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Beneficial Effect of Injected Air into Subsurface Drip Irrigation (SDI) on Plant Growth Using Runoff from a Feedlot

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BENEFICIAL EFFECT OF INJECTED AIR INTO SUBSURFACE DRIP IRRIGATION (SDI) ON PLANT GROWTH USING RUNOFF FROM A FEEDLOT

by

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Due to water scarcity and increasing food demand, nonconventional water sources (e.g., human and animal wastewater) represent a valuable alternative to traditional water resources for agricultural use. Among these alternatives, treated animal wastewater, particularly feedlot runoff may represent a valuable solution in states like Nebraska due to its abundance. Subsurface drip irrigation (SDI) is a low-pressure micro-irrigation system that delivers water to the crop root zone through buried drip tapes with embedded emitters at fixed intervals. Despite multiple advantages (great water application uniformity, high water use efficiency, and improve fertilizer application), SDI can lead to poor aeration in the rhizosphere while applying water as drops. Therefore, to prevent these low levels of oxygen, injected air into SDI has been applied during the past twenty years. Aerated SDI has also been used to increase the crop yield, its quality, weight, and dimensions, as well as the dimensions of the roots. However, to the best of my knowledge, no other studies have been conducted using treated wastewater (e.g., feedlot runoff) to grow crops in the presence of SDI coupled with air-injection.

This study evaluated the effect of irrigation with feedlot runoff into air-injected SDI on 1) soil properties (e.g., water content, oxygen, etc.) and 2) corn (*Zea mays*) and sugar beets (*Beta vulgaris*) production.

The soil oxygen increased with air injection and the soil moisture content increased during the multiple irrigation events. Injected air significantly increased soil oxygen. The aerated zone at 45 cm contained the same and/or even greater amount of soil oxygen that non-aerated zone at 25 cm depth. The soil moisture content was lower in the aerated zones compared to the non-aerated zones. The impact of injected air on the growth of the two crops was no statistically significant. This may be related to the limited number of crops manually harvested and investigated. Injected air enhanced the yield of the two crops. Corn yields were 7.7 ± 0.9 Mg/ha and 7.3 ± 1.0 Mg/ha with and without air injection respectively. A 5.50 % yield increase was achieved using injected air. Sugar beet yields were 54.23 ± 11.21 Mg/ha and 50.33 ± 11.65 Mg/ha with and without air injection, respectively with a 7.75 % yield increase. Sugar yield increased by 8.0 % in the presence of air injection (7.82 ± 1.61 Mg/ha with air and 7.24 ± 1.72 Mg/ha without air). Two hailstorms toward the end of the study damage the two fields and consequently negatively affected the study. These results are encouraging considering the expected increased yield after the first year.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

BENEFICIAL EFFECT OF INJECTED AIR INTO SUBSURFACE DRIP IRRIGATION (SDI) ON PLANT GROWTH USING RUNOFF FROM A FEEDLOT

1. INTRODUCTION

1.1 Water crisis and nontraditional water sources for agriculture

The world's supply of freshwater is finite and limited. Only 0.01% of the total water is readily accessible for human activity in the form of rivers and lakes (Ölmez, 2013). According to the World Health Organization (WHO), in 1995, thirty-one countries were classified as water-scarce or water-stressed, and the number would increase up to fifty-four by 2050 (WHO, 2006). An unbalanced distribution of rainfall, an increase of temperatures, an increase of extreme events (e.g., severe droughts), and a reduction in precipitation in semi-arid zones reduce the amount of available water.

While the amount of available water is decreasing, global food demand is foreseen to increase by 65% by 2025 (Alexandratos and Bruinsma, 2012) and consequently, more water for agriculture is required. Water use has been growing for more than twice the population increase (FAO, 2012). Unfortunately, 40% of the projected population increase is expected in areas already facing water scarcity (WHO, 2006). The global consumption of freshwater for agricultural irrigation is 70% and it decreases to 37% in the United States (FAO, 2012). Globally, over-irrigation and excessive expansion of agricultural lands reduce the available freshwater for human consumption. Groundwater withdrawal increased from 100–150 km^3 in 1950 to 950–1000 km^3 in 2000, making aquifer depletion a major issue (FAO, 2012).

Due to water scarcity and increasing food demand, nonconventional water sources (e.g., human and animal wastewater) represent a valuable alternative to traditional water resources for agricultural use. For example, in Israel, 70% of farming is achieved using treated wastewater (WHO, 2006), and in Jordan, this value increases to 50% (Alfarra et al., 2010). By 2006, Mexico and Egypt had over 40,000 ha of land irrigated using treated wastewater (Jiménez, 2006). In the United States, agricultural use of treated wastewater is 29% (EPA, 2012). These values reflect the public acceptance of treated wastewater for irrigation. For example, Ricart et al. investigating the usage of treated wastewater for irrigation around the world, observed that public acceptance of treated wastewater for irrigation ranges from as low as 40–50% to as high as 70–90% (Ricart et al., 2019). Dery et al. conducted a survey evaluating the perception of water reuse (human wastewater) in Arizona, and observed that irrigation of forage crops and dust control (62%) and irrigation of food crops (42%) were the most common agricultural practices for which the respondents would be willing to use nontraditional water sources (e.g., treated wastewater; Dery et al., 2019). To further improve the acceptability of recycled water in our society, the public must be informed and educated (Rock et al., 2012). Treated (human) wastewater has been adopted primarily in California (Miller, 2006; Toze, 2006), Arizona, Texas, and Florida (EPA, 2012). The annual volume of water reuse for agricultural purposes is 303,000 acre-feet per year in California and 287,000 acre-feet per year in Florida (EPA, 2012). Treated (human) wastewater has been used in California to grow lettuce, artichoke, strawberries, and grapes (Miller, 2006), and in Arizona to grow wheat, millet, barley, melons, pistachios, melons, olives, and vegetables (Cusimano et al., 2015).

The effect of treated wastewater on soil properties has been investigated during the past decade (Becerra-Castro et al. 2015; Bradford et al. 2008; Gelsomino et al. 2006; Xu et al. 2010; Wei et al., 2017). Treated wastewater has positive as well as negative effects on soil properties. Increased soil organic and consequently improved soil aggregate stability, and reduced structural degradation represents the main benefit. Soil hydraulic conductivity increases in the presence of stable aggregates (Hawke et al., 2006). Increased aggregate stability improves the movement of air and water within the soil and consequently root respiration and plant growth (Ibekwe et al., 2018). Treated wastewater from animal sources (e.g. feedlot runoff, wastewater from the slaughterhouse) can also be used for irrigational purposes. Feedlot water increases the drainage potential of the soil (Sparling et al., 2001). Churchman and Tate (1986) found that clay aggregation becomes stronger with feedlot water. Feedlot water contains compounds such as (Nitrate-nitrogen (NO_3^--N), ammonium-nitrogen (NH_4^+-N), total phosphorous, soluble phosphorous, sulfate-sulfur (SO_4^{2-}-S), nitrite-nitrogen (NO_2^--N), calcium (Ca^{2+}), and magnesium (Mg^{2+}) (Gilbertson and Nienaber, 1973; Woodbury et al., 2003; Bradford et al., 2008; Edwards et al., 1985; Olson et al., 2005; Sparling et al., 2001; D'Alessio et al., 2019) that can serve as nutrients for the plant growth and can reduce the use of synthetic fertilizer (Becerra-Castro et al., 2015).

Negative effects related to the application of recycled water on crops and soil properties are related to the presence of heavy metals (e.g., mercury (Hg), cadmium (Cd), lead (Pb), cobalt (Co), manganese (Mn), and selenium (Se)) (Khan et al., 2008), and organic compounds (e.g., chemicals of environmental concern (CECs – antibiotics and hormones) (D'Alessio et al., 2019; Khan et al., 2008; Sim et al., 2011; Wei et al., 2016). Intake of heavy metals such as Zn, Cu, and Mn into lettuce and onion were observed (Kalavrouziotis et al., 2005). For example, Kalavrouziotis et al. reported the intake of iron (Fe) in the roots, nickel (Ni), Co, and Pb in the leaves of broccoli and Brussels sprout (Kalavrouziotis et al., 2008). Concentrations of Cd, chromium (Cr), were observed in radish, corn, mustard, wild cabbage, and lettuce (Khan et al., 2008). Also, due to the application of treated wastewater, oxidized Arsenic (V) may become reduced Arsenic (III) in water which is 25-60 times more toxic to humans than Arsenic (V) (Malakar et al., 2019). Long term application of feedlot water can also cause accumulation of CECs in soil (Borgman et al., 2013; Boxall et al., 2006; D'Alessio et al., 2020, 2019; Malakar et al., 2019) and crops (Boxall et al., 2006; Christou et al., 2019; D'Alessio et al., 2020; Wu et al., 2015). In addition to metals and CECs, treated wastewater contains inorganic cations such as sodium (Na^+), potassium (K^+), Mg^{2+}, and Ca^{2+}. High levels of these cations increase the salinity of the treated wastewater and consequently increase the soil dispersion, reduce the soil aggregate formation, the infiltration rate (Malakar et al., 2019), the plant growth, and the crop productivity (Becerra-Castro et al., 2015).

1.2 Subsurface drip irrigation and air injection

Subsurface drip irrigation (SDI) is a low-pressure micro-irrigation system that delivers water and nutrients to the crop root zone through buried polyethylene drip tapes with embedded emitters at fixed intervals. The dripline space and depth are determined by the soil type, tilling, and cultural practices. The interest in SDI increased due to the reduction of water resources and the emergence of needs for water conservation. This method is a suitable method for irrigation using treated wastewater (human and animal). An SDI system usually include 1) a pump to distribute water from the water supply to the crops, 2) a backflow preventer to prevent the contamination of the water supply from backflow of chemicals, 3) a flow meter to measure the volume of water flowing through the system, 4) a chemical injection system to add fertilizer(s) and/or other chemicals to the irrigation water, 5) a filtration system to prevent the clogging of tapes and emitters, 6) a mainline to deliver water from the pump station to the driplines, 7) a zone valve to control the delivery of water to the crops, 8) one or more pressure regulators depending on the size of the field to regulate the pressure downstream from the pump station to the crops, 9) pressure gauges to monitor the inlet and outlet pressure of the filter system and 10) drip lines to deliver water to the crops. As water delivers through buried driplines and emitters that are smaller in size, it is crucial to prevent the physical and biological clogging of tapes and emitters (Liu and Huang, 2009). Sand, screen, and disk filters are the most common filters used with SDI systems to prevent dripline and emitter clogging from the solid particles in the water.

SDI has many advantages over traditional irrigation methods (e.g., furrow and sprinkler irrigation). For example, with a proper arrangement of drip tapes, SDI can deliver water to fields having different sizes and shapes, unlike sprinkler irrigation which has limited movement ability (O'Brien et al., 1998). SDI has higher water use efficiency compared to the sprinkler (Dhungel et al., 2012) and furrow (Smith et al., 2005) irrigation methods. SDI has higher water application uniformity (Ayars et al., 2015), limited loss of water and nutrients due to better control of the application of water (Ayars et al., 1999), and a better spread of water due to lateral movement water (Hanson and May 2004) than furrow and sprinkler irrigations. SDI has fewer mechanized parts comparing to sprinkler irrigation and since most of the components are made out of plastic, the corrosion is less (Aguilar et al., 2015). Due to its ability to efficiently apply water and nutrients (Camp et al., 2000; Ayars et al., 2015), it represents a preferable option for applying fertilizer (fertigation) and chemicals (chemigation) to the crops. SDI prevents the negative effect associated with wind and rain and reduces human contact with used agrochemicals (Ayars et al., 2015; Camp, 2000; Lamm, 2002; Vyrlas et al., 2014).

The high initial cost (system + installation) represents the main disadvantage related to SDI. The net profit of SDI depends on the price of the crop and the lifetime of the system. However, in the presence of large fields (e.g. 65 ha vs. 26 ha), a sprinkler irrigation system could generate more profit than an SDI system (O'Brien et al, 1998). SDI delivers a small amount of water compared with furrow and sprinkler irrigation systems, therefore multiple driplines may be needed (Ayars et al., 2015). Since the drip tapes are buried into the soil, insufficient water for the topsoil and limited germination can occur (Yuan et al., 2016). SDI increases the salinity of the soil above the drip lines due to the accumulation of salt (Hanson and May 2004). Physical clogging of the drip tapes as well as of the emitters due to the presence of organic and inorganic particles in the source water represents the main reason for the failure of an SDI system (Lamm et al, 2018). This limitation may be enhanced by using treated wastewater (e.g., feedlot runoff) as source water. As the drip tapes are not visible, identifying faults such as clogged emitters, leaks, and drip tape damages may be challenging. Therefore, it is important to take precautions including the use of good filtration when using surface or treated wastewater (Camp, 2000, Lamm, et al., 2018). Acid injection (Ayars et al., 2015) and frequently flushing (Trooien et al., 2000) represent common options used to prevent clogging. Root intrusion could plug the emitters (Camp, 2000; Hanson and May 2004; Lamm et al., 2012; Lamm et al, 2018) and rodents could damage the drip tapes (Lamm, 2016; Lamm et al., 2018; Pablo et al., 2007). Having proper soil is important for installing an SDI system. SDI is not recommended in shallow soils overlaying rock as well as in coarse sand, non-bridging soil, and in the presence of undulating topography (Lamm, 2009). Fewer tillage options, fixed row spacing, difficult to rotate crops, and restricted root development occur in the SDI due to the permanent installation of the system (Aguilar et al., 2015). Cultural practices such as crops, drip line depth, and drip line spacing could limit the use of the SDI.

Drip irrigation can lead to poor aeration in the rhizosphere while applying water as drops (Dhungel et al., 2012). Oxygen is essential for plant root respiration and to generate energy. Low levels of oxygen in soil can negatively affect the crops by creating hypoxia stress (Yuan et al., 2016). Low levels of oxygen prevent the diffusion of metabolites such as carbon dioxide and ethylene which can act as growth inhibitors, reduce the nitrogen fixation, and consequently the plant growth (Goorahoo et al., 2002). Salt stress can also occur in plants due to a decrease in membrane excursion when receiving low levels of oxygen in the root zone (Ben-Noah and Friedman, 2016). As a solution, the injection of air into the water in the SDI system can attenuate this problem (Ben-Noah and Friedman, 2016; Bhattarai and Midmore, 2009; Chen et al., 2011; Dhungel et al., 2012; Pendergastet al., 2014). During the past decade, aerated SDI has been used to increase the crop yield, its quality, weight and the dimensions, as well as the dimensions of the roots (Abuarab et al., 2013; Bhattarai et al., 2004; Dhungel et al., 2012; Goorahoo et al., 2002, 2007, 2008; Huber and Midmore, 2004; Pendergastet al., 2014; Vyrlas and Kalfountzos, 2014; Yuan et al., 2016). When pressurized water enters the injector inlet, it is constricted toward the injection chamber and changes into a high-velocity jet stream. The increase in velocity through the injection chamber results in a decrease in the absolute pressure, creating a vacuum, thereby enabling air to be drawn through the suction port into the water stream. The amount of air entering the injector depends on the strength of the vacuum (Goorahoo et al., 2002).

Aerated SDI resulted in improvements in yields and overall quality of crops such as potato (Shahien et al., 2014), corn (Abuarab et al., 2013), sugar beet (Vyrlas et al., 2014), strawberry (Goorahoo, 2007; Goorahoo et al., 2008), melon (Goorahoo, 2007; Goorahoo et al., 2008), lettuce (D'Alessio., et al., 2020), tomato (Goorahoo, 2007), pineapple (Dhungel et al., 2012), cotton (Bhattarai et al., 2004; Pendergast et al., 2014), bell pepper (Goorahoo et al., 2001), soybean (Bhattarai et al., 2004), pumpkin and edamame (Bhattarai et al., 2008). The impact of aerated SDI was particularly beneficial—yield increased by approximately 40%—while growing potato (Shahien et al., 2014), bell pepper (Goorahoo et al., 2001), and edamame (Bhattarai et al., 2008). Limited beneficial impact —yield increased by 10-15%—was observed while growing radish (Vivek et al., 2015), chickpea (Bhattarai et al., 2008), pumpkin (Bhattarai et al., 2008), and cotton lint (Pendergast et al., 2014). However, none of these studies used treated wastewater to grow these crops.

1.3 Thesis objectives

Nebraska accounts for 13.5% of total irrigated agricultural lands in the USA, and it increased from 1.7 million ha in 1970 to 3.5 million ha by 2007 (Irmak et al., 2010). The High Plains Aquifer supplies irrigation water to over 8.9 million acres of Nebraska farmland (https://water.unl.edu/documents/Section%20H.pdf). Groundwater management for irrigation and human use is controlled by the State's Natural Resource Districts (NRDs). Many NRDs have prescribed pumping limits for water applications, and these limits are set in terms of an annual average pumping with no exceedance of a set value over three or five years (Yonts et al., 2018). The recent drought cycles (e.g., 2002 to 2009) have caused more water allocation restrictions (Yonts et al., 2018). Combining these restrictions with the increasing demand for food production highlights the need for possible water alternatives. Among these alternatives, treated animal wastewater, particularly feedlot runoff may represent a valuable solution due to its abundance. Nebraska is ranked number one in the United States for both cattle on feed and beef slaughtering capacity (USDA-NASS, 2017).

The goals of this thesis were to evaluate the effect of irrigation with feedlot runoff into air-injected subsurface drip irrigation (SDI) on 1) soil properties (e.g., water content, oxygen), and 2) corn (*Zea mays*) and sugar beets (*Beta vulgaris*) production.

Corn and sugar beets represent two of the most abundant crops in Nebraska (Nebraska Department of Agriculture, 2019). In 2019, Nebraska ranked third in corn for grain production (45,349,668,000 kg; Nebraska Department of Agriculture, 2019) and seventh in sugar beet production (9,796,800 kg; Nebraska Department of Agriculture, 2019). More than half of the sugar production in the United States comes from sugar beets. The Panhandle region is responsible for approximately 90% of sugar beet production in Nebraska. Nebraska is ranked first in beef and veal exports in 2018 by making over 1 billion USD (Nebraska Department of Agriculture, 2019).

To the best of my knowledge, no other studies have been conducted using treated wastewater (e.g., feedlot runoff) to grow crops in the presence of SDI coupled with air-injection. The two closest studies available used freshwater instead of treated wastewater to irrigate corn and sugar beets (Abuarab et al., 2013; Vyrlas et al., 2014). For example, Abuarab et al. investigated the beneficial impact of SDI coupled with air injection while growing corn using freshwater as irrigation water in a greenhouse set-up (Abuarab et al., 2013). Similarly, Vyrlas et al. used SDI couple with air injection for sugar beets while irrigating with freshwater (Vyrlas et al. 2014). Figure 1 represents a conceptual representation of the thesis.

A manuscript will be submitted to ASCE–Journal of Environmental Engineering.

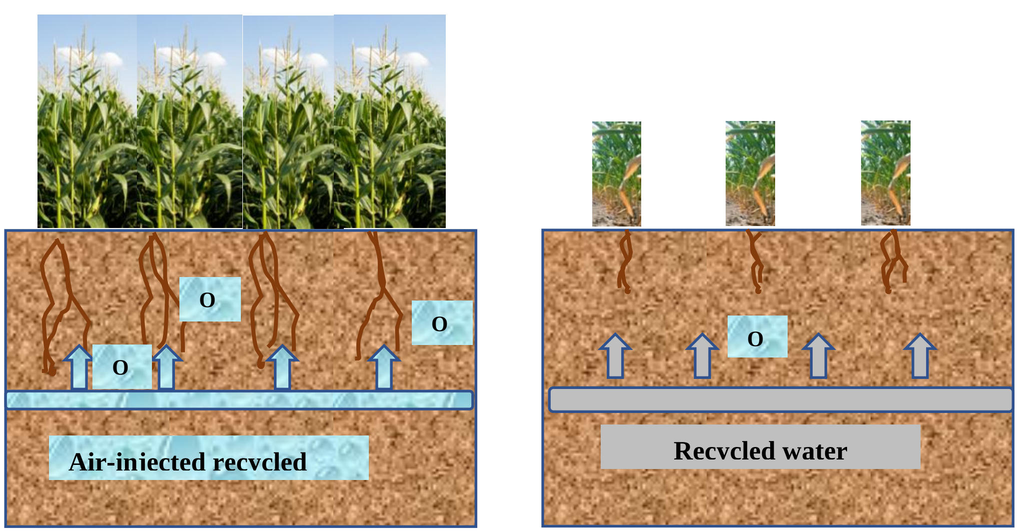


Figure 1. Schematic representation of the proposed research.

2. MATERIALS AND METHODS

2.1 Study location

The field experiment was conducted at the Mitchell Agricultural Laboratory part of the Panhandle Research and Extension Center, University of Nebraska-Lincoln, located in Scottsbluff, NE (41°57'11.5"N; 103°42'05.2"W, elevation: 1,317 m). The study area has a semi-arid/dry climate. The long-term (1981–2010) average cumulative annual precipitation was 331 mm and the average high and low temperatures are 17°C and 1.3°C (http://climod.unl.edu/). The soil of the experimental site is classified as a very fine sandy loam (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).

2.2 Experimental setup

2.2.1 Irrigation setup

The irrigation layout is shown in Figure 2A. A feedlot lagoon, approximately 350 m north of the field, served as a primary water reservoir (Figure 2B) while a freshwater lake, approximately 180 m northwest of the field, served as a secondary water reservoir. The SDI system (Figure 2C) was installed by 21st Century Water Technologies (Scottsbluff, NE, USA). The drip tapes (Rivulis D5000 PC; Rivulis, San Diego, CA, USA) (diameter: 1.6 cm) had an application rate of 0.64 liters per hour (lph). The drip tapes were placed approximately 25 cm below the soil surface. This depth was consistent with the available literature (Lamm, 2016; Sonbol et al., 2010; Vyrlas et al., 2014). In Lamm (2016), the driplines were placed between 20 to 60 cm for corn, while in Vrylas et al., they were placed between 15 (Sonbol et al., 2010) and 45 cm for sugar beets (Vyrlas., et al 2014). The emitters, along with each drip tapes, were located every 51 cm, while the tapes were placed 112 cm one from another (Figure 2D). The pump house, located approximately 700 m south of the field, included the motor (Figure 2E) and four sand filters to avoid possible clogging of the SDI tapes due to the large particles present in the feedlot water (Figure 2F).

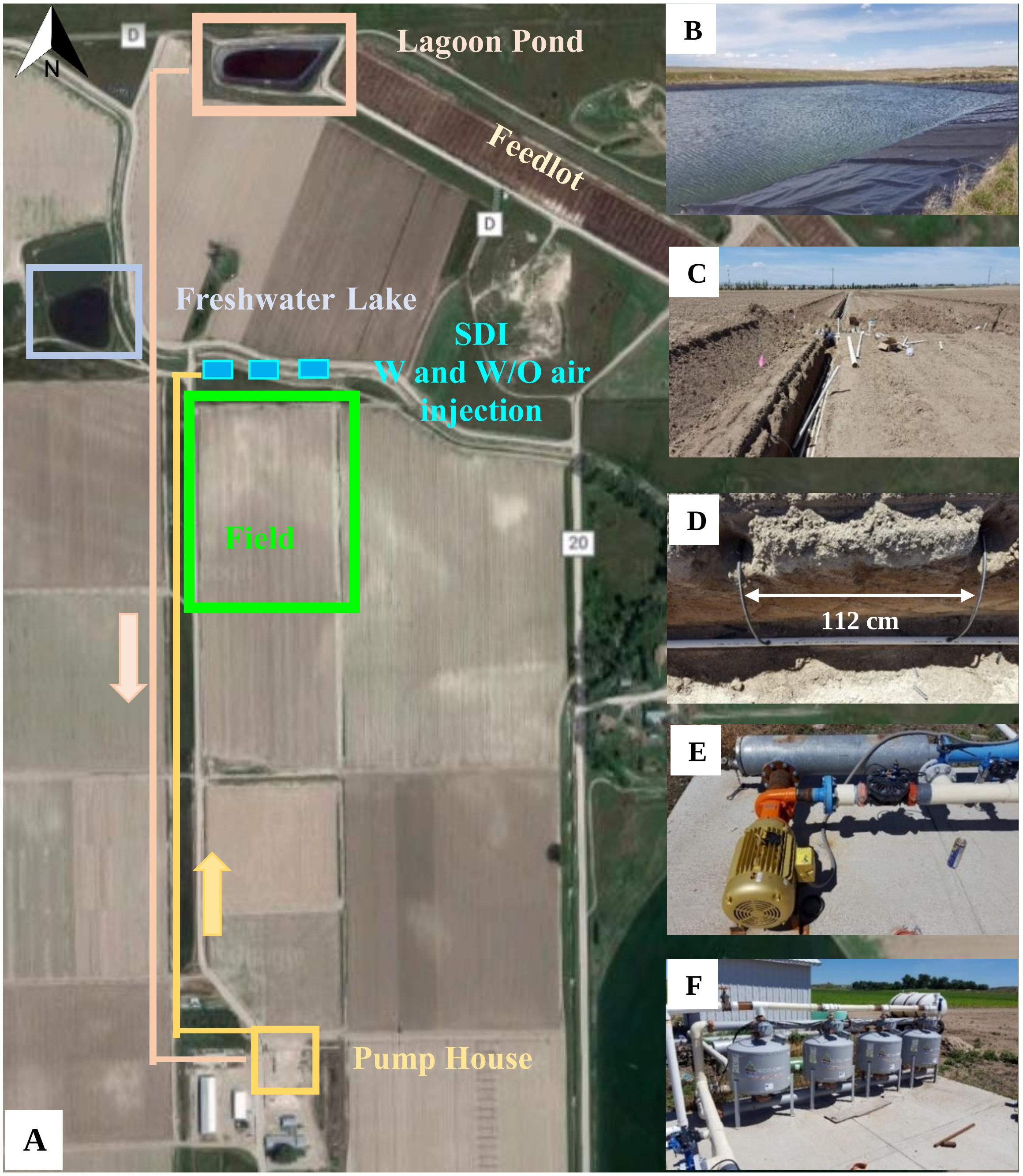


Figure 2: (A) Irrigation layout of the field, (B) lagoon pond, (C) drip line layout in the field, (D) dripline space, (E) water pump used for irrigation, and (F) sand filters for the filtration.

The water moved down from the feedlot pond to the pump house through the pipeline. After the filtration unit, the water was pumped towards the SDI air injection system in the northside of the field. After the air injection, the water was delivered through the drip tapes to the two crops.

2.2.2 Air injection

Due to the slope of the field (from north to south), the air injection system, three stations with eight air injectors at two locations and six injectors in one location, was installed at the north end of the field. The air, in the form of micro-bubbles, was delivered directly to the root system (Figure 3A). Venturi air injectors (Model A20) (Mazzei Injector Company LLC, Bakersfield, CA, USA) (Figure 3B) with an inlet pressure of 35 psi, the outlet pressure of 20 psi, an air suction rate of 88 lph (at 15ºC), and a flow rate of 1560 lph, were used to inject air into the SDI system. Caps were used for non-aerated zones (Figure 3C).

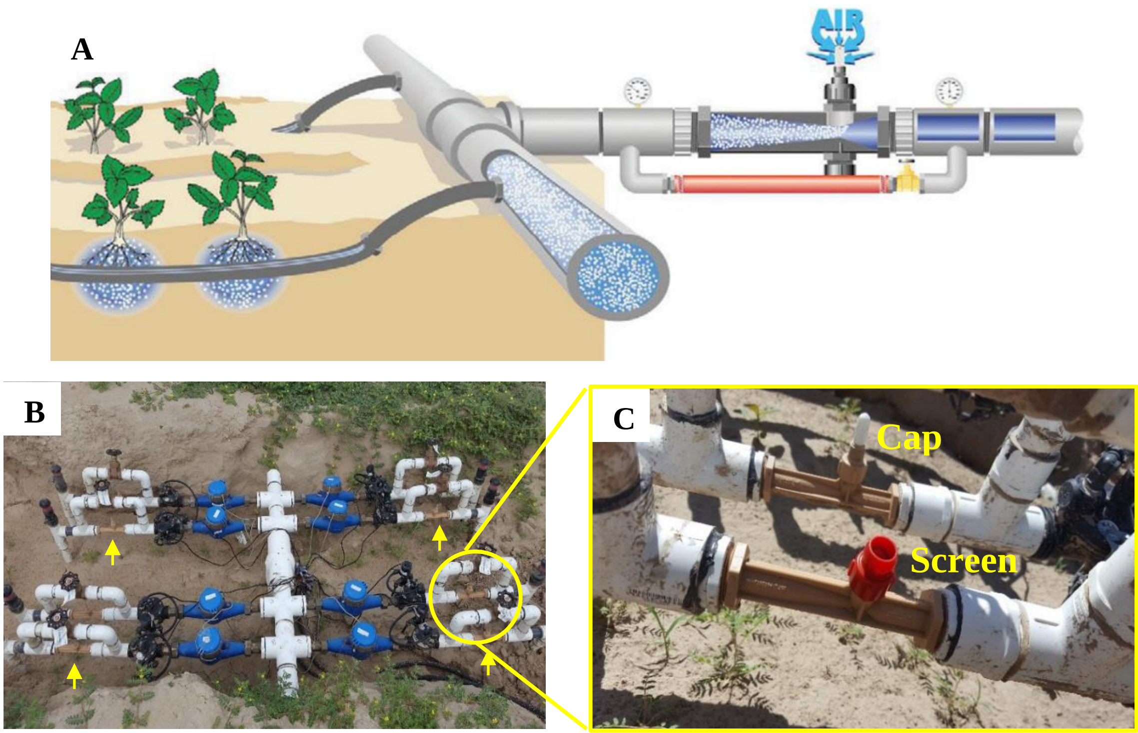


Figure 3: (A) Schematic representation of a Mazzei Air Injector (https://mazzei.net/wp-content/uploads/2019/04/2019-01_Venturi-Injectors-Make-Their-Impact_ModernPumpingToday_NoAd.pdf); (B) one of the three air injection systems used during the study. The blue circles represent the flowmeters used to measure the water rate while the yellow arrows highlight the air injectors; (C) caps were used for non-aerated zones and screens without caps were used for aerated zones to dictate the airflow.

2.2.3 Field dimensions

The experimental field (length: 183 m, width: 134 m) had a total area of 25,091 m^2. It was divided into two equal areas with corn planted on the west side and sugar beet on the east side (Figure 4A). Each area was divided into ten zones (total zones: 20). Each zone (length: 183 m, width: 7 m, and area: 1,281 m^2) was divided into twelve rows (width: 56 cm) (Figure 4B). Each zone was labeled based on the planted crop (corn vs. sugar beet) and the zone number (1 to 10). The first zone on the west side of the field was labeled as C-1 (crop: corn, zone number: 1), while the last zone on the west side of the field was labeled as C-10 (crop: corn, zone number:10). Similarly, the first zone on the east side of the field was labeled as SB-11 (crop: sugar beet, zone number: 11), while the last zone on the east side of the field was labeled as SB-20 (crop: sugar beet, zone number: 20). Corn (*Zea mays*) and sugar beet (*Beta vulgaris*) were planted on 05/16/2019 and 04/27/2019, respectively.

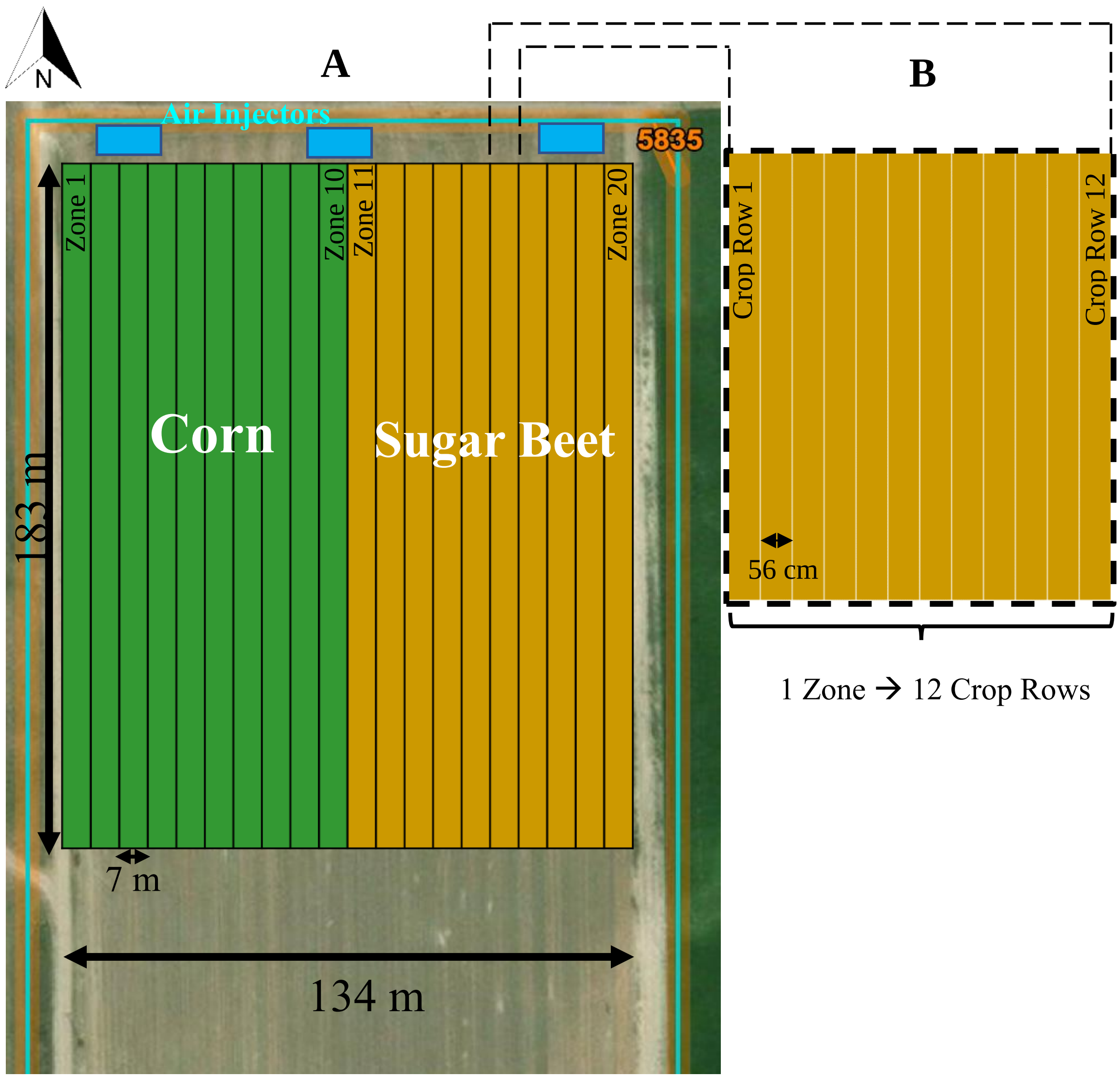


Figure 4: (A) Air injector location and dimensions of the field, and (B) dimension of the crop rows.

2.2.4 Experimental design

The experiment consisted of two treatments (with air injection or aerated and without air injection or non-aerated) replicated five times in each crop. Five zones per crop (corn: C-2, C-5, C-8, C-9, C-10; sugar beets: SB-12, SB-15, SB-18, SB-19, SB-20) were randomly selected as blocks for the air injection (Figure 5).

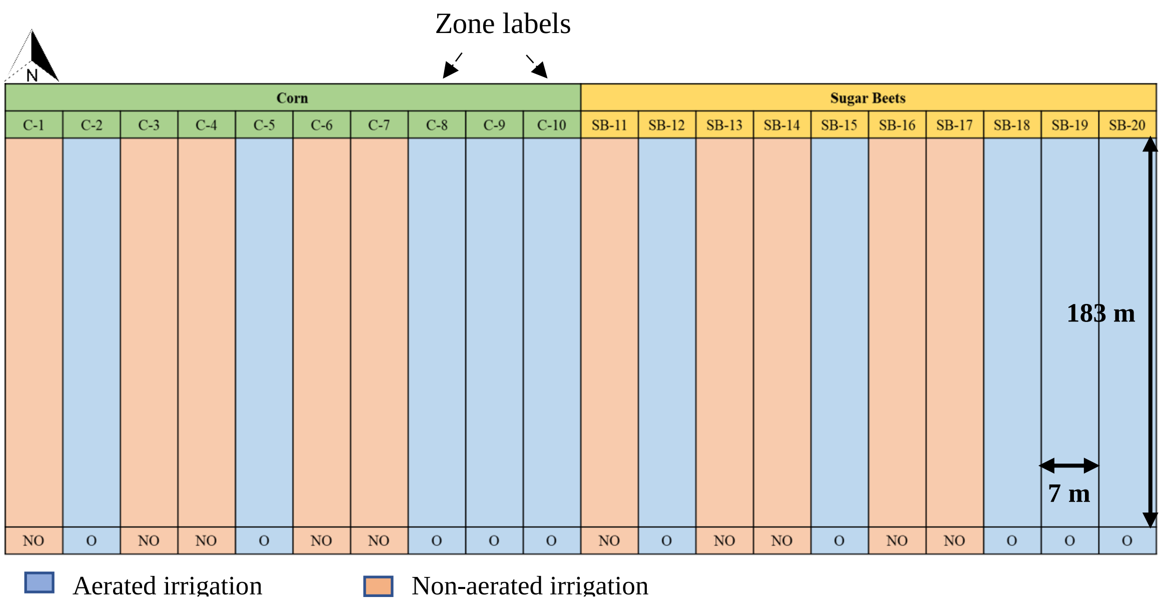


Figure 5: Treatment layout. Corn on the left and sugar beet on the right side of the field.

2.3 Sensors and field instruments

Irrometer soil solution suction access tubes (length: 30 cm; Figure 6A), also known as lysimeters (The Irrometer Company INC, Riverside, CA, USA), were used to collect soil pore water. Soil pore water was extracted using a vacuum pump (Figure 6B) and a syringe (Figure 6C), provided by the manufacturer.

Figure 6: (A) Lysimeter, (B) vacuum pump, and (C) syringe used for pore water sampling after an irrigation (https://www.certifiedmtp.com).

A total of 24 lysimeters were used during the study. Twelve lysimeters were installed in six of the zones used for growing corn (C-1, C-2, C-4, C-5, C-7, and C-8) and twelve in six of the zones used for growing sugar beet (SB-11, SB-12, SB-14, SB15, SB-17, and SB-18) (Figure 7). Two lysimeters, 30 m apart from one another, were installed in each of the selected zone 76 m and 106 m from the south end of the field (Figure 7). The lysimeters were soaked in water overnight and installed 25 cm below the soil surface (Figure 8) using a soil auger. Once the installation was completed, a small amount of soil was added to fill-up possible voids while a small amount of wet soil was added to the top to tighten up the lysimeter.

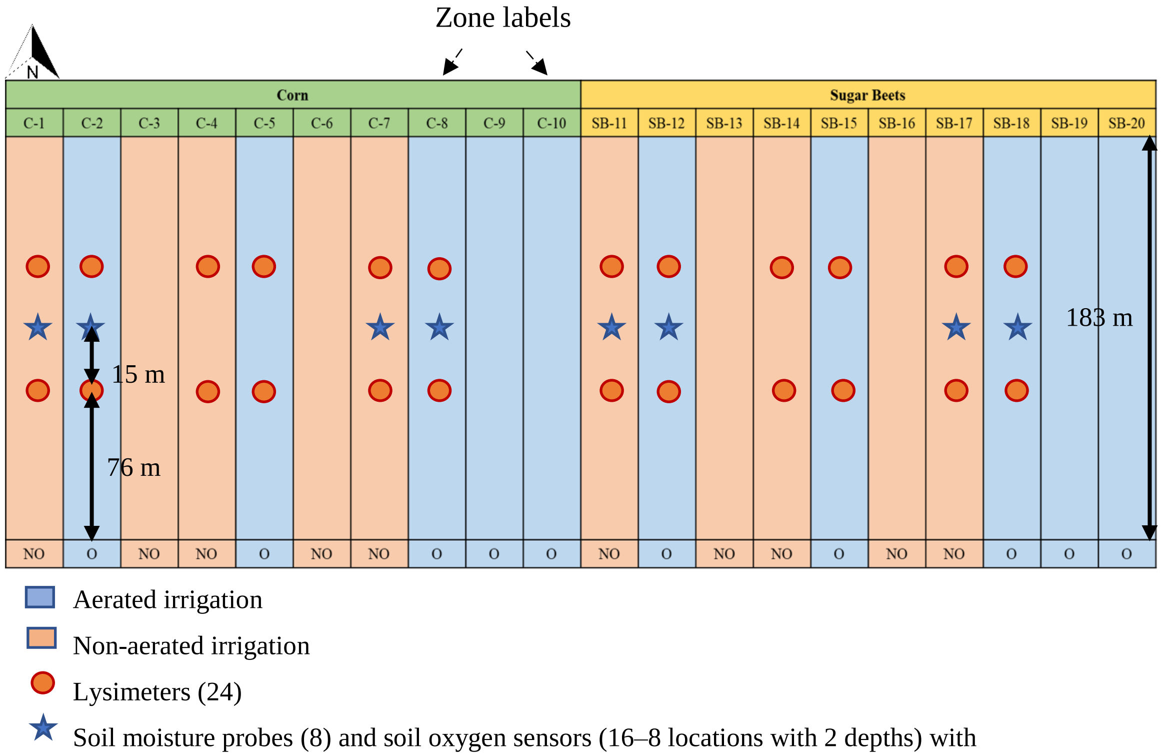


Figure 7: Layout used for sensors and field instruments in the experiment.

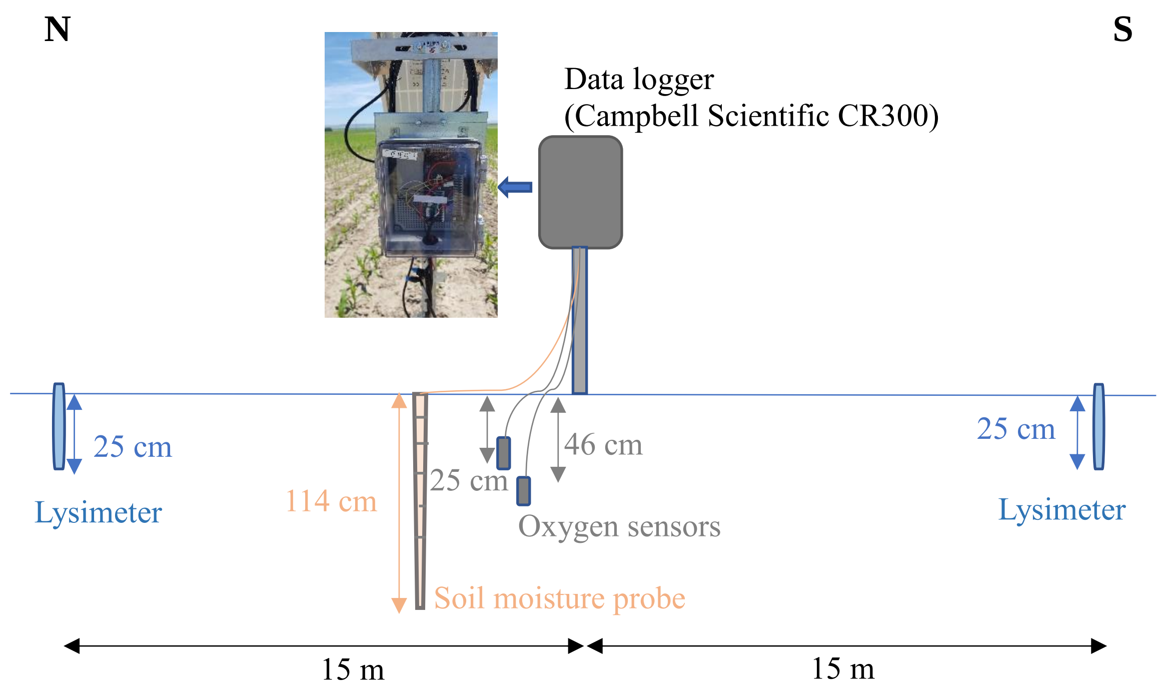


Figure 8: A cross-section of the layout of field probes.

Soil moisture sensors (length: 120 cm) (Model SDI-12, Sentek Sensor Technologies, Stepney, Australia; Figure 9) were used to measure soil moisture, soil salinity, and soil temperature at 5, 10, 15, 35, 45, 55, 65, 75, 85, 90, 105, and 115 cm below the soil surface. Eight soil moisture probes were installed using an auger and a tripod in eight selected zones (C-1, C-2, C-7, C-8, SB-11, SB-12, SB-17, SB-18) 91 m from the south end of the field (Figure 7).

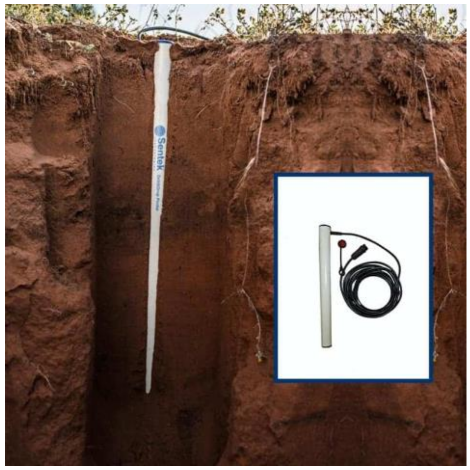


Figure 9: Soil moisture probe (https://sentektechnologies.com/product-range/soil-data-probes/drill-and-drop/) used to measure soil moisture, salinity, and soil temperature.

Soil oxygen sensors (Model 110, Apogee Instruments, Logan, UT, USA) (Figure 10) were used to measure the oxygen level in the soil at 25.4 and 45.7 cm below the soil surface (Figure 8). Sixteen oxygen sensors were installed in eight selected zones (C-1, C-2, C-7, C-8, SB-11, SB-12, SB-17, SB-18) (Figure 7).

Figure 10: Oxygen sensor (https://www.apogeeinstruments.com/oxygensensor/) used to measure soil oxygen content.

Soil moisture and soil oxygen data were collected using CR300 data loggers (Campbell Scientific, Logan, UT, USA) (Figure 11). The data logger programming code is found in Appendix A. Data were sampled every 30 seconds, five minutes-average were recorded and manually downloaded weekly.

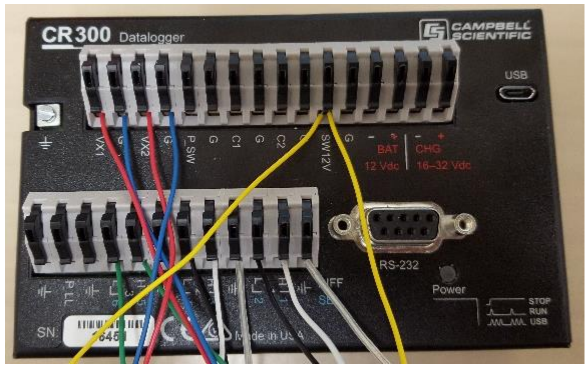


Figure 11: Campbell CR 300 data logger (https://www.campbellsci.com/cr300) was used to collect sensor data.

Each data logger was powered by a solar panel (10M-V, peak power, P_{max}: 10 W, voltage at P_{max}: 18.1 V, current at P_{max}: 0.55 A, Ameresco Solar, Tomball, TX, USA) and a 12-volt battery (Genesis NP0.8-12 12V/0.8AH Sealed Lead Acid Battery with JST Wire Terminal). The solar panel was set facing south and with a 45° angle from the horizon (Figure 12).

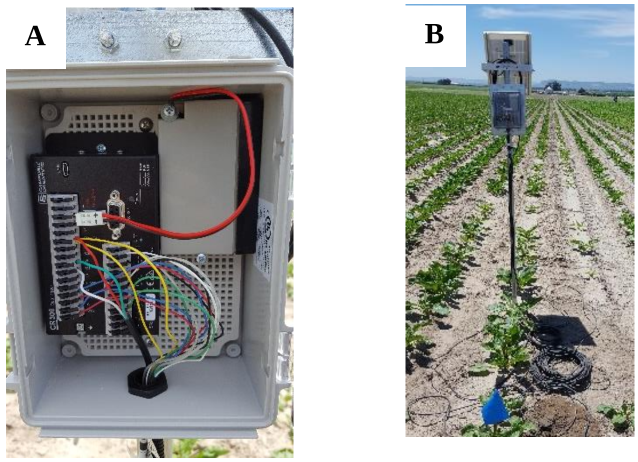


Figure 12: (A) Wired CR300 datalogger with battery, and (B) solar panel used to power the unit.

2.4 Irrigation: Time frame

Since the main pipe system was used to irrigate the surrounding fields with freshwater during the week, feedlot runoff was applied every Saturday for 20 hours. The weekly targeted amount of water for each crop was 25 mm. To provide sufficient water to the crops, two freshwaters and, one mixed (freshwater: lagoon water, 8:10) irrigation events were adopted (Table 1).

Table 1: Irrigation events, water source (lagoon water vs. freshwater vs. mixed water) used, and amount (mm) of water applied during each irrigation event.

Event	Date	Irrigation Water	Target (mm)
Test	7/16/2019	Test Run	N/A
I 1	7/19/2019	Lagoon water	27.94
I 2	7/24/2019	Freshwater	27.94
I 3	7/27/2019	Lagoon water	6.35
I 4	08/03/019	Lagoon water: Freshwater (10:8)	25.4
I 5	8/7/2019	Freshwater	6.35
I 6	8/10/2019	Lagoon water	25.4
I 7	8/17/2019	Lagoon water	25.4
I 8	8/24/2019	Lagoon water	20.32
I 9	8/31/2019	Lagoon water	25.4
I 10	9/7/2019	Lagoon water	25.4

[N/A: not applicable].

2.5 Field sampling

2.5.1 Crop sampling

Weekly measurements of plant height and assessment of the different growth stages were conducted throughout the study. At the end of the study, the two crops were manually and mechanically harvested. Manually harvested crops were used to estimate the effect of the injected air on their growth in terms of size and weight, while mechanically harvested crops were used to estimate the effect of the injected air on their yield as well as on the sugar content of the sugar beets.

Two corn plants were randomly selected from the six zones with lysimeters (C-1, C-2, C-4, C-5, C-7, and C-8) (Figure 13) and manually harvested on 10/07/2019. A total of 24 corn plants and 24 ears were collected near the lysimeters' locations (Figure 13), transferred to the laboratory, and stored -20°C before being used. Mechanized harvesting was done using a John Deere 9500 combine with an 8-row corn header on 10/22/2019 and the yields were recorded.

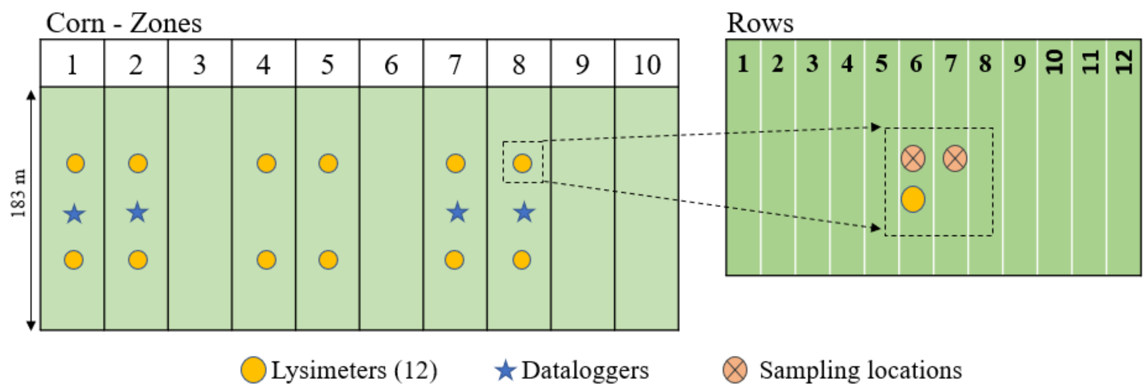


Figure 13: Map of manually harvested corn sample locations. Samples were collected near the lysimeters.

Sugar beets were manually and mechanically harvested on 09/23/2019. Sugar beets were manually harvested from zones with lysimeters (SB-11, SB-12, SB-14, SB-15, SB-17, and SB-18) (Figure 14). Each zone was divided into four blocks (46 m) and a sampling block (length:15 m, width: 1.1 m—two crop rows wide) was created in the middle of each block (Figure 14). Two sugar beet samples were randomly collected using a shovel during the manual harvest in zones 11, 12, 14, 15, 17, and 18 (Figure 14). A total of 48 sugar beets were manually harvested. Mechanical harvesting was conducted using a weigh wagon along with the blocks (15.0 × 1.1 m).

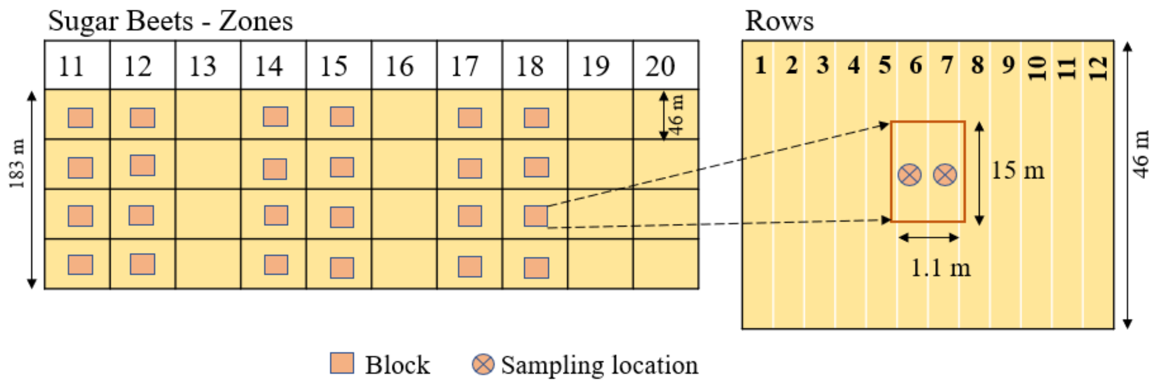


Figure 14: Map of manually harvested sugar beet samples. Samples were collected inside the block.

2.5.2 Water sampling

Two types of water samples, feedlot lagoon, and soil pore water (lysimeters) were collected throughout the study. Before each irrigation event, a water sample was collected at the feedlot lagoon using a 250 mL amber jar, stored in a cooler at approximately 4°C, and transferred to the laboratory at the end of each sampling event. Soil pore water samples were extracted using lysimeter (Figure 6). Before irrigating the field, a vacuum (approximately 10 psi) was applied to all the lysimeters using a vacuum pump. Soil pore water was then extracted at the end of each irrigation event using a 50 mL syringe, transferred into a 50 mL conical centrifuge tube (Thermo-Fisher, St. Louis, MO, USA), stored in a cooler at approximately 4°C, and transferred to the laboratory. To avoid possible cross-contamination of the collected soil pore water samples, the 50 mL syringe was carefully rinsed multiple times with deionized water after collecting each sample.

Water samples were analyzed in terms of pH and electrical conductivity (EC) using a multiparameter probe (Oakton, Global Test Supply, Wilmington, NC, USA; Figure 15A). To measure EC values greater than the upper analytical detection limit of the multiparameter probe, a high EC probe (Hanna Instruments, Carrollton, TX, USA) was used (Figure 15B).

Figure 15: (A) Multiparameter (pH, EC, and temperature) probe (http://www.4oakton.com/proddetail.asp?parent=2&prod=405&value=detail) and (B) high EC probe (https://www.hannainst.com/hi99301-portable-high-range-ec-tds-meter.html).

Every week, before measuring pH and EC, the multiparameter probe was calibrated using a pH 7.0 buffer and a 1.413 mS/cm EC buffer. The high EC probe was also calibrated using the same 1.413 mS/cm buffer used to calibrate the multiparameter probe. To further ensure the quality of these readings, the two buffers were measured every five samples, and if needed, the probes were recalibrated.

2.6 Crop measurements

At the end of the growing season, corn and sugar beet were harvested. Corn ears were separated from the plant and their weight and dimensions (length, diameter) were measured (Figure 16). The length of the corn plant (from the tip to the root end) was also measured (Figure 16A). After separating the roots from the plants, their weights were measured using an A&D scale (A&D Weighing, Wood Dale, IL, USA), and their lengths were recorded (Figure 16B-C). Each plant was cut into multiple smaller portions (length: approximately 10 cm), placed in a labeled freezer bag, and stored at -20 °C before being used.

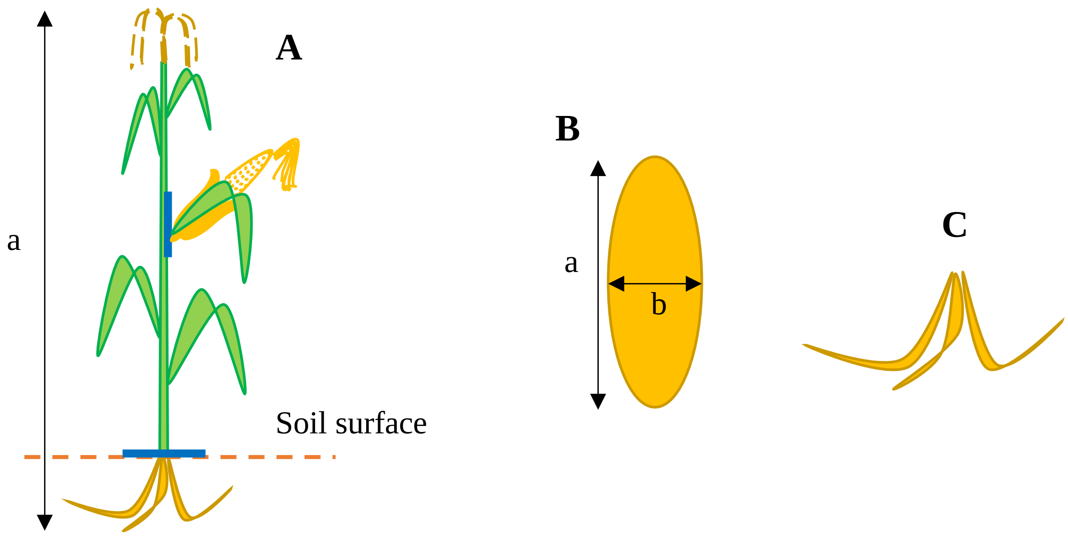


Figure 16: (A) Corn plant, (B) corn ear, and (C) root [*a*: length; *b*: width].

Leaves and tubers of sugar beets were separated (Figure 17A). Weights of the tuber and leaves were measured using an A&D scale (A&D Weighing, Wood Dale, IL, USA). Length, width, and height of the tuber were measured using a measuring tape (Figure 17B), while the weight was measured using an A&D scale (A&D Weighing, Wood Dale, IL, USA).

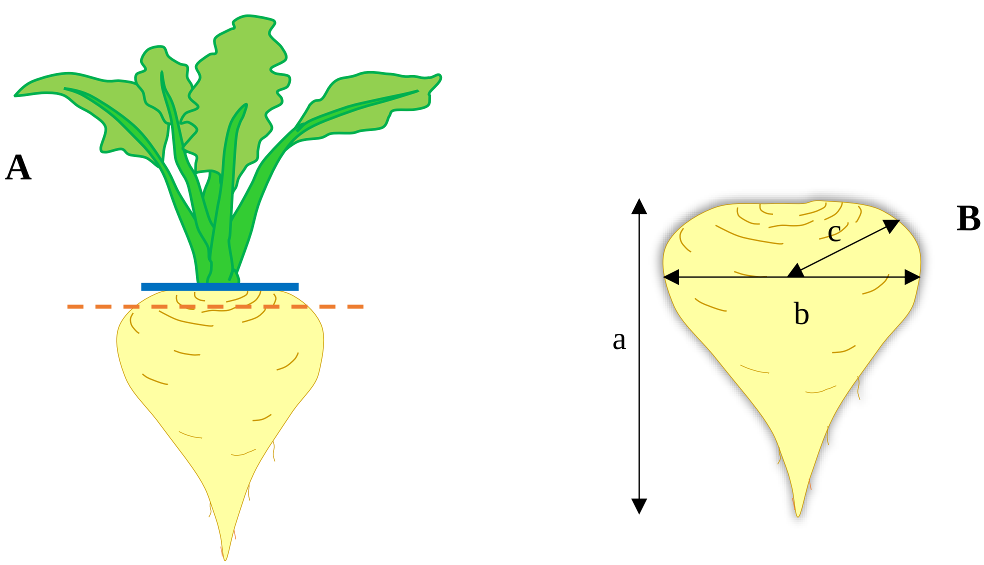


Figure 17: (A) Sugar beet plant and (B) sugar beet tuber [*a*: length; *b*: width; *c*: height].

2.7 Statistical analysis

Statistical analysis for crop yields and plant growth were conducted using one-way analysis of variance (ANOVA) in a randomized block design at $p<0.05$ (R Software, 2013).

3. RESULTS AND DISCUSSION

3.1 Preliminary results

3.1.1 Weather and irrigation during the study

Temperature and precipitation data for the growing season are shown in table 2. Precipitation and temperature data were taken between the seeding (04/27/2019 – sugar beets) to the harvesting (10/22/2019 – corn) data of the two crops. Two hail storms occurred on August 14th and on August 15th.

Table 2: Irrigation events, overall irrigation, cumulative precipitation, and lowest and highest temperature during the field study at the Mitchell Agricultural Laboratory.

No. of irrigation events	**Overall Irrigation (mm)**	**Cumulative Precipitation (mm)**	**Highest Temperature (ºC)**	**Lowest Temperature (ºC)**
10	216	310	36.8	-12.4

3.1.2 Water quality (pH and EC)

Figures 18 and 19 show the pH values of the water samples collected from the lagoon and the lysimeters (pore water). Due to the limited amount of water collected with the lysimeters at the beginning of the study, pH was only measured during the last six irrigation events (I-5 to I-10). With the exception of I-5, lagoon water had a higher pH (8.7 to 9.6) than soil pore water (7.0 to 8.7). In terms of pH, pore water samples were not statistically significantly different ($p > 0.05$) than lagoon water samples. The lower pH (8.2) observed in the lagoon water during I-5 was related to the different sources of water used (freshwater instead of feedlot runoff). A possible explanation for the decrease in soil pore water pH compared with the lagoon water pH may be related to the sand filters' impact. Lagoon water was filtered through four sand filters in series before being delivered to the crops. Measuring water pH after the sand filters would provide a better understanding of the changes in pH during the study. To prevent the emitters' clogging, the driplines were flushed with fresh water at the end of each irrigation. This may have also further reduced the soil pore water pH.

According to the guidelines proposed by the Food and Agriculture Organization (FAO, 2012), the recommended pH values for irrigation water ranges between 6.5 and 8.4. The lagoon water had consistently high pH values (8.6 to 9.6) throughout the study. To mitigate the negative effect of high pH values, the driplines were flushed for two hours with fresh water at the end of each irrigation event.

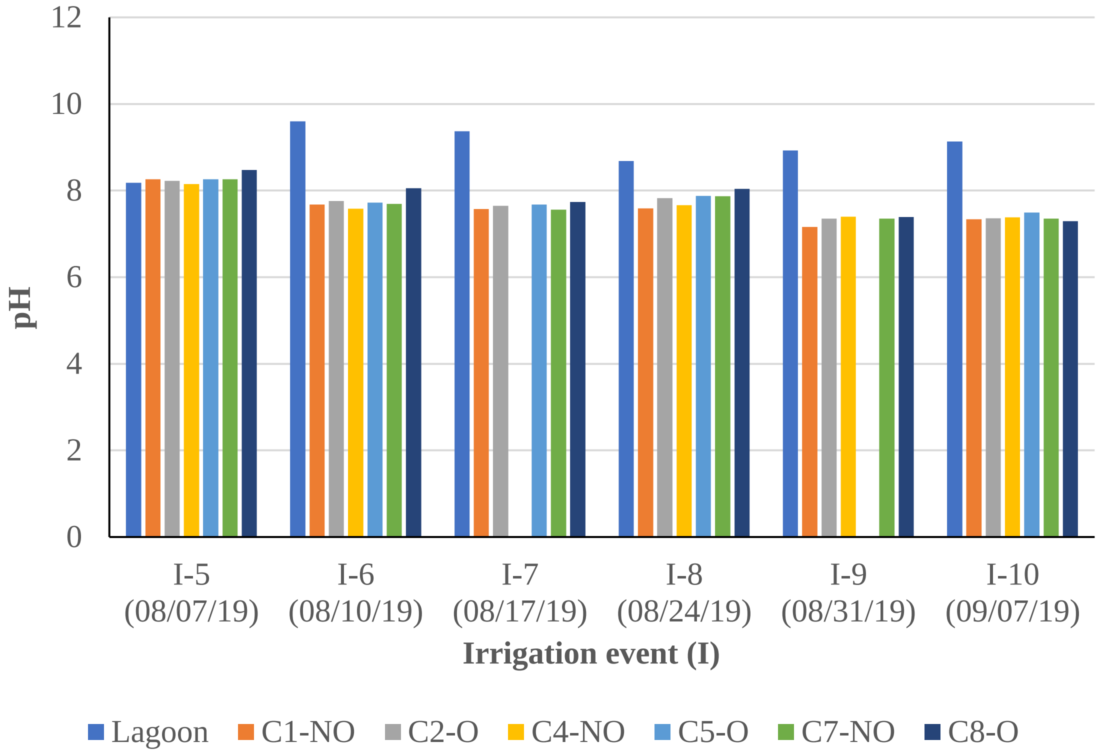


Figure 18: pH values for lagoon water and soil pore water samples collected on the west side of the field (corn only) after the last six irrigation events (Irrigation 5 to Irrigation 10).

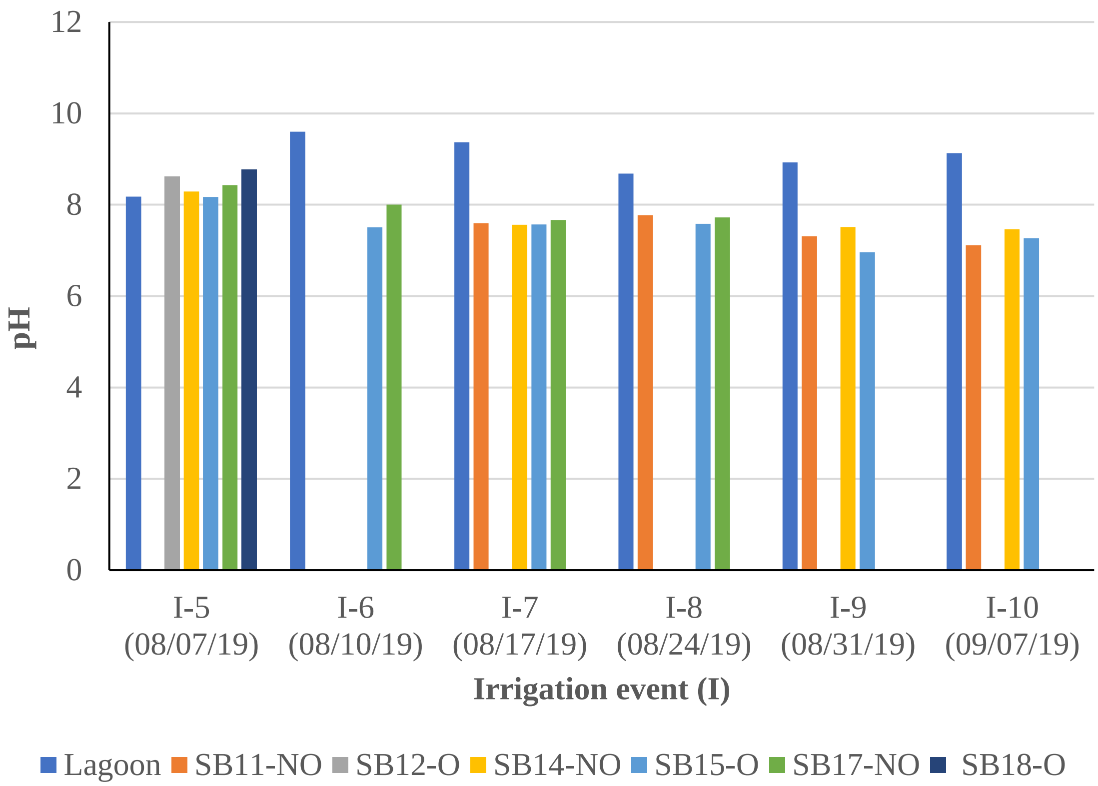


Figure 19: pH values for lagoon water and soil pore water samples collected on the east side of the field (sugar beets only) after the last six irrigation events (Irrigation 5 to Irrigation 10).

EC is an indicator of the salinity of the water. Figures 20 and 21 show EC values related to the lagoon water as well as to the pore water samples from the cornfield and the sugar beets field, respectively. Similarly, to pH, due to the limited amount of available at the different lysimeters, EC was measured during the last six irrigation events. In both fields, higher EC values were observed in the pore water samples (1.14 to 2.05 mS/cm) compared with the lagoon samples (0.45 to 1.12 mS/cm) (Figures 20 and 21). In terms of EC, pore water samples were not statistically significantly different ($p > 0.05$) than lagoon water samples. With the exception of the I-5 (fifth irrigation event), EC was constant in the lagoon water (approximately 1.00 mS/cm). The low EC value (0.50

mS/cm) observed during I-5 was related to the different sources of water (freshwater instead of feedlot runoff) used (Figure 21). Based on Hajiboland et al., 2009, these high EC values (and consequently high-water salinity) might negatively affect the overall yield of the two crops. Among the two crops, sugar beet seems to be more resistant to high EC values. Corn yield decreases with increased salinity (Amer 2010, Zorb et al., 2019), while sugar beet has a high EC threshold (7.0 mS/cm; Marschner 1995). Therefore, salinity may negatively affect corn yield but it shouldn't negatively affect sugar beet yield.

According to the guidelines proposed by the Food and Agriculture Organization (FAO, 2012), irrigation waters with EC values less than 0.7 mS/cm are considered non-restricted, while with EC values ranging between 0.7 and 3.0 mS/cm are considered slightly to moderately restricted. Lagoon water, EC approximately 1.1 mS/cm throughout the study, can be regarded as slightly restricted. To attenuate this slightly high EC value, the driplines were flushed for two hours with fresh water at the end of each irrigation event.

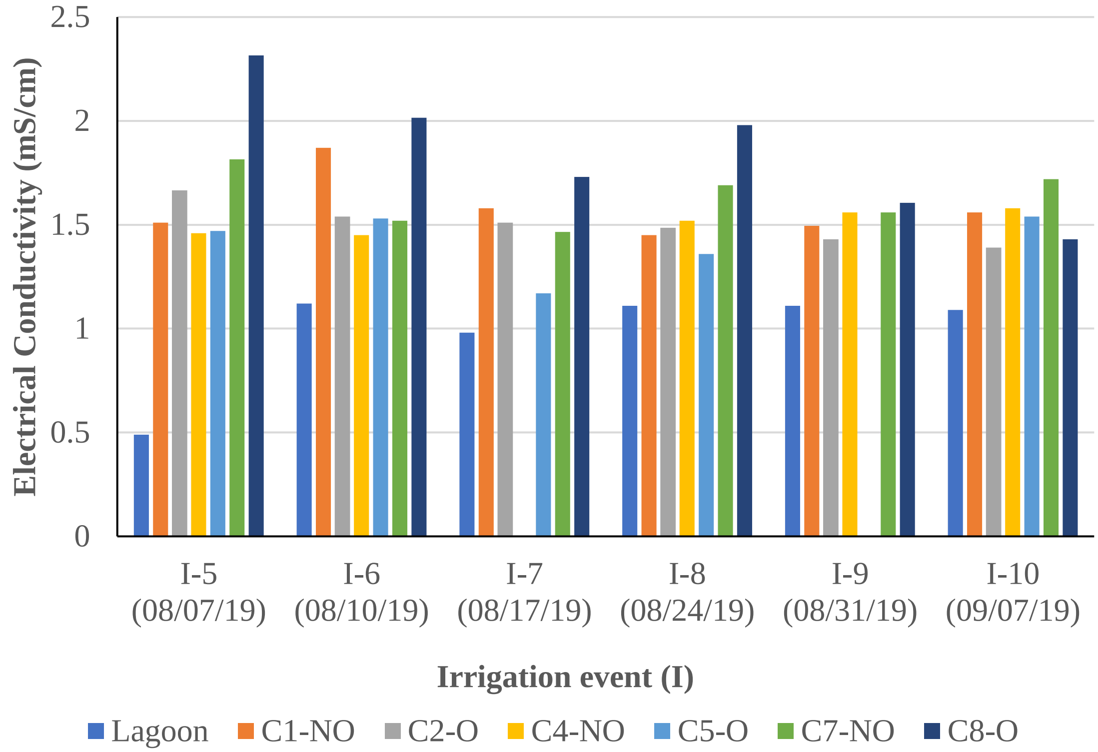


Figure 20: Electrical conductivity (EC) values for lagoon water and soil pore water samples collected on the west side of the field (corn only) after the last six irrigation events (Irrigation 5 to Irrigation 10).

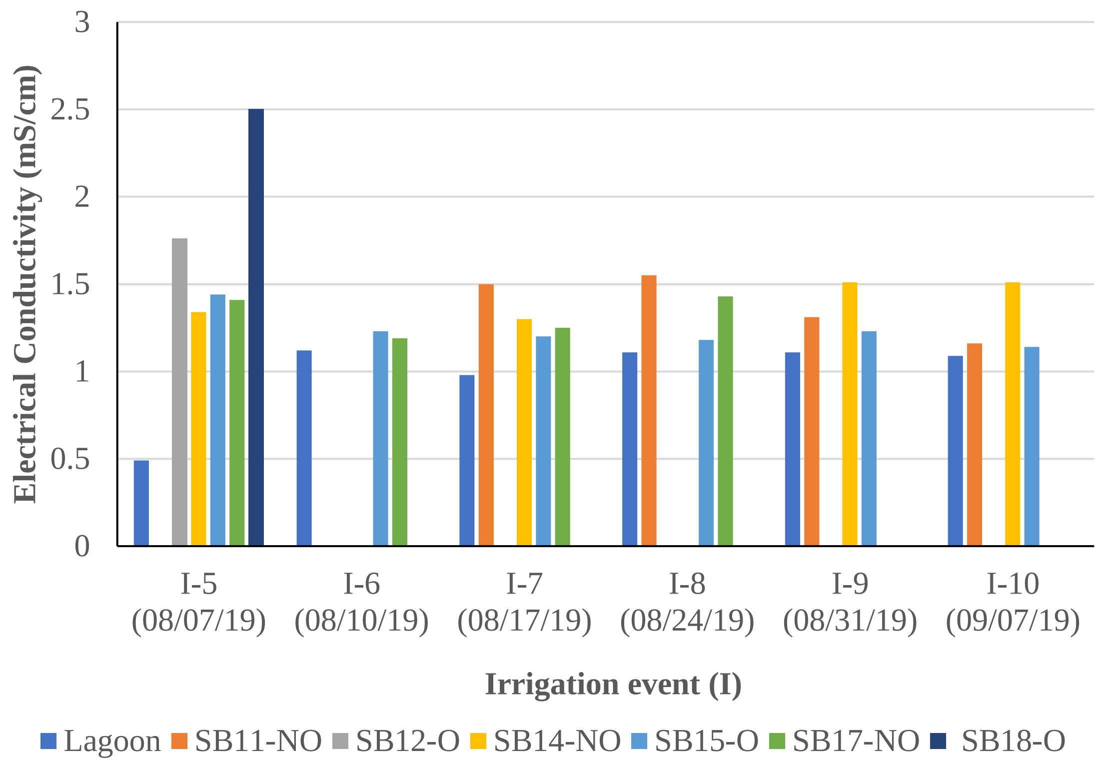


Figure 21: Electrical conductivity (EC) values for lagoon water and soil pore water samples collected on the east side of the field (sugar beets only) after the last six irrigation events (Irrigation 5 to Irrigation 10).

3.2 Effect of air injection on soil oxygen content and soil water content

3.2.1 Corn

Air injection increased the amount of oxygen in the soil. When the irrigation starts, the soil oxygen amount decreases. However, soil oxygen increases as time passes. Figure 22 shows a comparison between the zones C-1 (non-aerated) and C-2 (aerated). At 45 cm depth, the aerated zone contained almost the same amount of soil oxygen that non-aerated zone has at 25 cm depth. The dashed vertical lines indicate the irrigation events, black indicates the start and red indicates the end of each event. Soil oxygen graph for C-8 and C-7 is available in Appendix B (Figure B1).

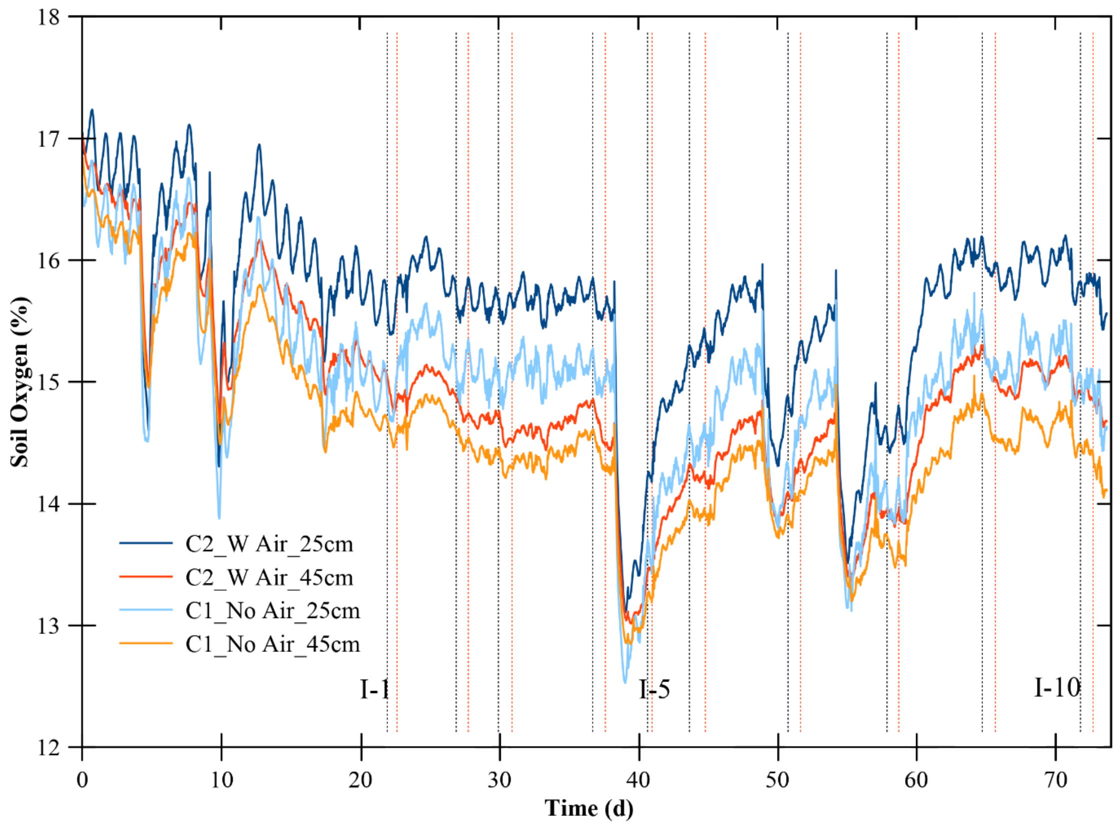


Figure 22: Effect of injected air on soil oxygen on the west side of the field (corn only).

In the cornfield, the soil water content in the aerated zone shows less soil water content compared with the non-aerated zone. The reason could be the higher root respiration leads to more water intake to the roots. The soil water amounts were shown in selected depths. The soil water content for the depths 5, 15, 35, 75, and 115 cm of C-2 (A; aerated) and C-1 (B; non-aerated) are shown in Figure 23. The graphs for soil water at all depths are shown in Appendix B (Figure B2, for C-1 and C-2; Figure B3 for C-8 and C-7).

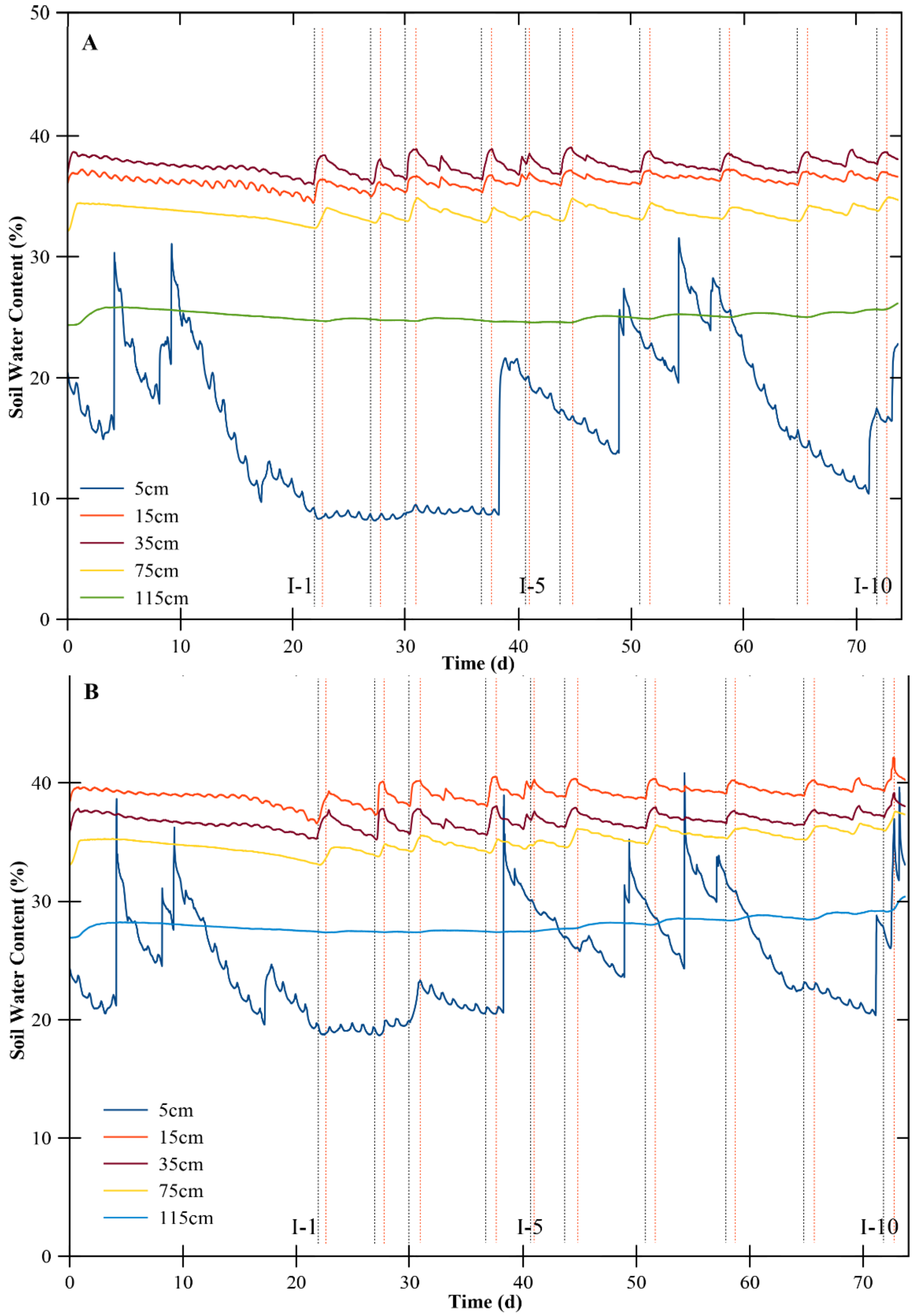


Figure 23: Effect of injected air on soil water content on the west side of the field (corn only). (A): C-2, aerated, and (B): C-1, non-aerated.

3.2.2. Sugar beet

Sugar beet plots have the same soil oxygen behavior as corn plots. As irrigation starts, the oxygen amount goes down, and then it increases as time goes (Figure 24). Similar to the corn, SB-18 (aerated zone) at 45 cm depth has almost the same amount of soil oxygen compared to SB-17 at 25 cm depth. The graph for sugar beet zones SB-12 and SB-11 are shown in the appendix (Figure B4)

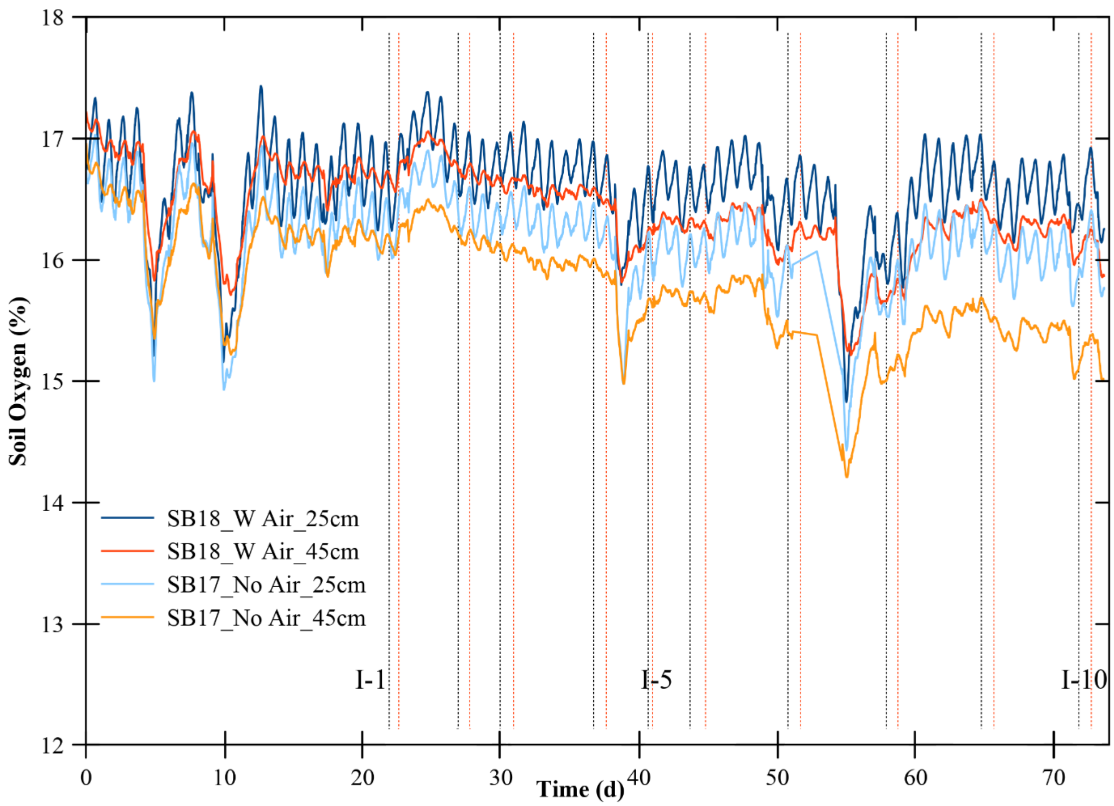


Figure 24: Effect of injected air on soil oxygen on the east side of the field (sugar beets only).

In the sugar beet field, the soil water content is less in the aerated zone compared to the non-aerated zone. This is due to the high-water intake of the plants in the aerated zone as mentioned previously. Figure 25 shows the changes in soil water content in SB-18 (A; aerated) and SB-17 (B; non-aerated) at 5, 10, 15, 35, 75, and 115 depths. The graphs for soil water at all depths are shown in Appendix B (Figure B5, for SB-12 and SB-11; Figure B6 for SB-18 and SB-17).

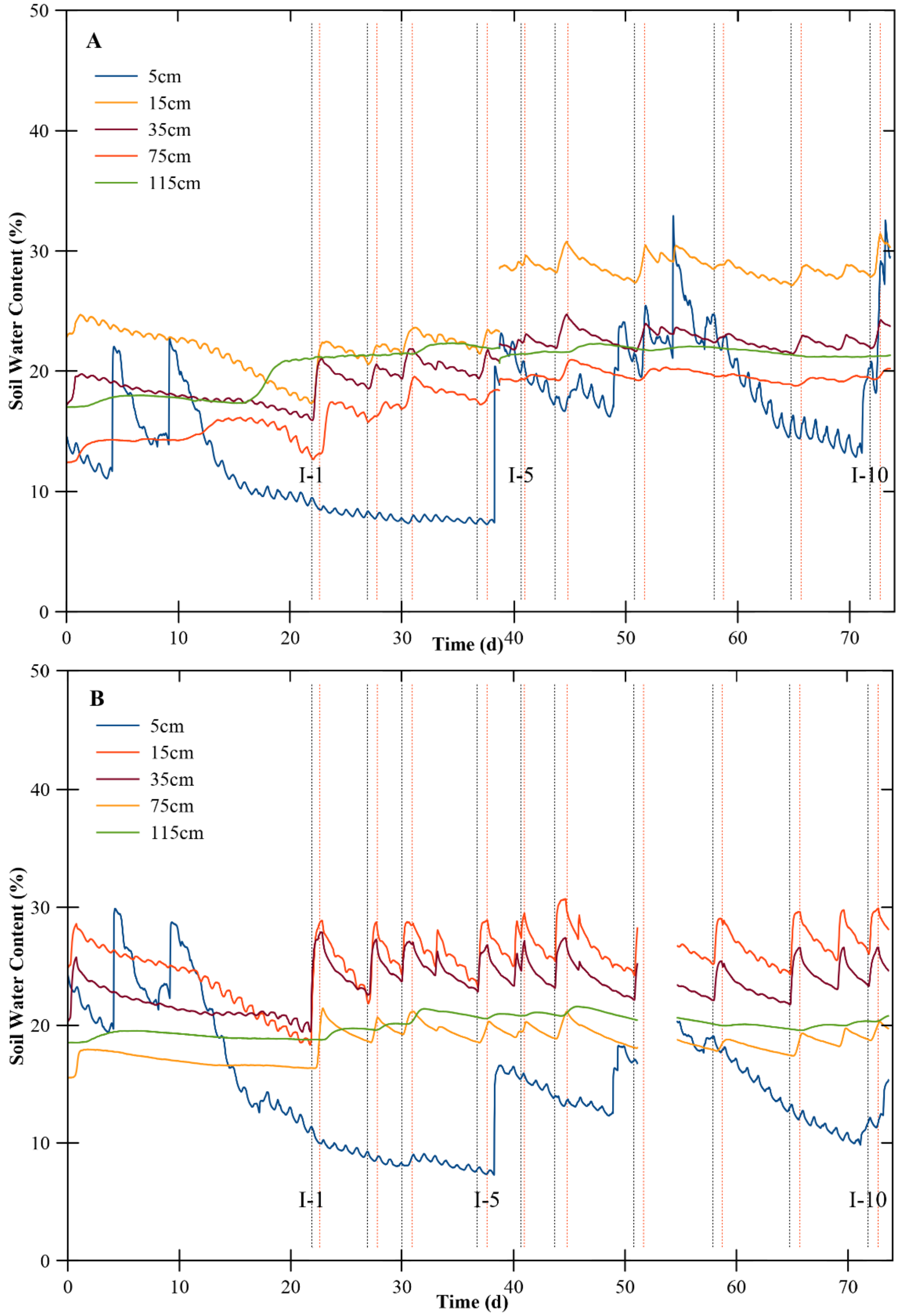


Figure 25: Effect of injected air on soil water content on the east side of the field (sugar beets only). (A): SB-18, aerated, and (B): SB-17, non-aerated.

However, in both corn and sugar beets, the changes in terms of soil moisture vary with different depths. For example, at 35 cm depth, soil moisture content was almost the same in both C-2 and C-1. The changes with the different depths could be due to the way of root systems spread in the ground and their ability to intake water as well as to the abundance of soil organisms. Top-soil (5 cm) shows the lowest amount of soil water content. This can be related to the evaporation occurring within the top-soil. The cornfield showed a smaller difference between the aerated zones and non-aerated zones than those observed in the field with sugar beets. Also, sugar beet showed higher soil water reduction than corn in both aerated and non-aerated zones. Reduction in the soil water content after aerated water irrigation was reported by other research (Dhungel et al., 2012, Pendergastet al., 2013, Vyrlas and Kalfountzos, 2014).

3.3 Effect of air injection on the growth of selected crops

3.3.1 Corn

The effect of injected air on the growth of corn was measured in terms of 1) plant height, 2) corn ear dimensions, 3) corn ear weight, and 4) roots weight.

Corn plant growth, expressed in terms of plant height, was measured in the field throughout the study and it is shown in Figure 26. During the first 21 days (from day 64 to 85) injected air did not affect corn growth (Figure 26). After that, injected air had a positive effect on corn growth. For example, after 90 days corn was 270 cm tall in the absence of injected air and 280 cm tall in the presence of injected that. On day 91, two hail storms occurred and damaged the corn growth (Figure 27). After the two hail storms, new leaves were observed.

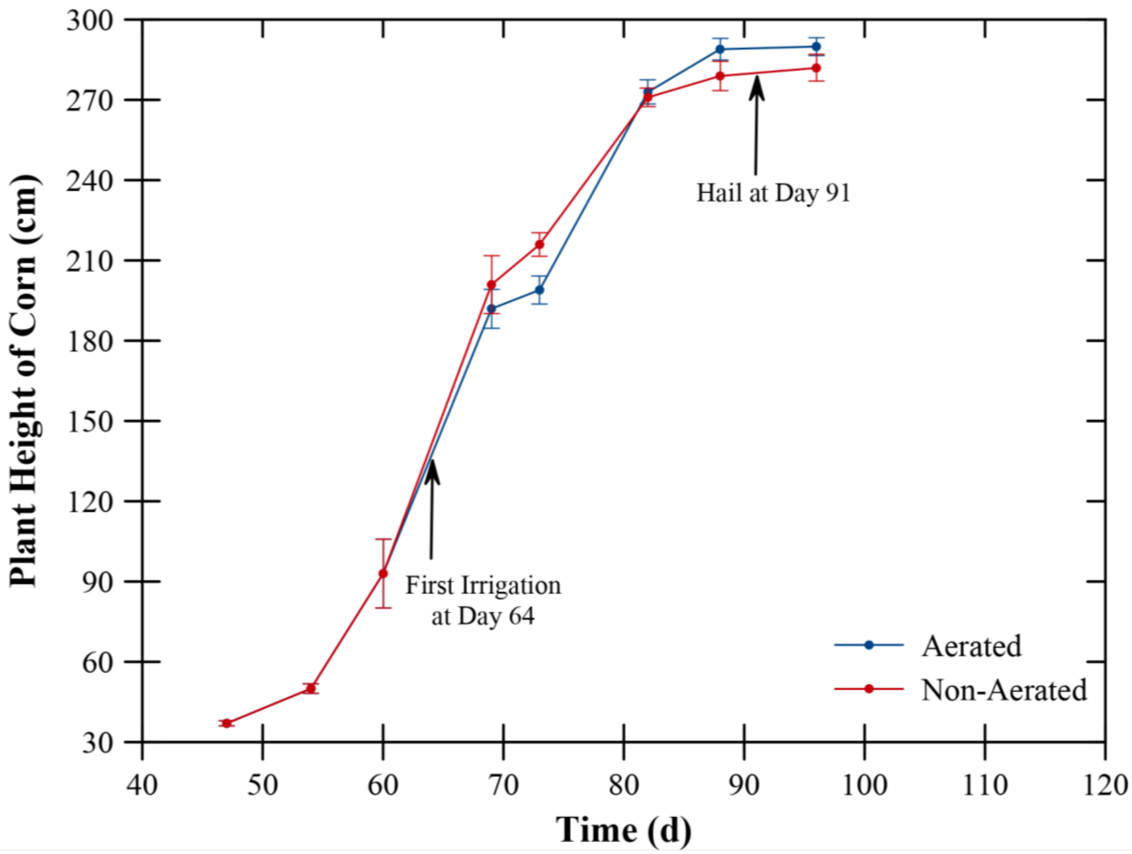


Figure 26: Corn plant growth expressed in terms of plant height with (aerated) and without air-injection (non-aerated).

Figure 27: Effect of the hail storms on corn.

Corn was manually harvested at the end of the study and the overall length (from the tip of the plant to the base) was measured in the laboratory. The average corn plant height/length ranged between 213 ± 22 cm (C1-NO) and 224 ± 15.7 cm (C4-NO), and it was not affected by the presence/absence of injected air (Figure 28). Abuarab et al. 2013, investigating the effect of injected air on corn in a greenhouse study using artificial water, highlighted the positive effect of injected air on the growth of corn. In fact, the average corn plant height in the presence of injected air was 284 cm in 2010 and 290 cm in 2011, while the average corn plant height in the absence of injected air was 265 cm in 2010 and 270 cm in 2011.

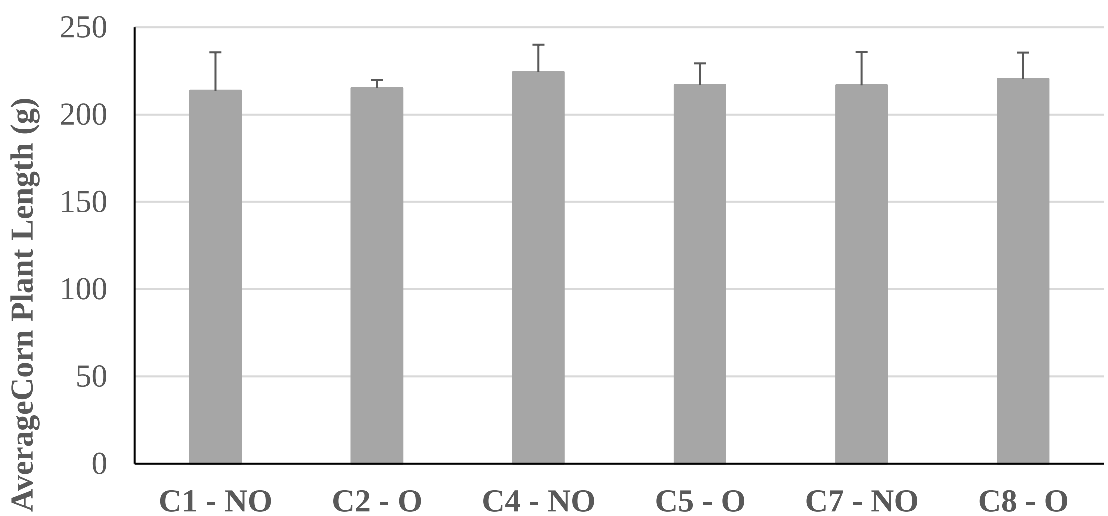


Figure 28: Average corn plant height in six zones (C: corn; 1–8: zone ID; O: Aerated, NO: Non-aerated). n = 4 (n samples/zone).

Corn ears grown in the presence of injected air were slightly longer and wider compared to those grown without injected air (Figure 29). The highest average of corn ear length (22.9 ± 0.4 cm) and the highest average corn ear width (5.3 ± 0.3 cm) were recorded in the aerated zone C-8 (Figure 30). Results from this study were consistent with Abuarab et al. as they observed a longer and larger corn ear in the presence of air injection (Abuarab et al., 2013).

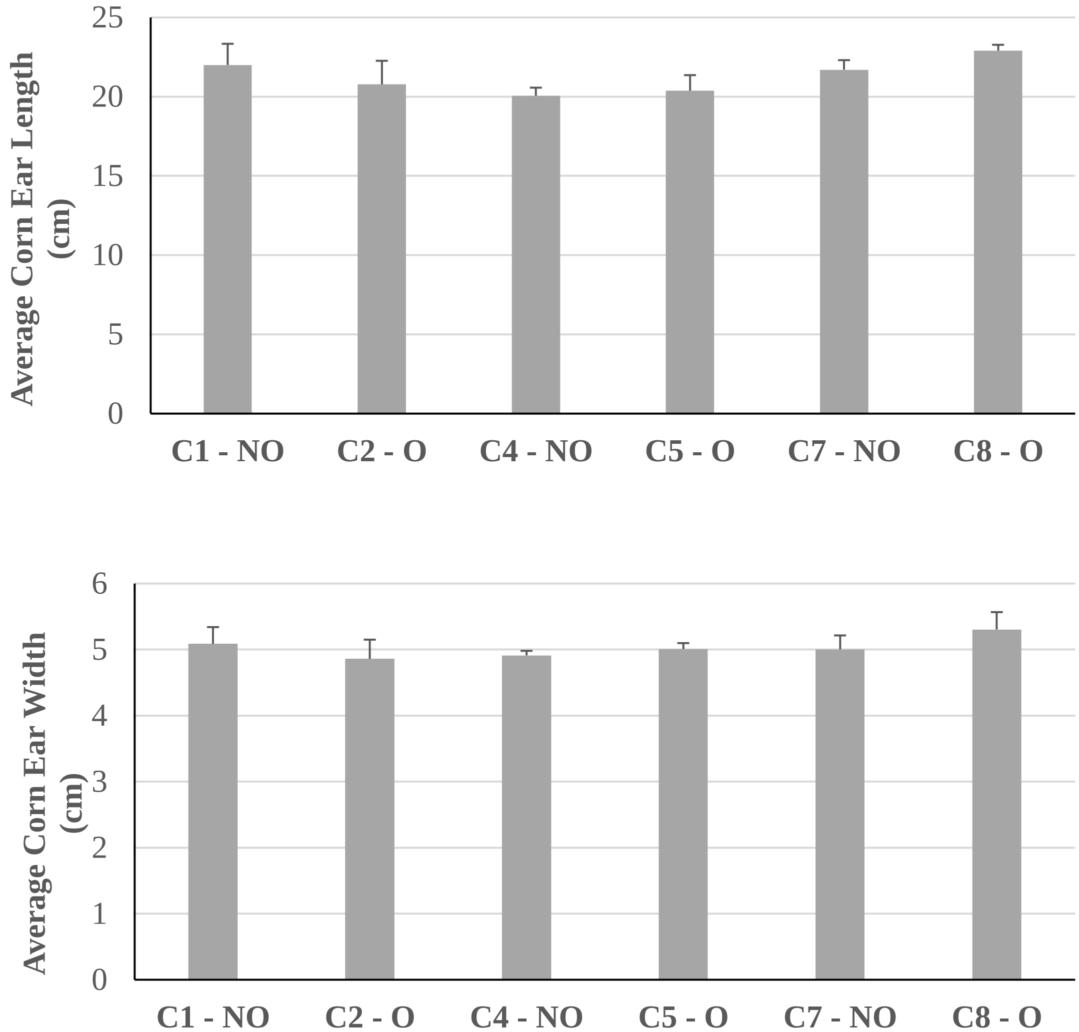


Figure 29: Average corn ears length (Top) and width (Bottom) in six zones (C: corn; 1–8: zone ID; O: Aerated, NO: Non-aerated). n = 4 (n samples/zone).

The average weight of corn ears ranged between 217.3 ± 20.3 g (C-5, aerated) and 282.7 ± 32.7 g (C-8, aerated). C-1, a non-aerated zone, showed the second-highest value (Figure 30).

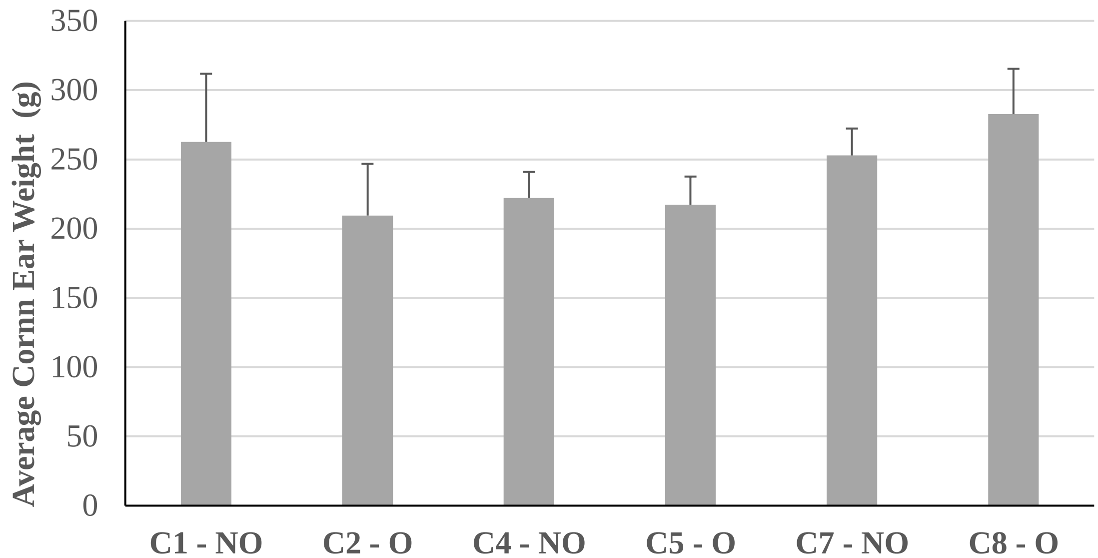


Figure 30: Average corn ears weight in six zones (C: corn; 1–8: zone ID; O: Aerated, NO: Non-aerated). n = 4 (n samples/zone).

The average corn root weight ranged been 25 ± 10 g (C2-O) and 50 ± 19.3 g (C1-NO) (Figure 31). Even if, corn roots were carefully removed, collected, and cleaned, multiple challenges were encountered. For example, roots were not completely removed from the soil due to the plants in close proximity in the field, and consequently, the weight would be underestimated. On the contrary, even after carefully cleaning the roots, small fractions of soil particles were still trapped within the roots and therefore, their weights were overestimated.

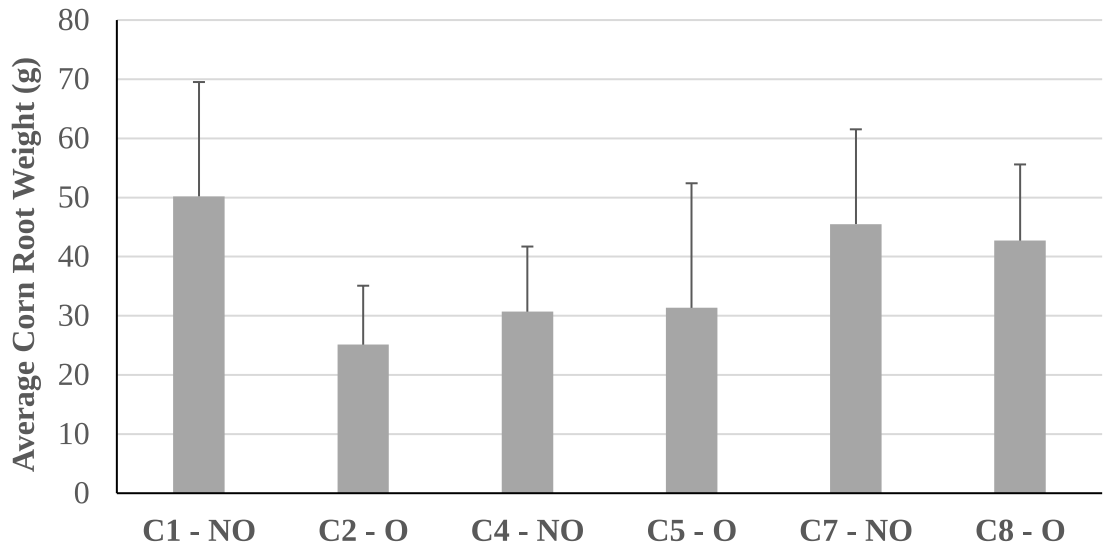


Figure 31: Average corn root weight in six zones (C: corn; 1–8: zone ID; O: Aerated, NO: Non-aerated). n = 4 (n samples/zone).

The effect of injected air on the corn growth, expressed in terms of dimensions and weight, was not statistically significant ($p > 0.05$) (Table 3).

Table 3: Effect of treatment (with or without air injection) on corn (dimensions and weight) [ANOVA, *p* values].

Crop Measurement	Treatment (w and w/out oxygen)
Plant height (cm)	0.85
Ear weight (gr)	0.74
Ear length (cm)	0.92
Ear diameter (cm)	0.64
Root weight (g)	0.31

3.3.2 Sugar beet

The effect of injected air to the growth of sugar beet was estimated in terms of 1) plant growth, 2) tuber dimensions, 3) leaves weight, and 4) tuber weight.

Sugar beet growth, expressed in terms of plant height, was measured in the field throughout the study by measuring the distance between the ground and the top of the mature leaves. At the beginning of the study, there was a difference between the sugar beets grown with and/or without injected air except for day 87 (Figure 32). After 100 days, injected air started to have a positive effect on the growth of the sugar beets. Sugar beets grown with injected air reached 57 cm, while sugar beets grown without injected air reached 52 cm (Figure 32). On day 110, two hail storms occurred and, similarly to corn, severely affected the sugar beets' growth (Figure 33). After the hail storms, the growth was reduced.

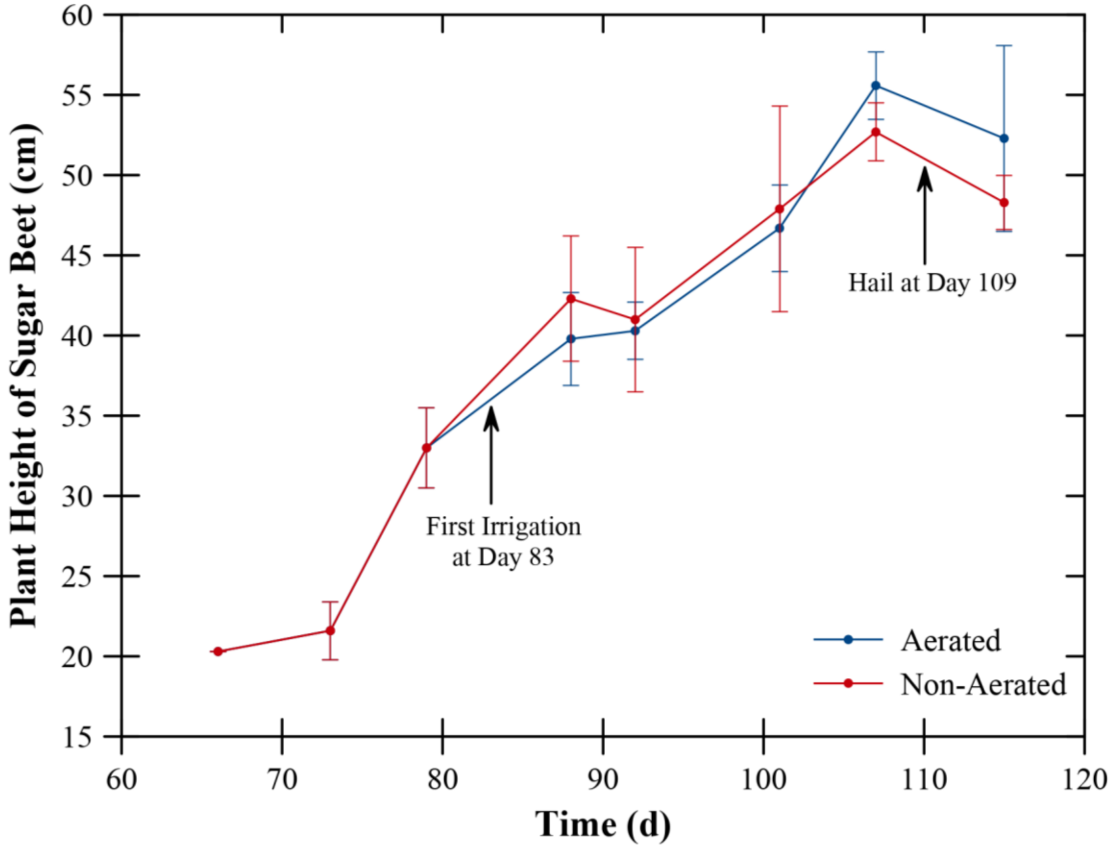


Figure 32: Sugar beet plant growth expressed in terms of plant height with (aerated) and without air injection (non-aerated).

Figure 33: Effect of the hail storms on sugar beets with visible plant damage.

Similarly, with the trend observed with corn, the injected air had limited to no effect on the growth of sugar beets throughout the field (Figure 34). This may be related to the limited number of sugar beets collected within each zone. The tuber's growth was affected by the soil around, therefore, physical heterogeneities combined with the limited number of beets collected may have underestimated the effect of injected air on the growth of sugar beets. Within adjacent zones, the length of the sugar beet tuber was affected by the presence/absence of air. For example, tubers in SB-12 (aerated; average length: 29.1 ± 4.9 cm) were longer than tubers in SB-11 (non-aerated; average length: 28.2 ± 6.2 cm). Similar behavior was also observed in terms of width and height (Figure 34).

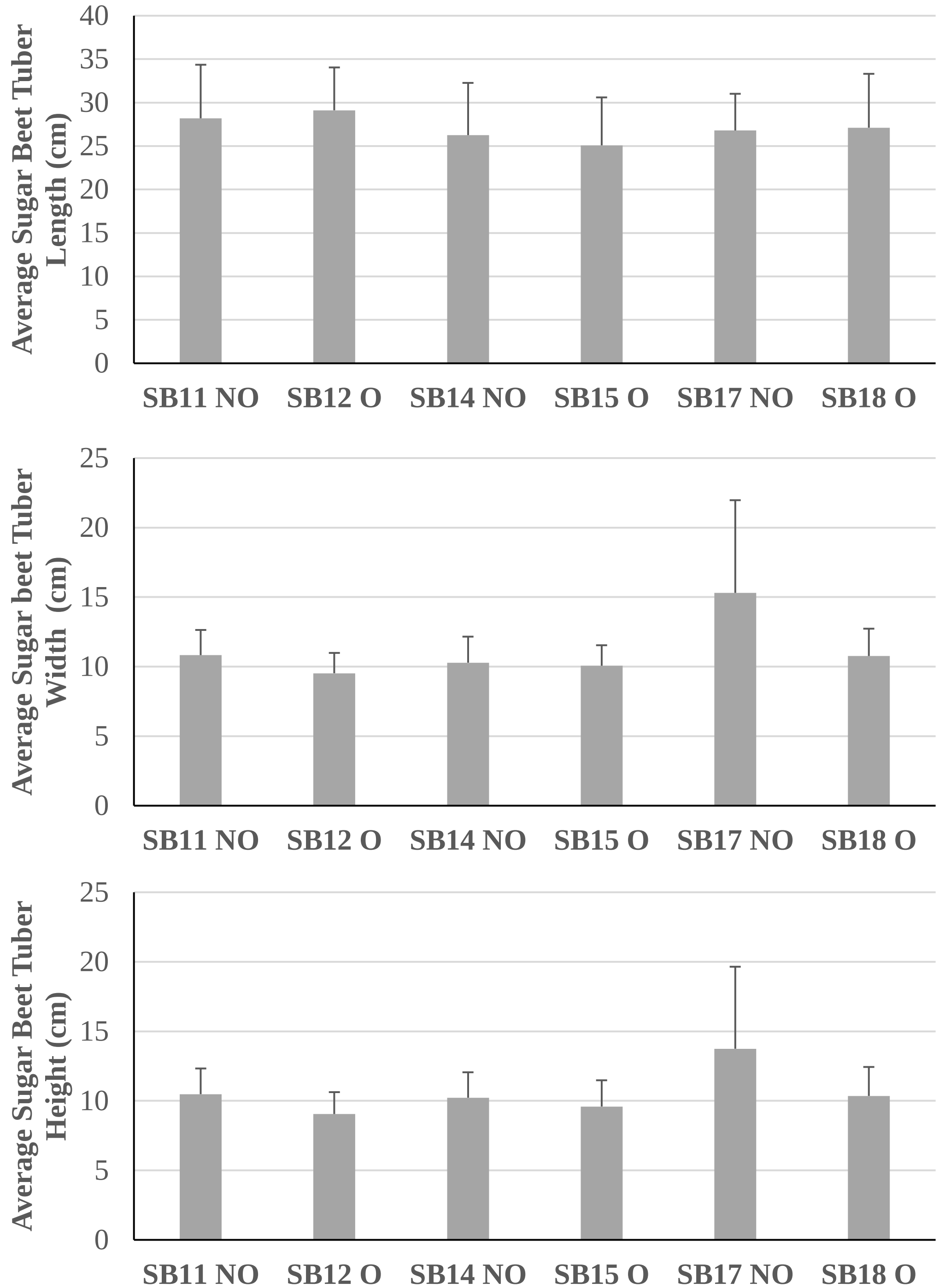


Figure 34: Average sugar beet tuber length (Top), width (Middle), and height (Bottom) in six zones (SB: sugar beets; 11–20: zone ID; O: Aerated, NO: Non-aerated). n = 8 (n samples/zone).

Selected leaves were heavier in non-aerated zone (e.g., SB-11; average weight: 347.4 ± 138.4 g) than in aerated zone (e.g., 227.0 g; average weight: 227.0 g ± 164.7) (Figure 35). The negative effect of injected air may be related to the limited number of crops harvested as well as to the severe effect of the two hail storms that occurred during the study.

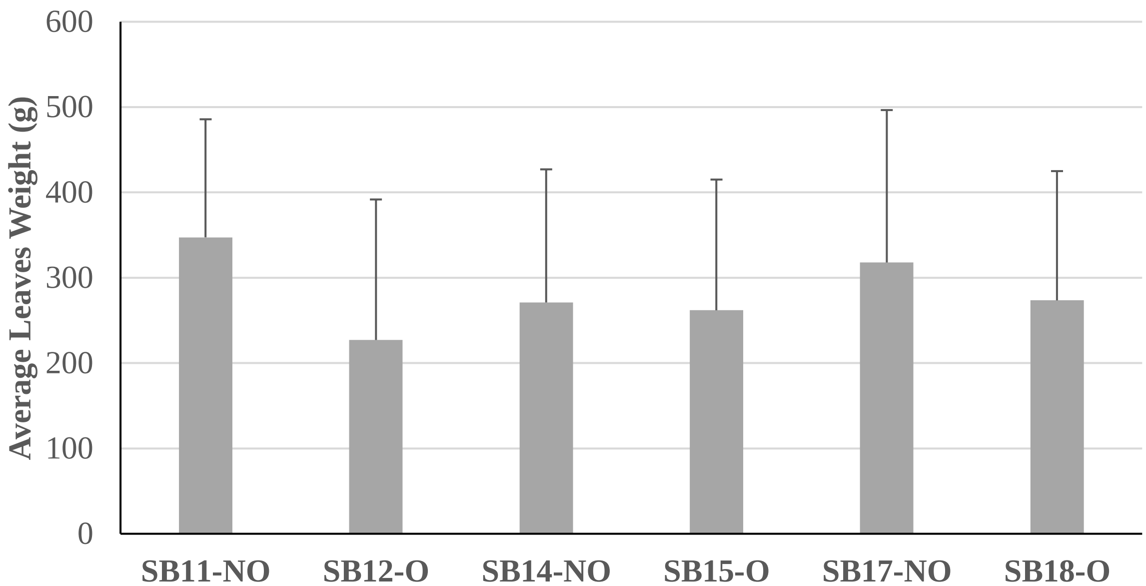


Figure 35: Average sugar beet leaves weight (O- Aerated, NO- Non-aerated) in six zones (SB: sugar beets; 11–20: zone ID; O: Aerated, NO: Non-aerated). n = 8 (n samples/zone).

The presence/absence of air had a limited effect on the weight of the tubers (Figure 36). SB-17, non-aerated, showed the highest weight average (1142.1 ± 583.8 g) among the randomly collected samples, while SB-12, aerated, showed the lowest value (685.4 ± 287.4 g). Again, this may be due to the limited number of sugar beets collected within each zone.

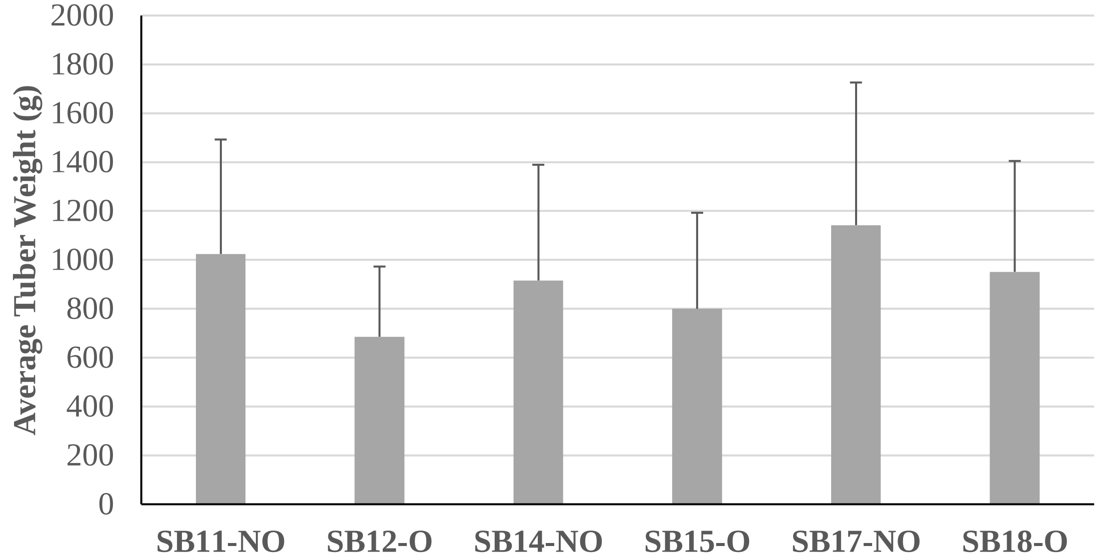


Figure 36: Average sugar beet tuber weight in six zones (SB: sugar beets; 11–20: zone ID; O: Aerated, NO: Non-aerated). n = 8 (n samples/zone).

The effect of injected air on the sugar beets growth, expressed in terms of dimensions and weight, was not statistically significant ($p > 0.05$) (Table 4).

Table 4: Effect of the treatment (with or without air injection) on sugar beets (dimensions and weight) [ANOVA, *p*>F values].

Crop Measurement	Treatment (w and w/out oxygen)
Sugar beet tuber length (cm)	1.00
Sugar beet tuber width (cm)	0.29
Sugar beet tuber height (cm)	0.21
Sugar beet tuber weight (g)	0.10
Leaf weight (g)	0.09

3.4 Effect of air injection on the yield of selected crops

3.4.1 Corn

From each zone, four blocks were selected and analyzed to evaluate the effect of injected air on corn yield. Table 5 shows the yield achieved in each of the four selected blocks across the ten zone. A 5.50 % incremental in corn yield was achieved in the presence of injected air. In fact, corn yield ranged between 7.7 ± 0.9 Mg/ha in the aerated zones and 7.3 ± 1.0 Mg/ha in a non-aerated zone similar trend, higher yield in the presence of injected air was also observed by Aburab et al. (2013). In their study, corn yield ranged between 12.605 Mg/ha and 12.857 Mg/ha in the presence of aerated SDI and between 11.226 Mg/ha and 11.428 Mg/ha in the presence non-aerated SDI.

Table 5: Corn dry yield (Mg/ha) (NO: Non-aerated zone; O: aerated zone).

	ZONES									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	NO	*O*	*NO*	*NO*	*O*	*NO*	*NO*	*O*	*O*	*O*
	6.9	6.0	6.0	5.6	6.2	7.1	7.0	7.5	7.0	7.3
	5.4	6.2	6.1	6.9	6.9	8.1	7.8	7.8	8.2	7.1
	7.3	7.6	7.6	7.0	7.3	7.6	8.0	8.8	7.9	8.5
	7.9	8.7	8.4	8.7	8.3	8.5	8.6	8.2	8.9	9.0
Average	6.9	7.1	7.0	7.1	7.2	7.8	7.9	8.1	8.0	8.0
Std.	1.1	1.3	1.2	1.3	0.9	0.6	0.7	0.6	0.8	0.9

Even if a 5.50 % increment of corn yield was achieved in the presence of injected air, the effect of injected air was not statistically significant (*p*-value >0.05) (Table 6).

Table 6: Effect the treatment (presence or absence of injected air) on corn yield [ANOVA analysis].

	Df	**Sum sq.**	**Mean sq.**	**F value**	***p*(>F)**
Treatment	1	0.29	0.29	1.26	0.29

At the Mitchell farm, the corn yield ranged between 116 ± 16 bu/ac for the non-aerated SDI and 122 ± 15 bu/ac for aerated SDI for corn (Table 7). These results are lower compared to those observed across the state of Nebraska as well as in the Scottsbluff County (Table 8). In fact, in 2019, the average corn (grain) yields in Nebraska ain Scottsbluff County were 182 and 151.1 bu/ac, respectively (https://www.nass.usda.gov/Statistics_by_State/Nebraska/index.php). The limited corn yield observed at the Mitchell farm can be related to the different irrigation strategies implemented in this study (SDI instead of pivot irrigation). Also, multiple hail storms had a negative effect on the yield at the Mitchell farm.

Table 7: Average corn yields in Scottsbluff County, NE over the past 5 years.

Corn (Grain) (bu/ac)				
Year	**Nebraska**	**Scottsbluff County**	**Mitchell Farm Non- Aerated**	**Mitchell Farm Aerated**
2019	182	151	116 ± 16	122 ± 15
2018	192	195	-	-
2017	181	183	-	-
2016	178	162	-	-
2015	185	165	-	-
Source: https://www.nass.usda.gov/Statistics_by_State/Nebraska/index.php				

3.4.2 Sugar beet

Sugar beet yield was higher in aerated zones by 7.75 % (54.23 ± 11.21 Mg/ha) compared to the non-aerated zones (50.33 ± 11.65 Mg/ha) (Table 8). Sugar content was also higher in the aerated zones (14.41 ± 0.57 %) compared to the non-aerated zones (14.39 ± 0.58 %). The sugar yield was also higher in aerated zones (7.82 ± 1.61 Mg/ha) than non-aerated zones (7.24 ± 1.72 Mg/ha) (Table 9). However, the effect of injected air on sugar beet yield, and sugar content and yield were no statistically significant (Table 10).

Table 8: Sugar beet yield in 2019 (Mg/ha). (NO: Non-aerated zone; O: aerated zone).

	Zones							
	11	**12**	**13**	**14**	**17**	**18**	**19**	**20**
	NO	*O*	*NO*	*NO*	*NO*	*O*	*O*	*O*
	58.06	40.48	56.99	63.92	61.78	62.32	61.78	67.11
	38.88	26.10	52.73	37.28	29.29	56.46	52.73	61.25
	61.25	64.45	53.26	65.51	47.40	42.08	50.07	53.80
	47.94	67.64	29.29	55.93	45.81	58.59	57.52	45.27
Average	51.53	49.67	48.07	55.66	46.07	54.86	55.53	56.86
Std	10.17	19.85	12.66	12.95	13.29	8.86	5.19	9.45

Table 9: Sugar beet yield (Mg/ha), sugar content (%), and sugar yield (Mg/ha) in 2019.

Treatment	Yield (Mg/ha)	Sugar content (%)	Sugar Yield (Mg/ha)
Aerated	54.23 ± 11.21	14.41 ± 0.57	7.82 ± 1.61
Non-aerated	50.33 ± 11.65	14.39 ± 0.58	7.24 ± 1.72

Table 10: Effect of the treatment (presence or absence of injected air) on sugar beet yield [ANOVA analysis].

	Df	Sum Sq.	Mean Sq.	F Value	*Pr.* (>F)
Treatment	1	30.42	30.42	2.21	0.188

Similar results were achieved by Vyrlas et al. (2014). While during their first year, they had lower yield and lower sugar content in aerated SDI (185.87 Mg/ha and 13.12%) compared to non-aerated SDI (189.60 Mg/ha and 13.51%), during the next two seasons aerated SDI showed an increase in the yield (170.50 Mg/ha and 194.60 Mg/ha) compared to the non-aerated SDI (169.54 Mg/ha and 187.09 Mg/ha).

Higher sugar beet yields occurred in the SDI system compared with the surface DI system (Sakellariou et al., 2002 and Vyrlas and Sakellariou, 2005). For example, Sakellariou et al. reported that sugar beet yield and sugar content were higher (62.48 Mg/ha, 14.03%) with SDI than surface DI (54.71 Mg/ha, 12.87%) (Sakellariou et al., 2002).

State and county sugar beet yields (Table 11) and sugar content (Table 12) data were obtained implementing different types of irrigation strategies (furrow, sprinkler, SDI, etc.) as well as different types of water (primarily groundwater). In 2019, at the Mitchell farm, in the presence of non-aerate SDI, the sugar beet yield was 22.45 ton/acre and increased to 24.19 ton/acre for the aerated SDI. The lower sugar beet yield achieved in 2019 may be related to the adverse weather events (two hail storms). In fact, the leaves were damaged during these events and were growing back by the time of the harvest, consuming some of the sugar stored.

Table 11: Average sugar beet yields in Scottsbluff County, NE over the past 5 years.

Sugar beet (ton/acre)				
Year	**Nebraska**	**Scottsbluff County**	**Mitchell Farm Non-Aerated**	**Mitchell Farm Aerated**
2019	25.4[b]	N/A	22.5 ± 5.2	24.2 ± 5.0
2018	31.9	32.8	-	-
2017	31.8	34.1	-	-
2016	29.9	31.4	-	-
2015	28.4	30.7	-	-

Source: https://www.nass.usda.gov/Statistics_by_State/Nebraska/index.php
[b]https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA

Table 12: Average sugar content (%) in Scottsbluff County, NE over the past 5 years.

Sugar content (%)				
Year	**Nebraska**	**Scottsbluff County**	**Mitchell Farm Non-Aerated**	**Mitchell Farm Aerated**
2019	N/A	N/A	14.39 ± 0.6	14.41 ± 0.6
2018	16.46	16.86	-	-
2017	17.73	16.86	-	-
2016	18.39	18.05	-	-
2015	17.7	17.32	-	-

Source: https://www.nass.usda.gov/Statistics_by_State/Nebraska/index.php).
[b]https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA

Comparing results obtained not only using different types of irrigation but also different types of water is quite challenging. To date and the best of my knowledge, feedlot runoff combined with air-injected SDI hasn't been used to grow sugar beets and corn even in the presence of different types of irrigation. However, a few studies highlighted the enhanced grow these two crops using human treated wastewater compared to freshwater in the presence of different types of irrigation (e.g., furrow irrigation). According to Hassanli et al., furrow irrigation with treated wastewater increased the yields of sugar beets (from 41.4 to 56.5 Mg/ha) and corn (from 9.97 to 10.57 Mg/ha in 2005 and from 9.21 to 10.30 Mg/ha 2006) compared to freshwater (Hassanli et al., 2010; 2009). Similarly, Mok et al. growing corn, observed an increased yield (10.30 t/ha to 11.71 t/ha) by replacing surface water with treated wastewater in the absence of fertilizer applications (Mok et al., 2014).

4. CONCLUSIONS

This study evaluated the effect of irrigation with feedlot runoff into air-injected SDI on soil properties (e.g., water content, oxygen, etc.) and on corn (*Zea mays*) and sugar beets (*Beta vulgaris*) production. To the best of my knowledge, no other studies have been conducted using treated wastewater (e.g., feedlot runoff) to grow crops in the presence of SDI coupled with air-injection. The two closest studies available used freshwater instead of treated wastewater to irrigate corn and sugar beets using air-injected SDI (Abuarab et al., 2013; Vyrlas et al., 2014).

Air-injected SDI had a positive effect on soil oxygen and soil moisture content (first objective). It increased the soil oxygen amount. At 45 cm depth, the aerated zone contained the same or even a higher amount of soil oxygen that non-aerated zone at 25 cm depth. Also, air injection reduced soil moisture content probably due to the increase in root water intake due to an increase in root respiration and soil respiration.

Air-injected SDI had a beneficial effect (second objective) on the growth (dimensions and weight) and the production (yield) of corn and sugar beets even if it was not statistically significant (p >0.05). Injected air accounted for a 5.50% increase in yield in corn and 7.75% yield in sugar beet. Those values are slightly lower than those previously reported in the literature. However, they are promising considering the adverse weather conditions experienced during the study. Also, delays and technical difficulties encountered at the beginning of the study may have limited the yield of the two crops. However, based on previous investigations, an increased yield is expected during the second year.

REFERENCES

Abuarab, M., Mostafa, E., and Ibrahim, M. (2013). Effect of air injection under subsurface drip irrigation on yield and water use efficiency of corn in a sandy clay loam soil. *Journal of Advanced Research*, *4*(6), 493-499.

Aguilar, J., Rogers, D. H., Lamm, F. R., and Kisekka, I. (2015). SDI applications in Kansas and the US, 71–82.

Alexandratos, N., and Bruinsma, J. (2012). World agriculture towards 2030/2050: The 2012 revision.

Alfarra, A., Kemp-Benedict, E., Hötzl, H., Sader, N., and Sonneveld, B. (2011). A framework for wastewater reuse in Jordan: utilizing a modified wastewater reuse index. *Water Resources Management*, *25*(4), 1153-1167.

Amer, K. H. (2010). Corn crop response under managing different irrigation and salinity levels. *Agricultural Water Management*, *97*(10), 1553–1563

Ayars, J. E., Fulton, A., and Taylor, B. (2015). Subsurface drip irrigation in California — Here to stay? *Agricultural Water Management*, *157*, 39–47.

Ayars, J. E., Phene, C. J., Hutmacher, R. B., Davis, K. R., Schoneman, R. A., Vail, S. S., and Mead, R. M. (1999). Subsurface drip irrigation of row crops : A review of 15 years of research at the Water Management Research Laboratory. *Agricultural Water Management*, *42*(1), 1–27.

Becerra-Castro, C., Lopes, A. R., Vaz-Moreira, I., Silva, E. F., Manaia, C. M., and Nunes, O. C. (2015). Wastewater reuse in irrigation: A microbiological perspective on implications in soil fertility and human and environmental health. *Environment International*, *75*, 117–135.

Ben-Noah, I., and Friedman, S. P. (2016). Aeration of clayey soils by injecting air through subsurface drippers : Lysimetric and field experiments. *Agricultural Water Management*, *176*, 222–233.

Bhattarai, S, P., Huber, S., and Midmore, D. J. (2004). Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean, and cotton in heavy clay soils. *Association of Applied Biologists*, *144*, 285–298.

Bhattarai, S. P., Midmore, D. J., and Pendergast, L. (2008). Yield, water-use efficiencies, and root distribution of soybean, chickpea, and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrigation Science*, *26*(5), 439.

Bhattarai, S. P., and Midmore, D. J. (2009). Oxygation enhances growth, gas exchange, and salt tolerance of vegetable soybean and cotton in a saline vertisol. *Journal of Integrative Plant Biology*, *51*(7), 675-688.

Borgman, O., Chefetz, B., 2013. Combined effects of biosolids application and irrigation with reclaimed wastewater on the transport of pharmaceutical compounds in arable soils. *Water Research 47*, 3431–3443.

Boxall, A.B.A., Johnson, P., Smith, E.J., Sinclair, C.J., Stutt, E., Levy, L.S., 2006. Uptake of veterinary medicines from soils into plants. *J. Agric. Food Chem. 54*, 2288–2297.

Bradford, S. A., Segal, E., Zheng, W., Wang, Q., and Hutchins, S. R. (2008). Reuse of concentrated animal feeding operation wastewater on agricultural lands. *Journal of Environmental Quality, 37*(S5), S-97-S-115.

Camp, C. R., Lamm, F. R., Evans, R. G., and Phene, C. J. (2000, November). Subsurface drip irrigation–Past, present, and future. In *Proc. Fourth Decennial Nat'l Irrigation Symp.*, (pp. 14-16).

Chen, X., Dhungel, J., Bhattarai, S. P., Torabi, M., Pendergast, L., and Midmore, D. J. (2011). Impact of oxygation on soil respiration, yield, and water use efficiency of three crop species. *Journal of Plant Ecology*, *4*(4), 236-248.

Churchman, G. J., and Tate, K. R. (1986). Effect of slaughterhouse effluent and water irrigation upon aggregation in seasonally dry New Zealand soil under pasture. *Australian Journal of Soil Research*, *24*(4), 505–516.

Christou, A., Papadavid, G., Dalias, P., Fotopoulos, V., Michael, C., Bayona, J. M., Piña, B., and Fatta-Kassinos, D. (2019). Ranking of crop plants according to their potential to uptake and accumulate contaminants of emerging concern. *Environmental Research, 170,* 422–432.

Cusimano, J., McLain, J. E., Eden, S., and Rock, C. M. (2015). Agricultural use of recycled water for crop production in Arizona. *The University of Arizona, College of Agricultural & Life Sciences.* Cooperative Extension.

D'Alessio, M., Durso, L. M., Williams, C., Olson, C. A., Ray, C., and Paparozzi, E. T. (2020). Applied injected air into subsurface drip irrigation: Plant uptake of pharmaceuticals and soil microbial communities. *Journal of Environmental Engineering*, *146*(2), p.06019008.

D'Alessio, M., Durso, L. M., Miller, D. N., Woodbury, B., Ray, C., and Snow, D. D. (2019). Environmental fate and microbial effects of monensin, lincomycin, and sulfamethazine residues in soil. *Environmental Pollution, 246,* 60–68.

Dery, J. L., Rock, C. M., Rosenberg, R., Onumajuru, C., Brassill, N., Zozaya, S., and Suri, M. R. (2019). Understanding grower perceptions and attitudes on the use of nontraditional water sources, including reclaimed or recycled water, in the semi-arid Southwest United States. *Environmental Research, 170,* 500–509.

Dhungel, J., Bhattarai, S. P., and Midmore, D. J. (2012). Aerated water irrigation (oxygation) benefits to pineapple yield, water use efficiency, and crop health. *Advanced Horticulture*, *23*(1), 3–16.

Edwards, W. M., Owens, L. B., White, R. K., and Fausey, N. R. (1986). Managing feedlot runoff with a settling basin plus tiled infiltration bed. *Transactions of the ASAE*, *29*(1), 0243–0247.

EPA, 2012. Guidelines for Water Reuse.

FAO, (2012). Coping with water scarcity An action framework for agriculture and food security. In the Food and Agriculture Organization of the United Nations.

Gilbertson, C. B., and Nienaber, J. A. (1973). Beef cattle feedlot runoff—Physical properties. *Transactions of the ASAE*, *16*(5), 997–1001.

Gelsomino, A., and Cacco, G. (2006). Compositional shifts of bacterial groups in a solarized and amended soil as determined by denaturing gradient gel electrophoresis. *Soil Biology and Biochemistry*, *38*(1), 91–102.

Goorahoo, D., Adhikari, D., Reddy, N., Cassel, F., Zoldoske, D., Mazzei, A., and Fannuchi, R. (2008). Optimizing crop water use efficiency with AirJection® irrigation. *Fresno, CA: California State Univ*.

Goorahoo, D., Adhikari, D., Zoldoske, D., Mazzei, A., and Fanucchi, R. (2007). Application of airjection irrigation to cropping systems in California. In *International Water Technology and Ozone V Conference,* Fresno.

Goorahoo, D., Carstensen, G., Mazzei, A. (2001). A pilot study on the impact of air injected into water delivered through subsurface drip irrigation tape on the growth and yield of bell peppers. *California Agricultural Technology Institute (CATI) Publication*, *10201*.

Goorahoo, D., Carstensen, G., Zoldoske, D. F., Norum, E., and Mazzei, A. (2002). Using air in sub-surface drip irrigation(SDI) to increase yields in bell peppers. *Int Water Irrig*, *22*(2), 39–42.

Hajiboland, R., Joudmand, A., and Fotouhi, K. (2009). Mild salinity improves sugar beet (*Beta vulgaris L.*) quality. *Acta Agriculturae Scandinavica Section B–Soil and Plant Science*, *59*(4), 295–305.

Hanson, B., and May, D. (2004). Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. *Agricultural Water Management*, *68*(1), 1-17.

Hassanli, A. M., Ebrahimizadeh, M. A., & Beecham, S. (2009). The effects of irrigation methods with effluent and irrigation scheduling on water use efficiency and corn yields in an arid region. *Agricultural water management*, *96*(1), 93-99.

Hassanli, A. M., Ahmadirad, S., & Beecham, S. (2010). Evaluation of the influence of irrigation methods and water quality on sugar beet yield and water use efficiency. *Agricultural Water Management*, *97*(2), 357-362.

Hawke, R. M., and Summers, S. A. (2006). Effects of land application of farm dairy effluent on soil properties: A literature review. *New Zealand Journal of Agricultural Research*, *49*(3), 307-320.

http://www.4oakton.com/proddetail.asp?parent=2&prod=405&value=detail [Accessed on 05/29/2020].

https://www.apogeeinstruments.com/oxygensensor/ [Accessed on 05/28/2020].

https://www.campbellsci.com/cr300v [Accessed on 05/28/2020].

https://www.certifiedmtp.com/ [Accessed on 05/28/2020].

https://extension.unl.edu/statewide/panhandle/panhandle-research-feedlot/ [Accessed on 05/30/2020]

https://www.hannainst.com/hi99301-portable-high-range-ec-tds-meter.html [Accessed on 05/29/2020].

https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA

[Accessed on 06/04/2020].

https://mazzei.net/wp-content/uploads/2019/04/2019-01_Venturi-Injectors-Make-Their-Impact_ModernPumpingToday_NoAd.pdf [Accessed on 05/29/2020].

https://sentektechnologies.com/product-range/soil-data-probes/drill-and-drop/ [Accessed on 05/28/2020].

https://water.unl.edu/documents/Section%20H.pdf [Accessed on 06/24/2020].

https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx [Accessed on 05/30/2020].

https://www.nass.usda.gov/Statistics_by_State/Nebraska/index.php [Accessed on 06/04/2020].

Ibekwe, A. M., Gonzalez-Rubio, A., and Suarez, D. L. (2018). Impact of treated wastewater for irrigation on soil microbial communities. *Science of the Total Environment*, *622–623*, 1603–1610.

Irmak, S., Rees, J. M., Zoubek, G. L., van de Walle, B. S., Rathje, W. R., DeBuhr, R., ... and Christiansen, A. P. (2010). Nebraska agricultural water management demonstration network (NAWMDN): Integrating research and extension/outreach. *Applied Engineering in Agriculture*, *26*(4), 599–613.

Jiménez, B. (2006). Irrigation in developing countries using wastewater. *International Review for Environmental Strategies*, *6*(2), 229–250.

Kalavrouziotis, I.K., Kanatas, P.I., Papadopoulos, A.H., Blademopoulou, S., Koukoulakis,

P.H., Leotsinides, M.N., 2005. Effects of municipal reclaimed wastewater on the macro and microelement status of soil and plants. *Fresenius Environ. Bull. 14* (11), 1050–1057.

Kalavrouziotis, I. K., Robolas, P., Koukoulakis, P. H., and Papadopoulos, A. H. (2008). Effects of municipal reclaimed wastewater on the macro-and micro-elements status of soil and of *Brassica oleracea var. Italica*, and *B. oleracea var. Gemmifera*. *Agricultural Water Management*, *95*(4), 419–426.

Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z., and Zhu, Y. G. (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental Pollution, 152*(3), 686–692.

Khan, S. J., Roser, D. J., Davies, C. M., Peters, G. M., Stuetz, R. M., Tucker, R., and Ashbolt, N. J. (2008). Chemical contaminants in feedlot wastes: Concentrations, effects, and attenuation. *Environment International, 34*(6), 839–859.

Lamm, F. R. (2002). Advantages and disadvantages of subsurface drip irrigation. In *International Meeting on Advances in Drip/Micro Irrigation, Puerto de la Cruz, Tenerife, Canary Islands* (pp. 1-13).

Lamm, F. R. (2009). Unique challenges with subsurface drip irrigation. In *American Society of Agricultural and Biological Engineers*, p. 1, Reno, Nevada, June 21-June 24.

Lamm, F. R. (2016). Cotton, tomato, corn, and onion production with subsurface drip irrigation: A review. *Transactions of the ASABE, 59*(1), 263-278.

Lamm, F. R. (2016). Subsurface drip irrigation and possibilities in alfalfa. In *California Alfalfa and Forage Symposium*.

Lamm, F. R., Bordovsky, J. P., Schwankl, L. J., Grabow, G. L., Enciso-Medina, J., Peters, R. T., ... and Porter, D. O. (2012). Subsurface drip irrigation: Status of technology in 2010. *Transactions of the ASABE*, *55*(2), 483-491.

Lamm, F. R., Rogers, D. H., and Aguilar, J. P. (2018). Filtration and maintenance for SDI systems in U.S. Great Plains. 69–79.

Liu, H., and Huang, G. (2009). Laboratory experiment on drip emitter clogging with freshwater and treated sewage effluent. *Agricultural Water Management*, *96*(5), 745–756.

Malakar, A., Snow, D. D., and Ray, C. (2019). Irrigation water quality—A contemporary perspective. *Water*, *11*(7), 1482.

Marschner, H. (1995). Mineral Nutrition of Higher Plants. 2nd Edn. Academic Press, London, UK.

Miller, W.C., 2006. Integrated concepts in water reuse: managing global water needs. *Chemosphere 187*: 66–75.

Mok, H. F., Dassanayake, K. B., Hepworth, G., & Hamilton, A. J. (2014). Field comparison and crop production modeling of sweet corn and silage maize (*Zea mays L.*) with treated urban wastewater and freshwater. *Irrigation Science*, *32*(5), 351-368.

Nebraska Department of Agriculture. (2019). Nebraska Agriculture Fact Card. (402), 2341.

O'Brien, D, Rogers, Danny H, Lamm, F. R., and Clark, G. A. (1998). An Economic Comparison of Subsurface Drip Irrigation and Center Pivot Sprinkler Irrigation Systems. *Applied Engineering in Agriculture, 14*(1997), 391–398.

Ölmez, H. (2014). Water consumption, reuse, and reduction strategies in food processing. *Sustainable food processing. John Wiley and Sons, Ltd, Chichester*, 401–434.

Olson, B. M., Miller, J. J., Joan Rodvang, S., and Jay Yanke, L. (2005). Soil and groundwater quality under a cattle feedlot in southern Alberta. *Water Quality Research Journal of Canada*, *40*(2), 131–144.

Pablo, R. G., O'Neill, M. K., McCaslin, B. D., Remmenga, M. D., Keenan, J. G., and Onken, B. M. (2007). Evaluation of corn grain yield and water use efficiency using subsurface drip irrigation. *Journal of Sustainable Agriculture*, *30*(1), 153–172.

Pendergast, L., Bhattarai, S. P., and Midmore, D. J. (2014). Benefits of oxygation of subsurface drip-irrigation water for cotton in a Vertosol. *Crop and Pasture Science*, *64*(12), 1171–1181.

R Software, 2013: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Ricart, S., Rico, A. M., Ribas, A. 2019. Risk-yuck factor nexus in reclaimed wastewater for irrigation: Comparing farmers' attitudes and public perception. *Water 11*(2): 187.

Rock, C., Solop, F. I., and Gerrity, D. (2012). Survey of statewide public perceptions regarding water reuse in Arizona. *Journal of Water Supply: Research and Technology – AQUA*, *61*(8), 506–517.

Sakellariou-Makrantonaki, M., Kalfountzos, D., and Vyrlas, P. (2002). Water-saving and yield increase of sugar beet with subsurface drip irrigation. *Global Nest: The International Journal*, *4*(2–3), 85–91.

Shahien, M. M., Abuarab, M. E., and Magdy, E. (2014). Root aeration improves yield and water use efficiency of irrigated potato in sandy clay loam soil. *International Journal of Advanced Research*, *2*(10), 310-320.

Sim, W., Lee, J., Lee, E., Shin, S., Hwang, S., and Oh, J. (2011). Occurrence and distribution of pharmaceuticals in wastewater from households, livestock farms, hospitals, and pharmaceutical manufactures. *Chemosphere*, *82*(2), 179–186.

Smith, R. J., Raine, S. R., and Minkevich, J. (2005). Irrigation application efficiency and deep drainage potential under surface irrigated cotton. *Agricultural Water Management*, *71*(2), 117-130.

Sonbol, H. A., El-Hadidi, E. M., Said, M. M., and Abo El-Soud, H. M. (2010). Effect of different surface and drip irrigation systems on sugar beet yield, irrigation performances, and soil salinity at the north delta. *Journal of Soil Sciences and Agricultural Engineering*, *1*(4), 407-420.

Sparling, G. P., Schipper, L. A., and Russell, J. M. (2001). Changes in soil properties after application of dairy factory effluent to New Zealand volcanic ash and pumice soils. *Soil Research*, *39*(3), 505–518.

Toze, S. (2006). Reuse of effluent water—benefits and risks. *Agricultural Water Management*, *80*(1–3), 147–159.

Trooien, T. P., Lamm, F. R., Stone, L. R., Alam, M., Rogers, D. H., Clark, G. A., and Schlegel, A. J. (2000). Subsurface drip irrigation using livestock wastewater: Dripline flow rates. *Applied Engineering in Agriculture*, *16*(5), 505.

Vivek, P., Pandiselvam, R., and Rajendaran, R. (2015). Yield Maximization in Radish Crop through Airjection Drip Irrigation System. *Trends in Biosciences, 8*(15), 3972–3975.

Vyrlas, P., Sakellariou-Makrantonaki, M., and Kalfountzos, D. (2014). Aerogation: Crop root-zone aeration through a subsurface drip irrigation system. *WSEAS Transactions on Environment and Development*, *10*, 446–451.

Vyrlas, P., and Sakellariou-Makrantonaki, M. (2005). Intermittent water application through surface and subsurface drip irrigation. In *2005 ASAE Annual Meeting* (p. 1). American Society of Agricultural and Biological Engineers.

Wei, R., Ge, F., Zhang, L., Hou, X., Cao, Y., Gong, L., Chen, M, Wang, R., and Bao, E. (2016). Occurrence of 13 veterinary drugs in animal manure-amended soils in Eastern China. *Chemosphere, 144*, 2377–2383.

WHO, 2006. WHO guidelines for the safe use of wastewater, excreta, and greywater. Volume II: wastewater in agriculture. Geneva, Switzerland.

Woodbury, B. L., Nienaber, J. A., and Eigenberg, R. A. (2003). Performance of a passive feedlot runoff control and treatment system. *Transactions of the ASAE*, *46*(6), 1525.

Wu, X., Dodgen, L. K., Conkle, J. L., and Gan, J. (2015). Plant uptake of pharmaceutical and personal care products from recycled water and biosolids: a review. *Science of the Total Environment*, *536*, 655–666.

Xu, J., Wu, L., Chang, A. C., and Zhang, Y. (2010). Impact of long-term reclaimed wastewater irrigation on agricultural soils: A preliminary assessment. *Journal of Hazardous Materials*, *183*(1–3), 780–786.

Yonts, C. D., Haghverdi, A., Reichert, D. L., and Irmak, S. (2018). Deficit irrigation and surface residue cover effects on dry bean yield, in-season soil water content, and irrigation water use efficiency in western Nebraska high plains. *Agricultural Water Management*, *199*, 138–147.

Yuan, L., Wenquan, N., Jingwei, W., Jian, X., Mingzhi, Z., and Kangyong, L. (2016). Review on advances of airjection irrigation. *International Journal of Agricultural and Biological Engineering*, *9*(2), 1–10.

Zörb, C., Geilfus, C. M., and Dietz, K. J. (2019). Salinity and crop yield. *Plant Biology*, *21*, 31–38

A. Appendix

A.1. Codes used in Data Loggers to collect and save data from sensors.

```
'Program created for Campbell CR300 datalogger
'1 Sentek Drill and Drop 120 cm SDI12 output, 2 apogee oxygen sensor analog
'Xin created on 06/20/2019

'{
'Declare Variables and Units---------

   Public BattLogger
   Public BattProbe
   Units BattLogger = Volts
   Units BattProbe = Volts


   'Sentek sensors arrays
   Public Sentek_VWC(9)
   Public Sentek_VWC_1(3)
   Public Sentek_Salinity(9)
   Public Sentek_Salinity_1(3)
   Public Sentek_Temp(9)
   Public Sentek_Temp_1(3)


   Units Sentek_VWC()=%
   Units Sentek_VWC_1()=%
   Units Sentek_Salinity()=VIC
   Units Sentek_Salinity_1()=VIC
   Units Sentek_Temp()=degreeC
   Units Sentek_Temp_1()=DegreeC


   Alias Sentek_VWC(1)=VWC_5cm
   Alias Sentek_VWC(2)=VWC_10cm
   Alias Sentek_VWC(3)=VWC_15cm
   Alias Sentek_VWC(4)=VWC_35cm
   Alias Sentek_VWC(5)=VWC_45cm
   Alias Sentek_VWC(6)=VWC_55cm
   Alias Sentek_VWC(7)=VWC_65cm
   Alias Sentek_VWC(8)=VWC_75cm
   Alias Sentek_VWC(9)=VWC_85cm
   Alias Sentek_VWC_1(1)=VWC_95cm
   Alias Sentek_VWC_1(2)=VWC_105cm
```

```
Alias Sentek_VWC_1(3)=VWC_115cm


Alias Sentek_Salinity(1)=Salinity_5cm
Alias Sentek_Salinity(2)=Salinity_10cm
Alias Sentek_Salinity(3)=Salinity_15cm
Alias Sentek_Salinity(4)=Salinity_35cm
Alias Sentek_Salinity(5)=Salinity_45cm
Alias Sentek_Salinity(6)=Salinity_55cm
Alias Sentek_Salinity(7)=Salinity_65cm
Alias Sentek_Salinity(8)=Salinity_75cm
Alias Sentek_Salinity(9)=Salinity_85cm
Alias Sentek_Salinity_1(1)=Salinity_95cm
Alias Sentek_Salinity_1(2)=Salinity_105cm
Alias Sentek_Salinity_1(3)=Salinity_115cm


Alias Sentek_Temp(1)=Temp_5cm
Alias Sentek_Temp(2)=Temp_10cm
Alias Sentek_Temp(3)=Temp_15cm
Alias Sentek_Temp(4)=Temp_35cm
Alias Sentek_Temp(5)=Temp_45cm
Alias Sentek_Temp(6)=Temp_55cm
Alias Sentek_Temp(7)=Temp_65cm
Alias Sentek_Temp(8)=Temp_75cm
Alias Sentek_Temp(9)=Temp_85cm
Alias Sentek_Temp_1(1)=Temp_95cm
Alias Sentek_Temp_1(2)=Temp_105cm
Alias Sentek_Temp_1(3)=Temp_115cm


'Analog sensors, oxygen sensor

Public Signal_10_inch, O2_10_inch, OSensorTC_10_inch 'Oxygen sensor 1
Public Signal_18_inch, O2_18_inch, OSensorTC_18_inch 'Oxygen sensor 2


'Declare Constants

Const CF = 0.379 'sensor specific,
Const Offset = 1.14 'sensor specific,


'Define Data Tables---------------

'{
```

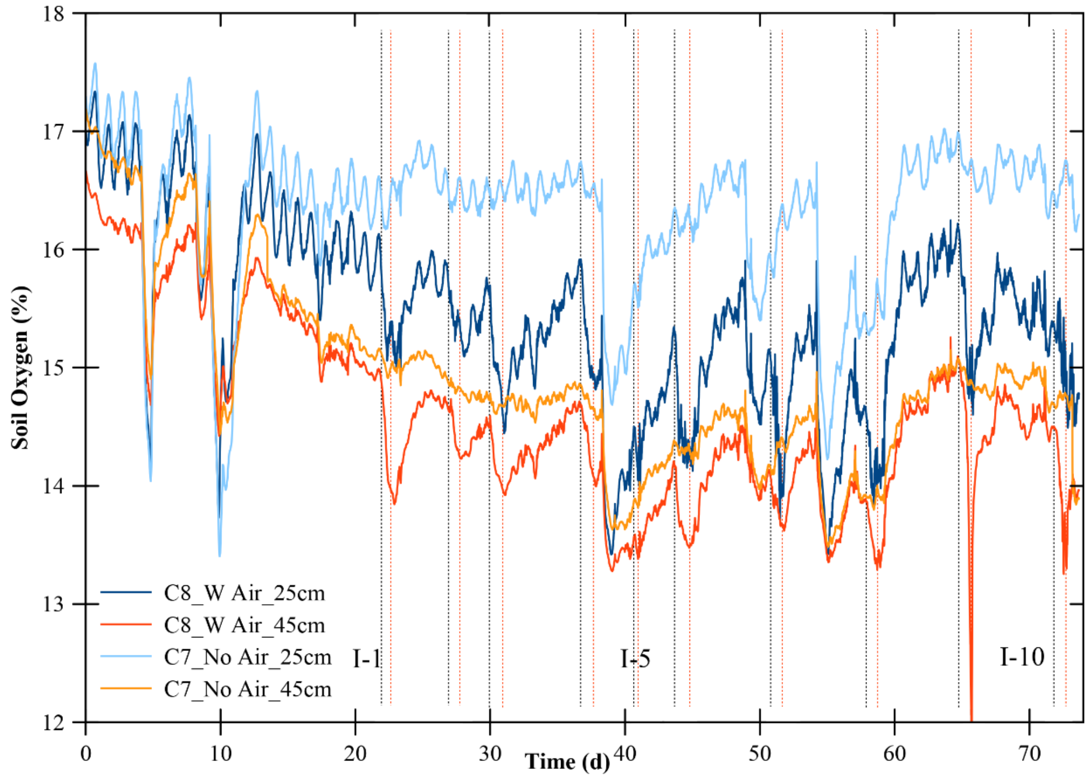
```
'   DataTable(average5min,True,-1)

'     DataInterval(0,5,min,0)

"     'Sentek

'     Average(1,Sentek_VWC(),IEEE4,False)
'     Average(1,Salinity(),IEEE4,False)
'     Average(1,Temp(),IEEE4,False)
'

'     'Oxygen

'     Average(1,O2_10_inch,IEEE4,False)
'     Average(1,OSensorTC_10_inch,IEEE4,False)
'     Average(1,O2_18_inch,IEEE4,False)
'     Average(1,OSensorTC_18_inch,IEEE4,False)

'   EndTable

    DataTable(Avg5min,True,-1)
      DataInterval(0,5,min,0)
      Maximum(1,BattLogger,FP2,0,1)


      'Sentek

      Average(9,Sentek_VWC(),FP2,False)
      Average(3,Sentek_VWC_1(),FP2,False)
      Average(9,Sentek_Salinity(),FP2,False)
      Average(3,Sentek_Salinity_1(),FP2,False)
      Average(9,Sentek_Temp(),FP2,False)
      Average(3,Sentek_Temp_1(),FP2,False)

      'Oxygen

      Average(1,O2_10_inch,IEEE4,False)
      Average(1,OSensorTC_10_inch,IEEE4,False)
      Average(1,O2_18_inch,IEEE4,False)
      Average(1,OSensorTC_18_inch,IEEE4,False)
    EndTable


'Main Program:--------------------
```

```
'{

BeginProg

  Scan(1,min,0,0)'Main Scan


    Battery(BattLogger)
    SW12(1) 'turn on 12v power
    Delay(0,1,sec)
'       Power up the Excitation channels
    ExciteV(Vx1,2500,0)
    ExciteV(Vx2,2500,0)


    'Apogee Oxygen--

    '{

    'Measure Absolute Oxygen Concentration and Sensor Temperature
    'Sensor 1, installed at 10 inches depth, differential channel 1
    VoltDiff (Signal_10_inch,1,mV2500,1,True,20,60,1.0,0)
    O2_10_inch = CF * Signal_10_inch - Offset
    Therm109 (OSensorTC_10_inch,1,5,Vx1,20,60,1.0,0)

    'Sensor 2, installed at 18 inches depth, differential channel 2
    VoltDiff (Signal_18_inch,1,mV2500,2,True,20,60,1.0,0)
    O2_18_inch = CF * Signal_18_inch - Offset
    Therm109 (OSensorTC_18_inch,1,6,Vx2,20,60,1.0,0)
'    }

    'Sentek--

    '{

    'VWC

    SDI12Recorder (Sentek_VWC(),C1,"0","M!",1,0) 'Measure the soil moisture values
  1-9
    If Sentek_VWC(1)=NaN Then Move(Sentek_VWC(),9,NaN,1)
    SDI12Recorder (Sentek_VWC_1(),C1,"0","M1!",1.0,0) 'Measure the soil moisture
  values 10-12

    If Sentek_VWC_1(1)=NaN Then Move(Sentek_VWC_1(),3,NaN,1)
    'Salinity
```

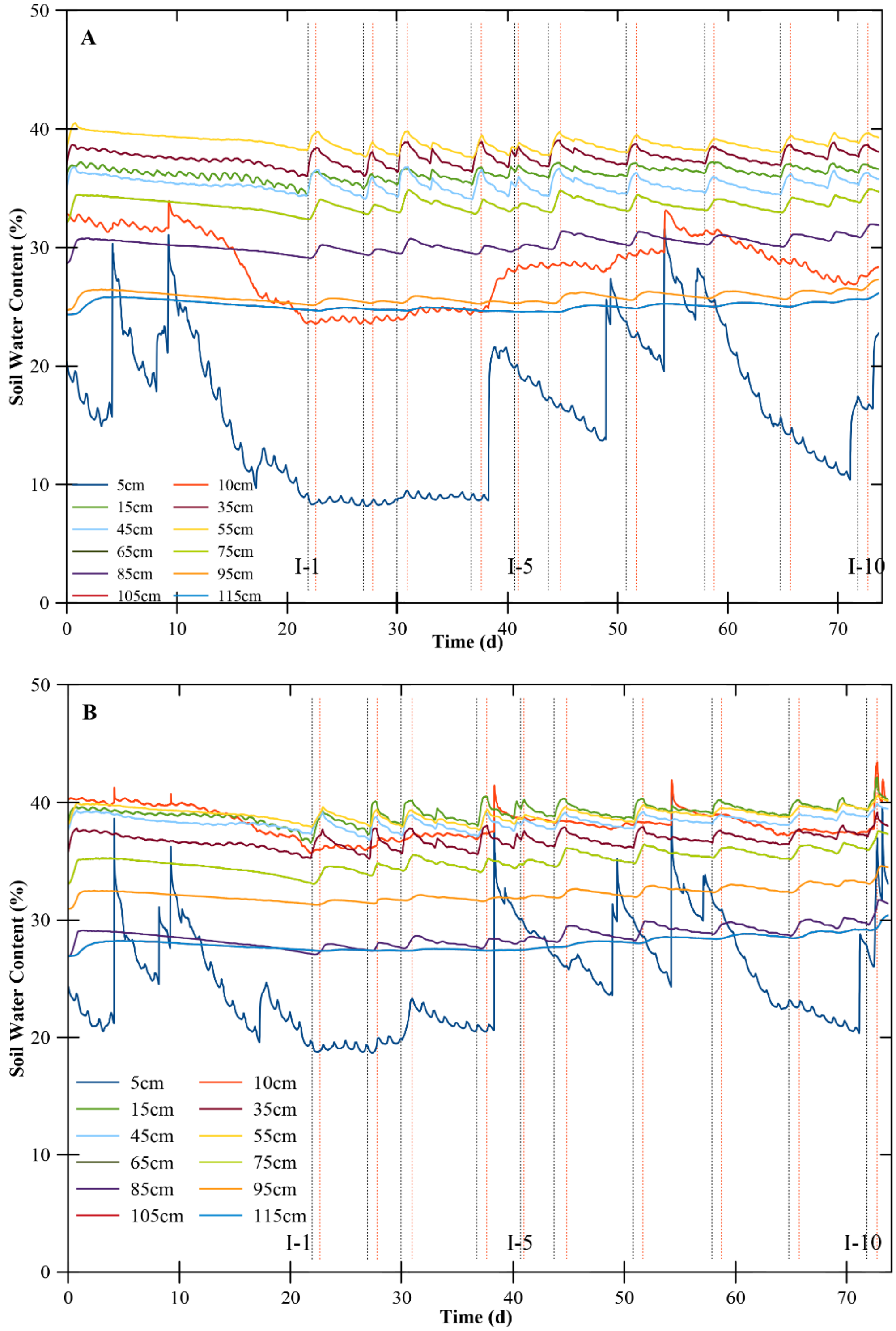
```
  SDI12Recorder (Sentek_Salinity(),C1,"0","M2!",1.0,0) 'Measure the Salinity Values
1-9
  If Sentek_Salinity(1)=NaN Then Move(Sentek_Salinity(),9,NaN,1)
  SDI12Recorder (Sentek_Salinity_1(),C1,"0","M3!",1.0,0) 'Measure the salinity
values 10-12

  If Sentek_Salinity_1(1)=NaN Then Move(Sentek_Salinity_1(),3,NaN,1)
  'Temperature
  SDI12Recorder (Sentek_Temp(),C1,"0","M4!",1.0,0) 'Measure the temperature
values 1-9
  If Sentek_Temp(1)=NaN Then Move(Sentek_Temp(),9,NaN,1)
  SDI12Recorder (Sentek_Temp_1(),C1,"0","M5!",1.0,0) 'Measure the temperature
values 10-12

  If Sentek_Temp_1(1)=NaN Then Move(Sentek_Temp_1(),3,NaN,1)

  'Sentek probe voltage

  SDI12Recorder (BattProbe,C1,"0","M9!",1.0,0) 'Measure the probe supply voltage

  SW12(0)

  CallTable Avg5min



 NextScan

EndProg

'}

'}
```

B. Appendix

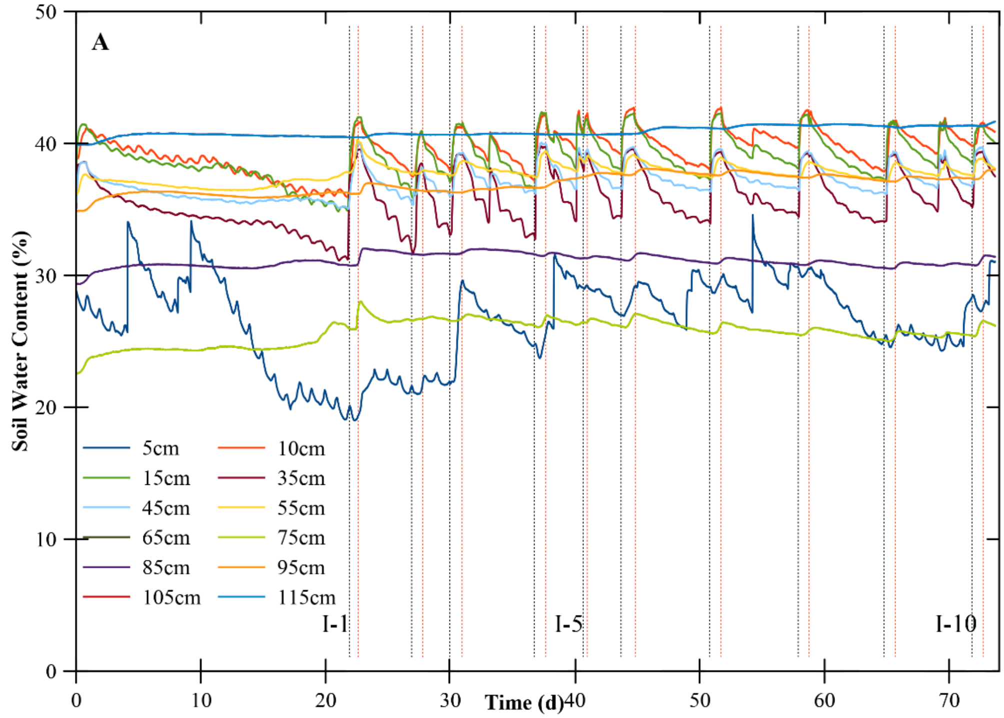
Soil Oxygen and Soil Moisture

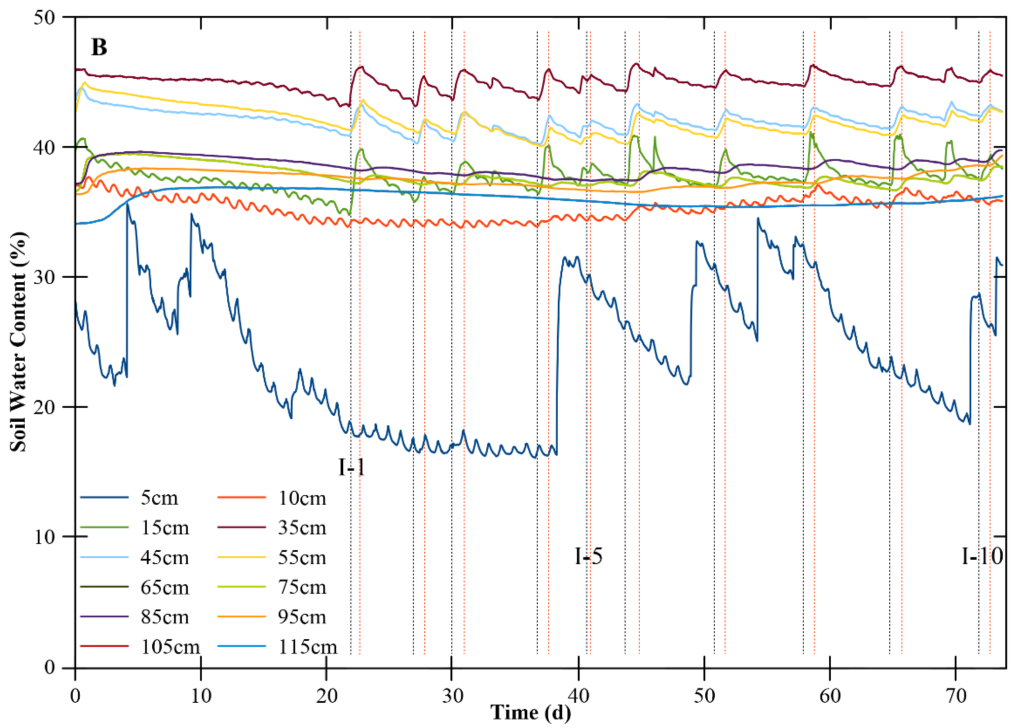


B1: Corn: soil oxygen content at 25 and 45 cm below the soil surface [C8_W air: corn, Zone 8, with injected air; C7_No Air: corn, Zone 7, without injected air].

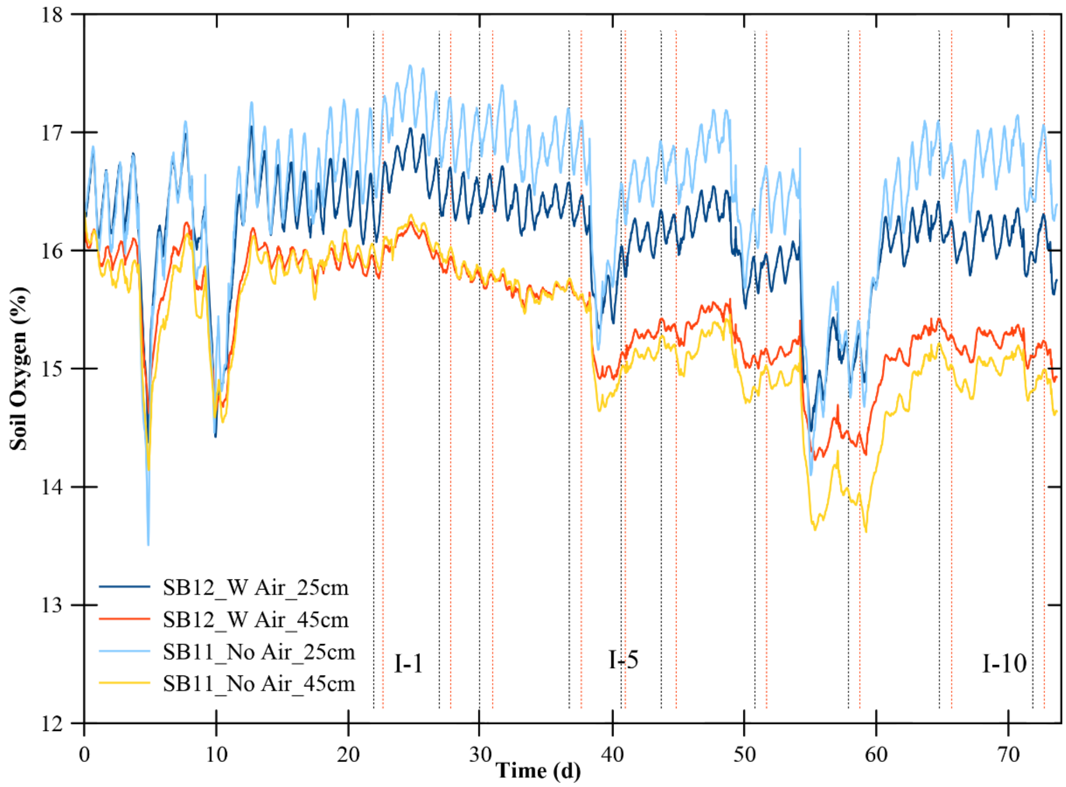


B2: Corn: soil water content for all depths. (A): C-2, aerated and (B): C-1 non-aerated.

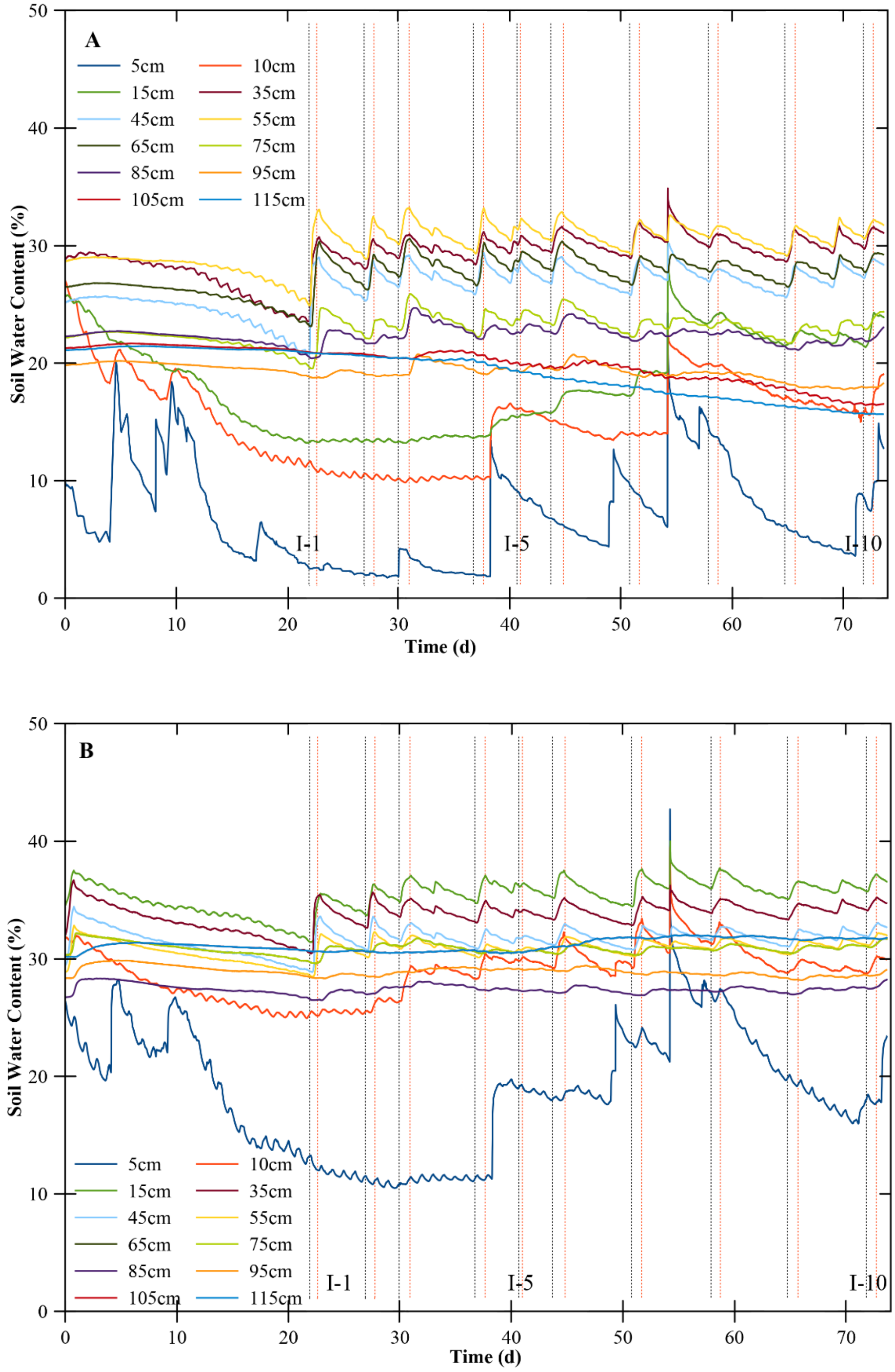




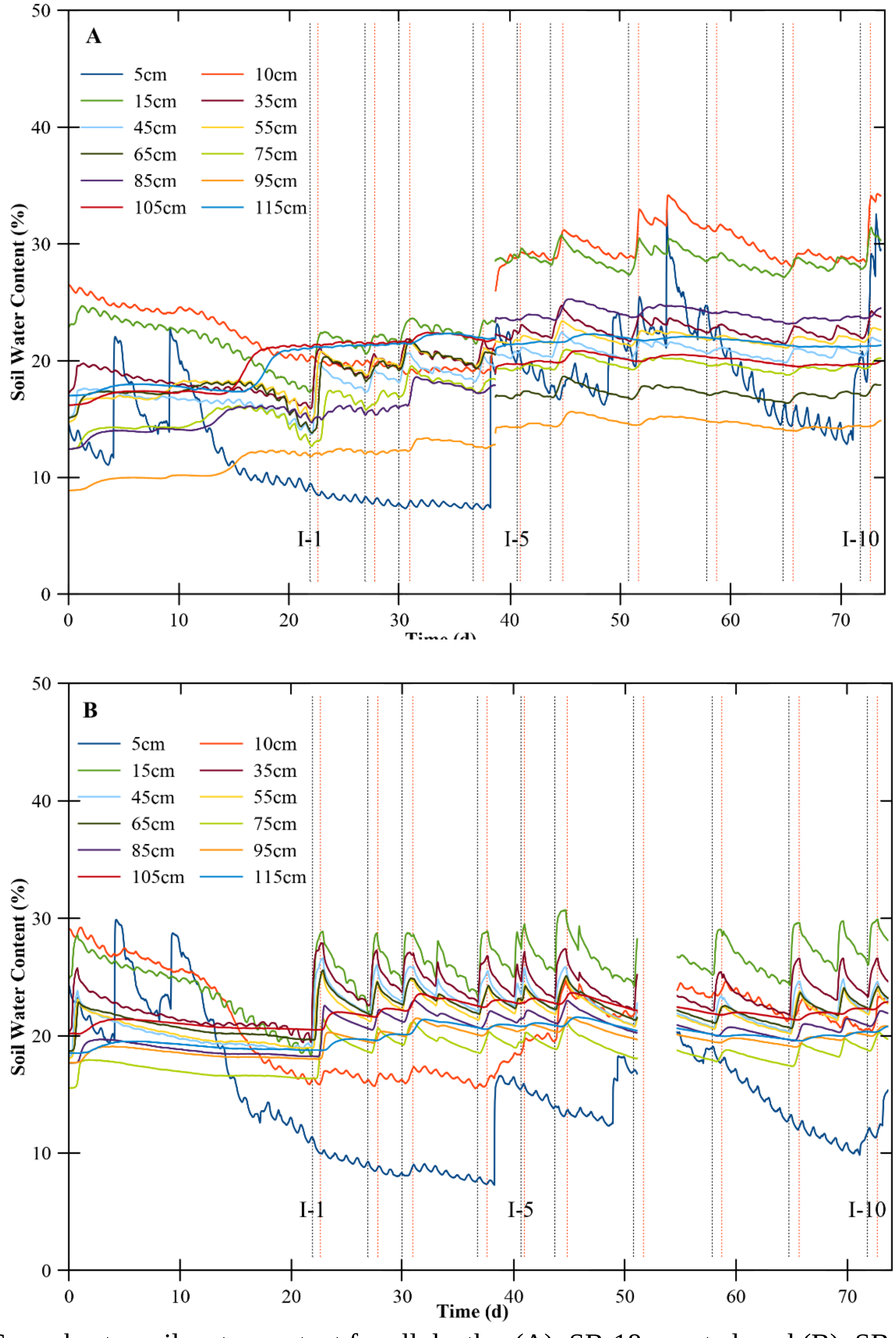
B3: Corn: soil water content for all depths. (A): C-8, aerated, and (B): C-7, non-aerated.



B4: Sugar beets: soil oxygen content at 25 and 45 cm below the soil surface [SB12_W Air: sugar beets, Zone 12 with injected air; SB11_No Air: sugar beets, Zone 11 without injected air].



B5: Sugar beets: soil water content for all depths. (A): SB-12, aerated and (B): SB-11, non-aerated).



B6: Sugar beets: soil water content for all depths. (A): SB-18, aerated, and (B): SB-17 non-aerated.