL	10YR 3/2	1	Level
	Bm	25-50	CL	10YR 3/2	1	
	Ck	Dec-50	Lsa-SaL	10YR 4/2	3	
31	Ap	0-18	SaL-SaCL	10YR 3/1	0	Level
	Bm	18-54	CL	10YR 3/2	1	
	ICk	54-120	SaL	10YR 4/2	3	
	IIC	120-121+	C	10YR 4/2	0	
32	Ap	0-10	SaL	10YR 3/1	0	Backslope
	Bm	10-56	SaCL-CL	10YR 3/2	0	
	k	56-118	SaL	10YR 4/2	3	
33	Ap	0-10	SaL	10YR 3/1	0	Level
	Bm	10-42	CL	10YR 3/2	1	
	Ick	42-76	SaCL	10YR 5/2	3.5	
	IICk	76-120	SaL	10YR 5/3	3	
	IICk	120-123+	C	10YR 5/3	3	
34	Ap	0-12	SaL	10YR 3/2	0	Midslope
	Bm	12-46	SaCL	10YR 4/3	1	
	Ck	46-120+	SaL	10YR 4/2	3	
35	Ap	0-27	SaL	10YR 3/2		Level
	Bm	27-83	SaCL	10YR 4/3		
	IC	83-106	SaL	10YR 4/2		
	IIC	106-124+	C	10YR 4/2		

(Continued on next page)

Table B.1 - continued

Sampling Location	horizon	depth	Hand Texture	colour (moist)	Effervescence (0-3)	Slope Position
36	C	0-23	Sa	10YR 5/3		Level
	Ahb	23-33	CL	10YR 3/1		
	Bmb	33-62	CL	10YR 4/3		
	IC	62-94	SaL	10YR 4/2		
	IIC	94-123+	SiC	10YR 4/2		
37	C	0-21	Sa	10YR 4/2	0	Level
	Ahb	21-32	CL	10YR 3/1	0	
	Bmb	32-62	CL	10YR 3/2	1	
	Ck	62-120+	SaL-Lsa	?	3	
38	C	0-37	Sa	10YR 4/2	0	Footslope
	Ahb	37-46	CL	10YR 3/1	0	
	Bmb	46-93	SaCL	10YR 3/2	1	
	Ck	93-115+	SaL	10YR 4/2	3	
39	C	0-20	Sa	10YR 4/2	0	Midslope
	Ahb	20-27	LSa	10YR 3/2	0	
	C	27-68	Sa	10YR 4/2	0	
	Ahb	68-80	CL	10YR 3/1	1	
	Bm	80-105	CL	10YR 3/2	1	
	Ck	105-120+	SaL	10YR 4/2	3	
40	C	0-80	Sa	10YR 5/2	0	Shoulder
	Ahb	80-92	CL	10YR 3/1	1	
	Bmb	92-122+	CL	10YR 3/2	1	
41	Ap	0-28	Sa	10YR 4/2	0	Shoulder
	Ah	28-36	LSa	10YR 3/2	0	
	C	36-66	Sa	10YR 5/3	0	
	Ahb	66-83	SaCL	10YR 2/1	0	
	Bmb	86-125+	SaCL	10YR 4/3	1	
42	Ap	0-25	Sa	10YR 4/2	0	Footslope
	Ah	25-38	CL	10YR 3/1	1	
	Bm	38-69	CL	10YR 4/3	1	
	Ck	69-115	Sa	10YR 5/2	2	
	Ck	115-120	C	10YR 5/3	3	
43	Ap	0-26	Sa	10YR 4/2	0	Depression
	Ah	26-37	CL	10YR 3/1	1	
	Bm	37-65	CL	10YR 3/3	1	
	Ick	65-112	SaL	10YR 4/2	3	
	IICk	112-115+	C	10YR 4/2	3	

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Table B.1 - continued

Sampling Location	horizon	depth	Hand Texture	colour (moist)	Effervescence (0-3)	Slope Position
44	Ap	0-33	Sa	10YR 4/2	0	Footslope
	Ah	33-48	SaCL	10YR 3/1	0	
	Bm	48-93	SaCL	10YR 4/3	1	
	Ck	93-126+	SaL	10YR 4/2	3	
45	Ap	0-35	Sa	10YR 4/2	0	Backslope
	C	35-51	Sa	10YR 5/2	0	
	Ah	51-58	CL	10YR 3/1	0	
	Bm	58-94	SaCL	10YR 4/3	1	
	Ck	94-102+	SaL	10YR 4/2	3	
46	C	0-45	Sa	10YR 4/2	0	Backslope
	Ahb	45-54	CL	10YR 3/1	0	
	Bmb	54-74	SaL	10YR 4/4	0	
	Ck	74-115+	LSa	10YR 5/3	3	
47	C	0-30	Sa	10YR 4/2	0	Level
	Ahb	30-43	CL	10YR 3/1	2	
	Bmbk	43-68	CL	10YR 4/3	3	
	ICk	68-120	SaL	10YR 4/2	3	
	IICk	120-121+	C	10YR 4/2	3	
48	C	0-27	Sa	10YR 4/2	0	Level
	Ahb	27-38	CL	10YR 3/2	0	
	Bmb	38-66	CL	10YR 4/2	1	
	Ick	66-110	LSa	10YR 4/2	3	
	IICk	110-120+	C	10YR 4/2	3	

Note: classification based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998).

Table B.2: Coordinates for the 48-sampling locations in coordinate system WGS 1984 UTM Zone 13N.

Sampling location	Northing	Easting	Elevation
1	360320.2691	5704089.425	518.143
2	360310.9279	5704090.929	518.057
3	360320.5603	5704082.57	518.141
4	360322.1603	5704068.454	518.184
5	360323.7398	5704049.544	517.917
6	360326.0217	5704033.942	517.849
7	360328.2032	5704022.78	518.223
8	360329.6803	5704014.308	518.547
9	360332.8457	5703999.999	518.604
10	360336.3776	5703989.667	518.513
11	360340.8489	5703977.102	518.283
12	360345.9233	5703963.717	518.037
13	360350.6181	5703952.709	517.981
14	360355.2947	5703942.046	518.116
15	360360.7068	5703930.581	518.285
16	360366.5034	5703919.448	518.332
17	360372.3867	5703909.194	518.437
18	360378.701	5703898.435	518.631
19	360385.2811	5703888.751	518.754
20	360392.439	5703878.339	518.885
21	360400.1036	5703868.407	519.051
22	360407.1149	5703859.487	519.095
23	360415.3679	5703849.722	519.164
24	360423.254	5703841.272	519.197
25	360431.6567	5703832.401	519.222
26	360440.7945	5703823.719	519.448
27	360449.8891	5703815.492	519.366
28	360459.4506	5703807.56	519.533
29	360468.1363	5703800.636	519.657
30	360477.7586	5703793.65	519.656
31	360488.0272	5703786.66	519.609
32	360498.5513	5703780.117	519.803
33	360510.1571	5703773.226	519.96
34	360520.5138	5703767.166	520.167
35	360531.2232	5703762.052	520.37
36	360542.4973	5703756.238	520.598
37	360554.2145	5703751.631	520.707
38	360564.4583	5703747.281	520.93

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Table B.2 - continued

Sampling location	Northing	Easting	Elevation
39	360576.3054	5703743.351	521.217
40	360588.1146	5703739.311	521.485
41	360599.0095	5703736.144	521.435
42	360611.985	5703732.809	521.177
43	360623.8568	5703730.286	521.117
44	360635.3395	5703728.532	521.22
45	360647.8641	5703726.497	521.416
46	360660.3178	5703725.172	521.441
47	360671.9268	5703724.219	521.316
48	360684.2403	5703723.613	521.356

APPENDIX C: ANCILLARY DATA: NEUTRON PROBE

The Neutron probe was calibrated by plotting a regression between a 15-s neutron probe count and measured soil moisture at several locations at the field site (Fig. C.1). Soil cores where collected with a hydraulic punch at 8 locations with varying available water holding capacities and divided into 0 – 10 cm, 10 – 30 cm, 30 – 50 cm, 50 – 70 cm, 70 – 90 cm, and 90 – 110 cm increment. A neutron probe access tube was installed into the cavity left behind by the core and 15-s counts were completed using the neutron probe at 20, 40, 60, 80, 100 cm increments. The samples were analysed using the gravimetric water content method and volumetric water content was calculated using bulk density values.

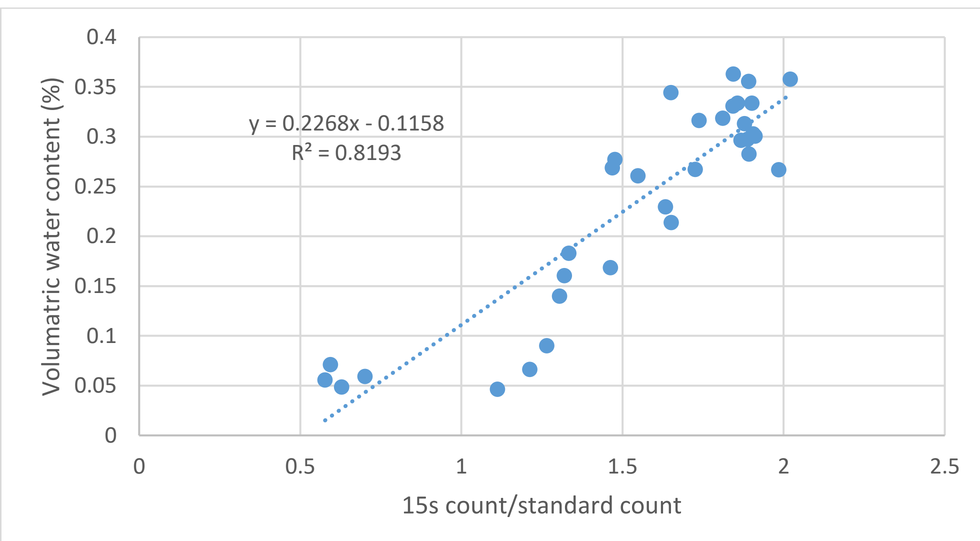
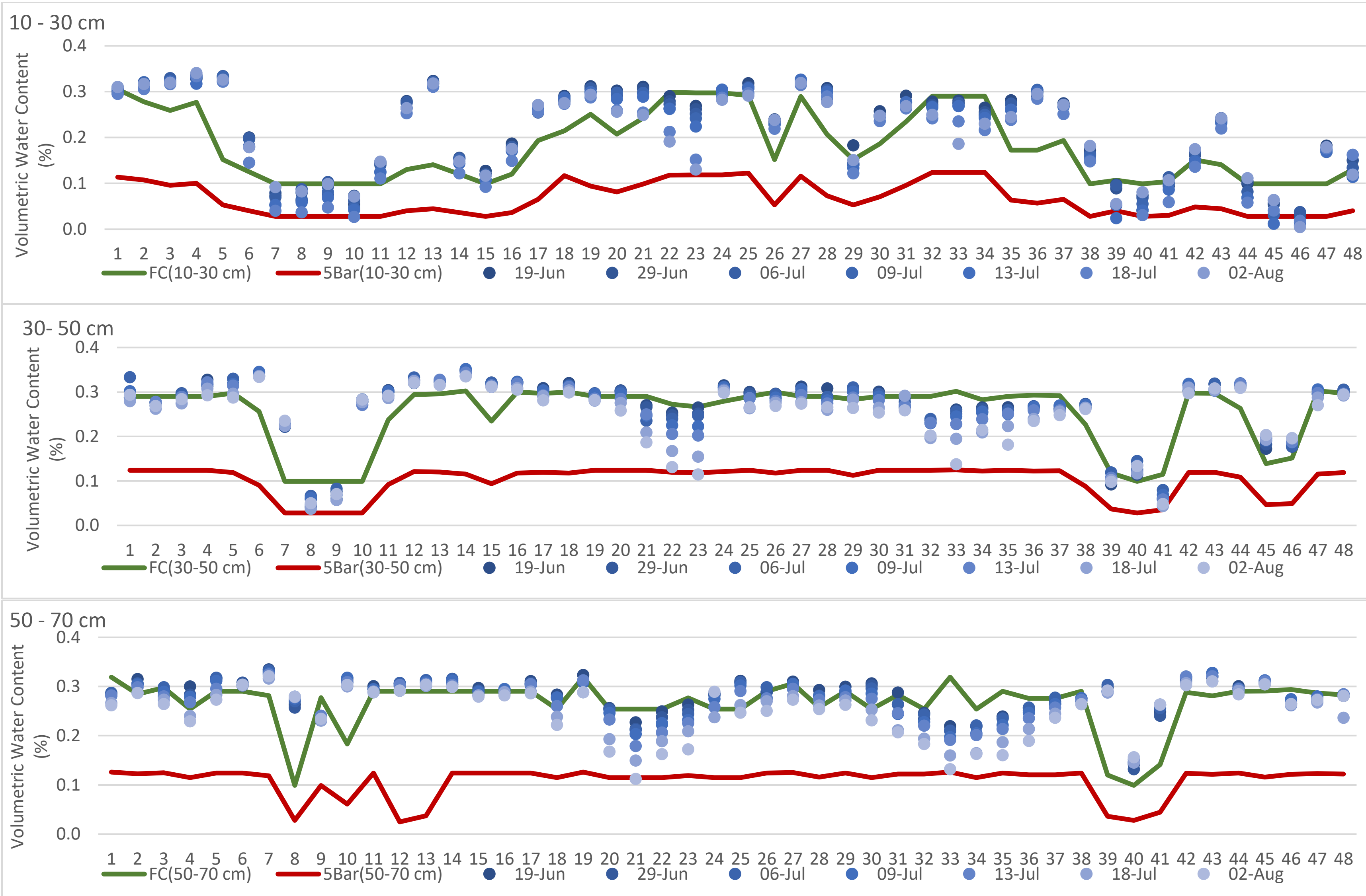


Fig. C.1: Neutron probe 15s count Calibration.


10 - 30 cm
Volumetric Water Content (%)
FC(10-30 cm)
5Bar(10-30 cm)
19-Jun
29-Jun
06-Jul
09-Jul
13-Jul
18-Jul
02-Aug
30- 50 cm
Volumetric Water Content (%)
FC(30-50 cm)
5Bar(30-50 cm)
50 - 70 cm
Volumetric Water Content (%)
FC(50-70 cm)
5Bar(50-70 cm)

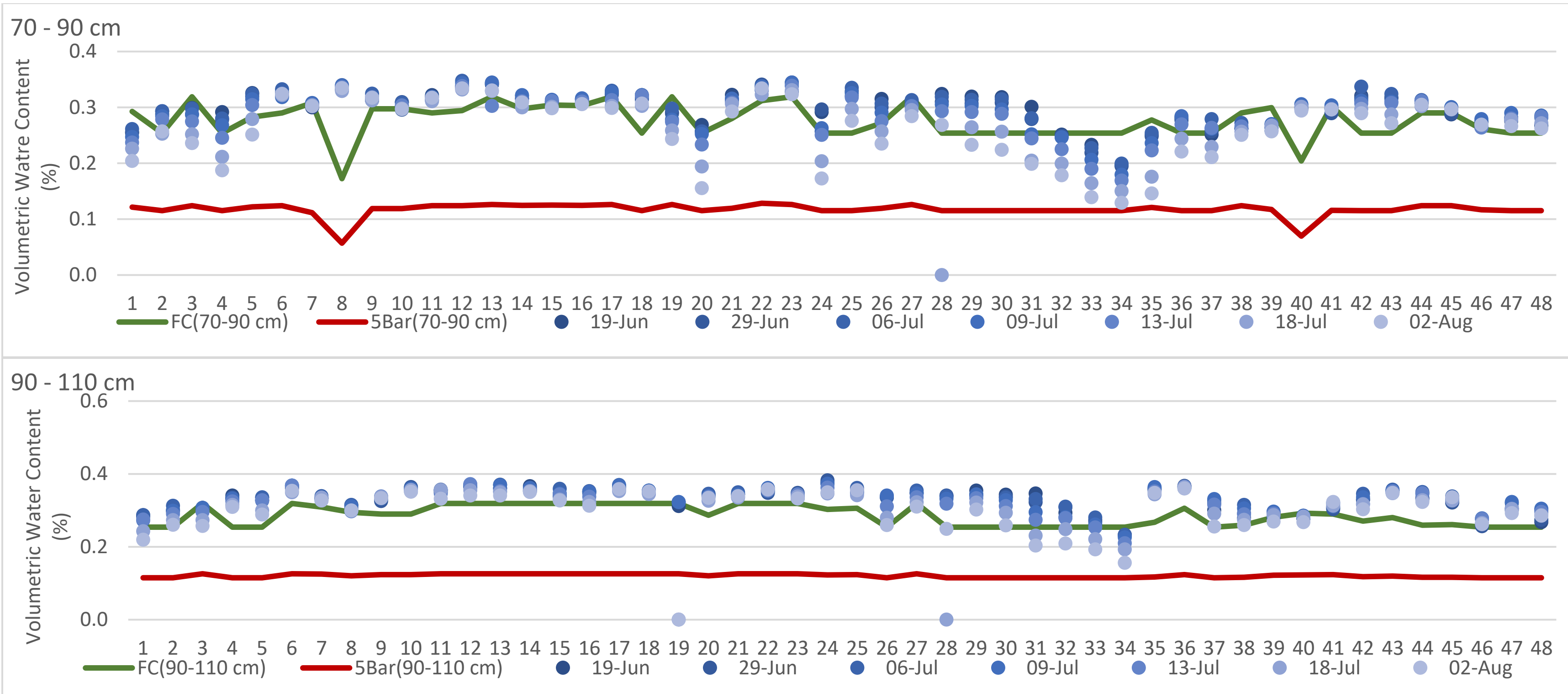


Fig. C.2 Neutron probe data from the 48-sampling locations in 20 cm increments from July 19 to August 2, 2018.