EFFECT OF WATER TABLE LEVEL ON SOYBEAN WATER USE, GROWTH AND YIELD PARAMETERS

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Yavuz Fatih Fidantemiz

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Yavuz Fatih Fidantemiz

The Supervisory Committee certifies that this thesis complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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SUPERVISORY COMMITTEE:

Dr. Halis Simsek
Chair

Dr. Xinhua Jia

Dr. Aaron Daigh

Dr. Chiwon W. Lee

Approved:

December 5, 2018
Date

Dr. Sreekala Bajwa
Department Chair

ABSTRACT

Responses of soybean (*Glycine* max) water uptake and crop growth to four constant water table depths (30, 50, 70, and 90 cm) were studied under a controlled environment using lysimeters. Additionally, control lysimeters with irrigation and no water table were used for comparison. A randomized complete block design (RCBD) was used with six replications in each treatment. The results indicated that the water table depths of 30, 50, 70 and 90 cm contributed to 77, 71, 65 and 62% of soybean water use, respectively. Thus, the water use efficiency, total grain yield (g lysimeter^{-1}) per unit water use (mm) was 0.008, 0.022, 0.018, 0.025, and 0.031 for irrigation, 30, 50, 70, and 90 cm water table depth treatments, respectively. Soybean was found to be tolerant to shallow groundwater conditions, and root mass distribution in the soil profile was significantly influenced by the presence of shallow water table depths.

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DEDICATION

I dedicate this thesis to my family,

and

to my fiancée, Basak Kucuk,

who never stopped to support and believe in me throughout my life.

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LIST OF ABBREVIATIONS

ET_0	Reference evapotranspiration
ETc	Evapotranspiration (crop water use)
RCBD	Randomized complete block design
RAM	Readily available moisture
WUE	Water use efficiency
WTD	Water table depth.
TAM	Total available moisture

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1. INTRODUCTION

Increases in the world population will increase the global demand for water use in urban, industrial, environmental and agricultural areas. The world population is estimated to approach about 9 billion in 2050, which means water demand will be increased significantly during the upcoming decades (Ayars et al., 2006). Thus, it is assumed that many arid and semi-arid regions will have difficulties to reach a sufficient and reliable water source (Hamdy et al., 2003; Steduto et al., 2017). Annual available water resource per capita is expected to decrease from 6,600 m^3 to 4,800 m^3 in 25 years due to the increasing global population. Since water resources are not evenly distributed in the world, around 3 billion people living in the arid and semi-arid regions greatly suffer from water scarcity and will have less than 1,700 m^3 annual water resource per capita (Cosgrove and Rijsberman, 2000).

Since a significant portion of the world’s water resources is used for agricultural production, improved and well-managed water use efficiency (WUE) in agriculture provides opportunities to conserve limited water resources (Ayars et al., 2006). Water use for agricultural purposes accounts for more than 80% of all water withdrawals in arid and semi-arid regions such as Asia and Africa (Hamdy et al., 2003). The water use in agriculture is considerably higher than the combination of industrial and municipal sectors. Hence, increasing WUE in agriculture could be an effective way to save water.

To deal with the potential water crisis that may occur in the future, new water management techniques and strategies are required in agriculture. Improved understanding of water table contributions to crop water use could help improve agricultural water management (Ghamarnia et al., 2011; Kahlown and Ashraf, 2005). Water table contribution to plant water use can be significant element in crop production by reducing the drainage and irrigation water volume by enhancing crop water uptake from groundwater (Hutmacher et al., 1996).

Shallow water table contributions to crop growth have gained attention recently, with research in the controlled environments (laboratories and greenhouses) using weighed lysimeters and in the field using controlled drainage practices (Ayars et al., 2006; Kahlown and Ashraf, 2005; Li et al., 2018; Soppe, 2001). When optimal water table depth is maintained for a crop, groundwater can be considered as an excellent water source to support the crop water use. Hence, the crop water requirement can be obtained with less amount and frequency of surface irrigation. Additionally, the optimum water table depth can supply the necessary respiration and aeration for plant roots (Franzen, 2013).

Shallow groundwater is considered an alternative water resource for both dry and irrigated agriculture when the quality of groundwater is acceptable for sustainable crop production (Hutmacher et al., 1996). Optimum water table depth not only supplies a significant amount of water to crops but it eliminates waterlogging in the root zone (Kahlown and Ashraf, 2005). Whilst much evidence exist for groundwater contribution to crop water use in the literature (Ayars and Schoneman, 1986; Ayars et al., 2001; Benz et al., 1978; Dugas et al., 1990; Hutmacher et al., 1996), most irrigation programs assume groundwater is deep enough so that capillary flux does not reach root zone and that irrigation water is required to meet the plant water demand (Gao et al., 2017). However, shallow groundwater can be a water source which helps to decrease the need for irrigation water (Ghamarnia and Daichin, 2013; Gowing et al., 2009).

Several variations are affecting crop growth under shallow groundwater. Crop growth is a complex system under shallow groundwater levels due to limited information on the potential contribution of groundwater to plant water-use. Therefore, a lysimeter study was used to determine water table contributions to soybean water demands and plant growth (Ghamarnia and Daichin, 2013; Talebnejad and Sepaskhah, 2015).

1.1. Statement of Objective

The primary interest of this study was to answer the question of how shallow groundwater could potentially be used for soybean production. Hence the focus of this study was to determine groundwater contributions to soybean water use and the soybean response to different water table levels. The specific objectives are as follows:

- To determine crop water use of soybean from the different water table depths of 30, 50, 70, and 90 cm without irrigation condition.
- To determine the effects of shallow groundwater depth on soybean growth and yield parameters.
- To investigate the effect of groundwater depth on root distribution of soybean.

2. REVIEW OF LITERATURE

2.1. Importance of the Study

The world population is growing dramatically, and water scarcity is becoming a challenge throughout the world that nearly 40% of the population experience water shortage. On the other hand, the rate of water utilization increases at twice the rate in the world as compare to the increases in the human population. Population growth, urbanization, industrialization, and environmental pollution cause water shortages to an extent that water can no longer be considered as an infinite source (Hamdy et al., 2003; Steduto et al., 2017).

The Food and Agricultural Organization (2016) reported that agriculture is 69% of the total water consumption, while it is 19 and 12% in industrial, and municipal utilization in the world, respectively. It was projected that increases in world population cause an intensification of industrial development, and water utilization in this sector could be increased accordingly. This water demand could affect the amount of water utilization in agricultural sectors since more water could be used in industrial area (Ayars et al., 2006; Hamdy et al., 2003). To deal with this potential water crisis, new water management approaches and strategies are required for all sectors, in particular, agricultural area.

Projected restrictions on availability of water for food production could be overcome by improving WUE, which is a strong indication of the improved agricultural water management. Improved WUE is possible through innovations in irrigation, technological development in drainage systems, improved crop tolerance, and productive land use (precision agriculture). Deficit irrigation applications combined with water use from shallow groundwater could be an approach to increase WUE in arid and semi-arid areas where water supply is limited (Franzen, 2013). The term, WUE, is used for both engineering and agronomic perspective (Howell, 2001).

The precise definition of agronomic WUE made by ASABE Standards (2015) as total biomass or grain yield produced per unit of water used for crop production. Also, Payero et al. (2005) used the term crop water productivity to describe the same equation instead of WUE.

2.2. North Dakota Soybean Production

Soybean (*Glycine max (L.) Merrill*) is an oilseed crop commonly cultivated all around the world. Average soybean seed contains about 40% protein and 20% oil and soybean is considered as one of the principal sources of food and industrial sectors (Lee et al., 2007). Soybean, as a legumes plant, is well acknowledged for its good agronomical performance as well as for its importance in the sustainable agricultural systems. North Dakota (ND) is one of the leading states in the United States (US) where soybean is grown extensively. Statistics from ND Soybean Council announced that ND is the 4th biggest states in terms of acres planted soybean in the US in 2014. In 2017, North Dakota had 2.87 million hectares of soybeans with an average yield of 2.3 Mg per hectare for a total production of around 6.6 million tons. Production of soybean in ND increased between the years of 1980 and 2017. Particularly, based on soybean yield (Mg/ha), five counties in ND were ranked in first 20 soybeans producing counties in the US in 2014 (ND Soybean Council, 2017).

North Dakota is located in the center of North America, and it has a continental climate that is a characteristic feature of the Great Plains and Midwest. The climate of North Dakota is characterized by high-air temperature variations, irregular rainfall, and low humidity. Annual precipitation ranges between 355 and 550 mm from northwestern to southeastern North Dakota (NOAA, 2018). In Cass County, which is a place where this research was conducted, the average temperature and wind speed are 15 °C and 3.5 m/s, respectively in the growing season. The lowest and highest temperatures are observed in January and July, respectively. The water table in North Dakota is relatively shallow and it's rise is one of the challenges that influence in both positive and negative ways to the growth and yield of many agricultural products including soybean (Niaghi and Jia, 2017)

2.3. Effect of Water Table Depth on Plant Water Use and Crop Yields

Plant water uptake from shallow groundwater is affected by water table depth, plant salt tolerance and plant root characteristics, soil hydraulic properties, salinity level of the groundwater, and presence of irrigation and drainage systems. Plant salt tolerance is the leading factor affecting water extraction from shallow groundwater. Each plant has a different tolerance to salinity, and plant tolerance differs in each growth stage. All the plants tend to be more susceptible to salinity in their early stage (Kruse et al., 1993; Talebnejad and Sepaskhah, 2015).

2.4. Previous Researches and Results

Several studies were conducted to describe water table-crop relations, and these studies quantified water table contributions to crop water use by utilizing both saline and non-saline groundwater (Ayars et al., 2006). However, in the literature, studies concerned with soybean-water table relations were not discussed in detail. Therefore, in this study, water table effects on other crops, including wheat, cotton, corn, alfalfa, and sugar beet along with soybean were reviewed chronologically.

One of the early research on crop water use from water table was conducted by Namken et al. (1969) who used lysimeter to determine the contribution of shallow groundwater to plant water use with high and low irrigation frequency (duration between irrigation). The soil used in the lysimeter was fine sandy loam. The cotton crop was planted in the study and groundwater levels were maintained at 91, 183, and 274 cm depths. In the first year of the study, the salt concentrations of groundwater ranged from 6 to 8 dS/m, then salinity levels were reduced to 0.9

and 1.6 dS/m for the following three years. Groundwater contributions to crop water use at 91, 183, and 274 cm water table depths were approximately 54, 26, and 17% for the treatments that have high irrigation frequency (wet conditions), and around 61, 49, and 39% for the treatments that have low irrigation frequency (dry conditions), respectively. It has been found that low-frequency irrigation applications triggered crops to utilize water from groundwater (Namken et al., 1969).

In North Dakota, Benz et al. (1978) carried out a field study to examine yield response of three crops (corn, alfalfa, and sugar beet) by applying different water table depths. The soil was a Hecla sandy loam and three different water table depths (1.2, 1.8, and 2.3 m) along with 4 irrigation treatments which ranged from no-irrigation to 1.5 times of the weekly estimated water requirements of the crops were studied during three years of study. The highest yield was obtained from the shallow water table (1.2 m) with no irrigation, and applying irrigation to shallow water table did not increase the yield at the 1.2 m water table depth treatment. Thus, crop yields of medium (1.8 m) and deep (2.3 m) water table treatments increased with irrigation applications. However, even with irrigation applications, the yields from the medium, and deep-water tables were less than the shallow water table with no irrigation.

Meek et al. (1980) investigated the relationship between different water table depths and growth performance of cotton in a field study. The soil texture of the field classified as a silty clay, and three different water table depths (30, 60, and 90 cm) were set in the field. The parameters of soil aeration, plant water relations, cotton yield, and nutrient uptake by the plant were measured. As expected, soil aeration (soil oxygen content and redox potential) was found highest at 90 cm, compared to 60 and 30 cm water table depths. While the nutrient concentrations of N, Ca, K, and Cu in soil were found the highest at the 90 cm depth, P, Mg, Na, and Cl concentrations were found the highest at 30 cm depth. The highest values of soil aeration at 90 cm were observed 25% greater than at 60 cm and 43% greater than at 30 cm water table depths.

Shih and Asce (1983) examined the evaporation rates occurred from different water table depths by comparing them to standard pan evaporation. Two water table depths (8 and 38 cm) with one replication were used in the four concrete lysimeters, and each lysimeter was packed with Pahokee series soil. The surface evaporation from lysimeters was measured as 14, and 26% less than that for standard pan evaporation, respectively. This study has shown that the depth of the water table directly influences the rate of evaporation from the soil surface.

Torres and Hanks (1989) performed greenhouse experiments using lysimeters to determine groundwater contribution to crop water use and developed a numerical model to simulate a saturated and unsaturated flow to capillary zone. Two different soils, silty clay loam, and fine sandy loam were used in the lysimeters, and spring wheat was grown. Four different treatments including no water table, 50, 100, and 150 cm steady-state water table depths were applied in the experiment. Irrigations were scheduled when the 50% of available water was depleted in the root zone. The estimation of the model and observed data from lysimeters were compared to each other, and model estimations were almost identical to the observed values in the study. The results released by this study indicated that nearly 90% of crop water requirement of wheat could be met with a 50 cm water table depth in both soil textures. Groundwater contribution of 100 cm water table depth was found 41 and 31% for silty clay and fine sandy loam soils, respectively. When the groundwater depth decreased to 150 cm depth, groundwater contribution decreased to 7 and 6% for both soil textures, respectively.

Meyer and Mateos (1990) investigated the effect of soil type on soybean water use from shallow groundwater. Two lysimeters, packed with undisturbed block loam and clay loam soils, were used and soybean was grown in the lysimeters. Water tables were equally set up at 100 cm depth from the soil surface. At the end of the season, the contributions of groundwater to soybean water use were found 24 and 6.5% in loam and clay loam soils, respectively. Therefore, soybean's root length density was measured in both lysimeters, and the measured root density for loam soil was twice as high as clay loam soil.

The relationship between shallow saline water tables and plant water use characteristics for three years were investigated using lysimeter techniques (Kruse et al., 1993). All the lysimeters were packed with a fine sandy loam soil for all layers, and three plants, which were corn, alfalfa, and winter wheat were grown. Water table level maintained at 60 and 105 cm, and salinity levels ranged from 0.66 to 6 dS/m. Crop water use from 60 cm water table depth was significantly higher than 105 cm water table depth for alfalfa that the average of three years of groundwater contributions were 76 and 27% at the 60 and 105 cm water table depth, respectively. Therefore, groundwater contribution reduced by around 12% from 76 to 62% as groundwater salinity increased from 0.66 to 6 dS/m at the 60 cm water table depth. However, the increase in salinity did not impact the crop water use at 105 cm. A similar study conducted by Gao et al. (2017) and reported that 41% of the maize growing season water demand could be met with 1 m of groundwater depth. When the groundwater reached 2 m depth, the groundwater contribution reduced to 6%.

Two years of field study was conducted in Ontario, Canada to investigate the effect of water table on corn and soybean grain yields with two different controlled water table levels, which were set at 50 and 75 cm depths. Conventional free drainage treatment was applied and drainage tubes were installed 100 cm below the surface. Corn yields for the first year of the study were compared between water table depths and conventional drainage application. A significant increase was found at the 50 cm water table depth (14% higher corn yields were produced than conventional drainage treatment). In the second year of the study, both controlled water table treatments (50 cm and 75 cm) had higher yields (6.6 and 6.9%) than conventional drainage treatment. Similarly, regarding soybean yields, the highest yield was obtained from the controlled water table plots both in the first year and second year. In conclusion, the highest yields were observed at the controlled drainage treatments (Mejia et al., 2000).

Studies showed that under irrigation conditions, plant water uptake from the groundwater could be significant. To determine the effect of salinity on safflower water uptake, two lysimeters studies were compared in terms of their seasonal plant water requirements (Soppe and Ayars, 2003). The first lysimeter had 90 cm saline water table (14 dS/m) and the other lysimeter did not have a water table. Irrigation scheduled for each lysimeter when 2/3 of the available water in the root zone was depleted. The study showed that 46% less water applied to the lysimeter, which had water table depth at 90 cm. However, due to the salinity, 15% yield loss was found at 90 cm water table treatment. This study concluded that presence of groundwater could be considered as the alternative water source during the drought season. Thus, shallow water table could reduce the amount of irrigation and increase the irrigation frequency, and high salt concentration in the root-zone is associated with lower seasonal plant uptake and yield reduction.

Kahlown and Ashraf (2005) studied groundwater contribution to plant water use with six different crops using lysimeters. The highest groundwater contributions were observed at the shallowest water table depth in their study and the contribution of groundwater for each crop varied with the water table depth. Thus, the groundwater contribution decreased gradually with the increase in water table depth. It was also found that, among the six crops, wheat and sunflower were more tolerant to shallow groundwater depth (50 cm depth). Even groundwater at 50 cm could meet wheat water requirements entirely without any yield loss, and around 80% of the sunflower water requirements can be maintained by groundwater at the 50 cm water table depth. However, maize and sorghum were susceptible plants to the shallow water table, so that yield losses were observed due to the waterlogging at the root-zone. As stated by Gowing et al. (2009), under deficit irrigation conditions, about 40% of water requirement of the wheat crop was obtained from groundwater sources, even if the salinity limited the total water uptake by the wheat crop. This study concluded that shallow groundwater could be considered as a water source which helps to decrease the need for irrigation water.

The evaporation rates from different water levels ranged from 0.09 to 3.33 m were studied (Johnson et al., 2010). The evaporation rates were measured as 3.7 mm d^{-1} and 0.1 mm d^{-1} at the shallowest and the deepest water table, respectively. The results showed that close correlation was found between evaporation rates and groundwater depth. The highest evaporation rate was observed in the coarse-grained soils.

Helmers et al. (2012) evaluated the performance of different drainage practices by comparing them in term of their effects on drainage volume and crop production for four years in field conditions. The study consisted of eight plots, which were four different drainage treatments including no drainage, shallow drainage, controlled drainage, and conventional drainage with two replications. The study was conducted on silty clay loam soil, and corn-soybean rotation was applied for each treatment. Both corn and soybean yield of no-drainage treatments were the lowest compared to those of other treatments. It is likely that crops, which were subjected to very shallow water table (around 20 cm) affected by waterlogging in the root zone and waterlogging hampered crop growth throughout the growing period. Soybean yields were found similar for all drainage treatments, however, compared to shallow and conventional drainage, controlled drainage produced significantly lower soybean yields. Thus, shallow and controlled drainage plots decreased the average drainage volume by 46 and 37%, respectively when they compared to the conventional drainage plots over the four-year experiments.

2.4.1. Root System

As an essential organ of plants, roots are not only responsible for controlling water and nutrient uptake from the soil, but they also create sub-structure to support above-ground biomass mechanically. Although roots generally account for only 20-30% of the total biomass of a plant, well-developed roots are the critical indicator of healthy plants. Root growth is mostly denoted by root density, root length, and root mass (Fageria and Moreira, 2011). Root mass is considered one of the most useful parameters in root studies (Lesczynski and Tanner, 1976).

Generally, the study of the root system is relatively overlooked in the literature even though it is one of the leading components of the whole plant system since it constitutes a connection between the vegetative part of the plant and soil (Ayars et al., 2006). Root development depends on several factors including high water table, high bulk density, low fertility, and low pH (Borg and Grimes, 1986). Roots become capable of providing water to plants when they reach to the water table so that higher water uptake by roots from the groundwater can be possible with the plant's root system. The density of root in 30 cm soil profile accounts for about a third of the total root density which means that there is a negative correlation between the root density and soil depth (Ayars et al., 2006). However, the majority of water used by the crop is extracted from the bottom part of the roots since the roots are developed to reach the water table (Soppe and Ayars, 2003).

Crop root development increased with an increase in the growing period. Plants that have short growing session are not capable of well-developing root-zone compared to plants having a long growing period. Thus, maximum water uptake from shallow groundwater occurs during the last period of the growth cycle. Crop tolerance to groundwater salinity is also variable for each growth stage. While crops more susceptible to groundwater salinity in early growth stages, salinity tolerance increases in crops because having well-developed root zone in their later stages. Since crop’s water demand increases in the last growing stages, groundwater can be considered as a favorable potential water source for plants. Similarly, perennial crops have more opportunity to use shallow groundwater because of their well-positioned roots. (Ayars et al., 2006).

2.4.2. Soil Hydraulic Properties

Water fluxes in the presence of shallow groundwater are mainly influenced by the atmospheric conditions, depth of water table, and hydraulic characteristics of the soil, among other parameters (Lehmann et al., 2008; Shokri and Salvucci, 2011). The flux from the water table to the root zone and evaporation from the soil is governed by unsaturated hydraulic conductivity that is a property of the soil type (Ayars et al., 2006). Kahlown et al. (2005) also stated that evaporation rate mainly depends on several factors including climate, the unsaturated hydraulic conductivity, soil moisture content, soil salinity, and water table depth.

2.4.3. Presence of Drainage, Irrigation System and Management

Drainage systems are used mostly in shallow water table conditions and they primarily discharge excess water and provides aeration to roots in the root zone. Drainage tubes are installed into subsoil with varied depths and lateral spaces. Determination of depth and tile space is based on several factors including soil permeability, outlet depth, and capacity of trenching equipment (Scott and Renaud, 2007). Drainage system management is essential because inefficient management of drainage may cause excessive water discharge from the root zone and since water is not available for crop use, yield loss occurs as a result of water stress. Ideal drainage system management was described by Ayars et al. (2006) that firstly the salinity of the groundwater should be less than crop salt tolerance, then water table should be maintained to the bottom of rootzone in the growing season, and water table should be deepened with the root growth.

Currently, surface irrigation (flood irrigation) is assumed to be the conventional irrigation method throughout the world, which has a low irrigation efficiency lower than 50% in general Unlike modern irrigation methods such as drip and sprinkler, surface irrigation methods (flood and furrow) requires a large volume of water. Applying a large amount of water to the soil in a short period of time causes several problems including poor water distribution, waterlogging, and excessive deep percolation. When the soil is waterlogged due to poor system design and installation, aeration becomes restricted in the root zone that may cause crop health issues and yield loss (Ayars et al., 2006).

Irrigation management is also critically significant for the potential crop water use from the shallow groundwater. The parameters of irrigation management such as irrigation depth (volume of water applied per irrigation), frequency (number of days between each irrigation), and water distribution (uniformity) have directly affected crop use of the shallow groundwater. Crop water use from shallow groundwater maximizes the late periods of the irrigation interval which means that maximum water uptake by plant occurs just before the next irrigation. Thus, increasing volume of water applied to the field with each irrigation reduces the contribution of the shallow groundwater to plant water use (Ayars et al., 2006). Similar findings have been found by Huo et al. (2012) that crop water use from the groundwater has a strong relationship with the amount of irrigation water and the level of water table. Irrigation water and energy are wasted when irrigation scheduled without considering water table level so that water uptake from the shallow groundwater is limited or even eliminated with the improper irrigation management (Benz et al., 1981). The knowledge of the volume of water available in the groundwater for crop water use could decrease the number and frequency of irrigation in the plant growing period (Grismer and Gates, 1988).

2.4.4. The Method Used to Determine Groundwater Contribution

Many researchers investigated the groundwater contribution to crop water use, and to calculate changes occurred in water content in the root zone in a specific period of time; they utilized the water balance equation. This equation describes the water fluxes in the soil system. When irrigation, precipitation and upward flow from groundwater are considered as gains; conversely, runoff, deep percolation, evaporation from the soil and transpiration by crops are regarded as losses. One of the water balance equation from the literature is presented at Equation 2.1 (Hillel, 1998)

$$(\Delta S) \quad = (P + I + Cr) - (R + Dp + ET) \qquad \text{(Eq. 2.1)}$$

Where; ΔS refers to change occurred in water content in the root zone; ET is the water used by the plant for vegetative growth; P is precipitation; I is irrigation; Cr is groundwater contribution to root zone; R is runoff from the soil surface; and Dp refers to deep percolation. All parameters indicated above are expressed as depth units (cm or inch, which state volume of water per unit area (Hillel, 1998). Although the field studies could be preferable to determine the water contributions from the groundwater due to the undisturbed soils, there are some limitations to use water balance approach in the field conditions since water table level and salinity of water table is fluctuating and affecting the plant growth. Therefore lysimeters have been utilized to investigate the effect of water table on plant water use. Since the variables such as water table depth, salinity, and soil characteristics can be controlled by using lysimeters, water balance equation is more applicable, and hence, more accurate results could be determined by lysimeter studies. Lysimeter study has an advantage over field study that it can be carried out in a controlled environment such as in a greenhouse. Accurate and more precise measurements of the water table depth can be taken in lysimeter study (Williamson and Van Schilfgaarde, 1965).

3. EFFECT OF WATER TABLE LEVEL ON SOYBEAN WATER USE, WATER USE EFFICIENCY AND ROOT DISTRIBUTION

3.1. Abstract

Understanding the groundwater contribution to plant water use is a significant element in improving WUE for agricultural water management. This understanding could reduce either the drainage or irrigation water volume by enhancing the crop water uptake from available groundwater. In the current study, the responses of soybean (*Glycine max*) water uptake and crop growth to four constant water table depths (WTDs), including 30, 50, 70, and 90 cm were studied in the greenhouse using lysimeters. Additionally, control lysimeters with irrigation and no water table were used for comparison. During the experiment, 50% of the total available moisture (TAM) was considered as readily available moisture (RAM) in the soil profile to apply the irrigation on the irrigated lysimeters. Soybean crop water use, WUE, and root distribution under different WTD were examined. A RCBD was used with six replications in each treatment. The results indicated that the WTD of 30, 50, 70 and 90 cm contributed to 77, 71, 65 and 62% of soybean water use, respectively. Thus, the WUE, total grain yield (g lysimeter^{-1}) per unit water use (mm), was 0.008, 0.022, 0.018, 0.025, and 0.031 at five different conditions including the irrigation, 30, 50, 70, and 90 cm WTD treatments, respectively. In terms of crop water use, and WUE; 70-90 cm WTD interval was found to be an optimum depth interval for soybean in this lysimeter study.

3.2. Introduction

Accounting for groundwater contribution to plant water use can aid in improving WUE for agricultural water management. In response to decreases in water resources and increases water demand, water use from shallow groundwater along with deficit irrigation applications became necessary for agricultural water management (Kahlown and Ashraf, 2005). Accounting for groundwater use by plants may reduce irrigation needs to maintain crop production with less amount and frequency of irrigation (Kruse et al., 1993; Soppe and Ayars, 2003)

A considerable amount of research has been conducted to quantify the proportion of groundwater contribution to crop water use and to determine crop yield and biomass variations related to different WTD during the growing season. Many of these studies were conducted to determine effects of different variables such as crop variety, soil type, salinity level, presence of irrigation and drainage systems on groundwater contribution to crop water use (Ayars et al., 2006; Kahlown and Ashraf, 2005). Kahlown and Ashraf (2005) studied the effect of different WTD on various crops and showed that under different WTD ranging 0.5 to 3 m, groundwater contribution reached the maximum level for all crops when it was maintained at the shallowest depth. Also, depending on crop's growth stage, different evapotranspiration rates were observed for each crop. Luo and Sophocleous (2010) found that 75% water requirements of wheat could be met from 100 cm WTD, and contributions from groundwater decreased with increasing WTD from 0.30 to 0.90 m, which means there was an inverse relationship between WTD and groundwater contribution.

Since variables of the water balance equation can be easily controlled, lysimeters were used to determine potential groundwater contribution to crop water use, and to find optimum WTD for various crop production (Mueller et al., 2005; Ayars et al., 2006). The objective of this study was to quantify crop water use, WUE, and determine the root distribution under different WTD conditions.

3.3. Materials and Methods

3.3.1. Experimental Design and Preparation of Lysimeters

The experiment was conducted at a climate-controlled greenhouse located at North Dakota State University, Fargo, North Dakota. A total of thirty lysimeters were used in this study (Figure 3.1). Six lysimeters were used as a control treatment with irrigation from the soil surface with no water table. In these controls, 50% of the TAM was considered as a RAM in the soil profile, and this point was used to give a decision point for applying irrigation. The remaining twenty-four lysimeters were used to test the groundwater contribution without any surface irrigation on crop production using four WTD treatments of 30, 50, 70 and 90 cm (measured from the top of the lysimeters) and all the treatments were replicated 6 times (6*4 = 24 lysimeters). Tap water was used in this study for both the irrigated (controls) and non-irrigated WTD treatments.

A RCBD with six blocks was used to design the distribution of the lysimeters in the greenhouse. Treatment 1 was the irrigation treatment and was called as $T_{control}$ while treatments 2, 3, 4, and 5 were non-irrigated treatments and they were called as T_{30}, T_{50}, T_{70}, and T_{90}. Non-irrigated treatments were feed from the bottom of the lysimeters upward using Marriot bottle method to supply constant rate of flow to the lysimeters to maintain the designed WTD (30, 50, 70, and 90 cm). The volume of Marriotte bottles were 8 liters with a working volume of 6 liters and they were placed on adjustable shelves. A total of 24 Marriotte bottles were used and the height of each shelf was adjusted for the desired level based on the water depth in the lysimeters. The water volume in the Marriotte bottles were measured periodically (15 days) and the measured difference were considered as the portion of crop water use in the soil column. The water reduction in the Marriott bottles were replenished back to run the system continuously.

The volume of water for each replenishment in the Marriott bottles was measured with graduated cylinders and recorded on a chart. Total losses from the Marriotte bottles were calculated to determine groundwater contribution to plant water use.

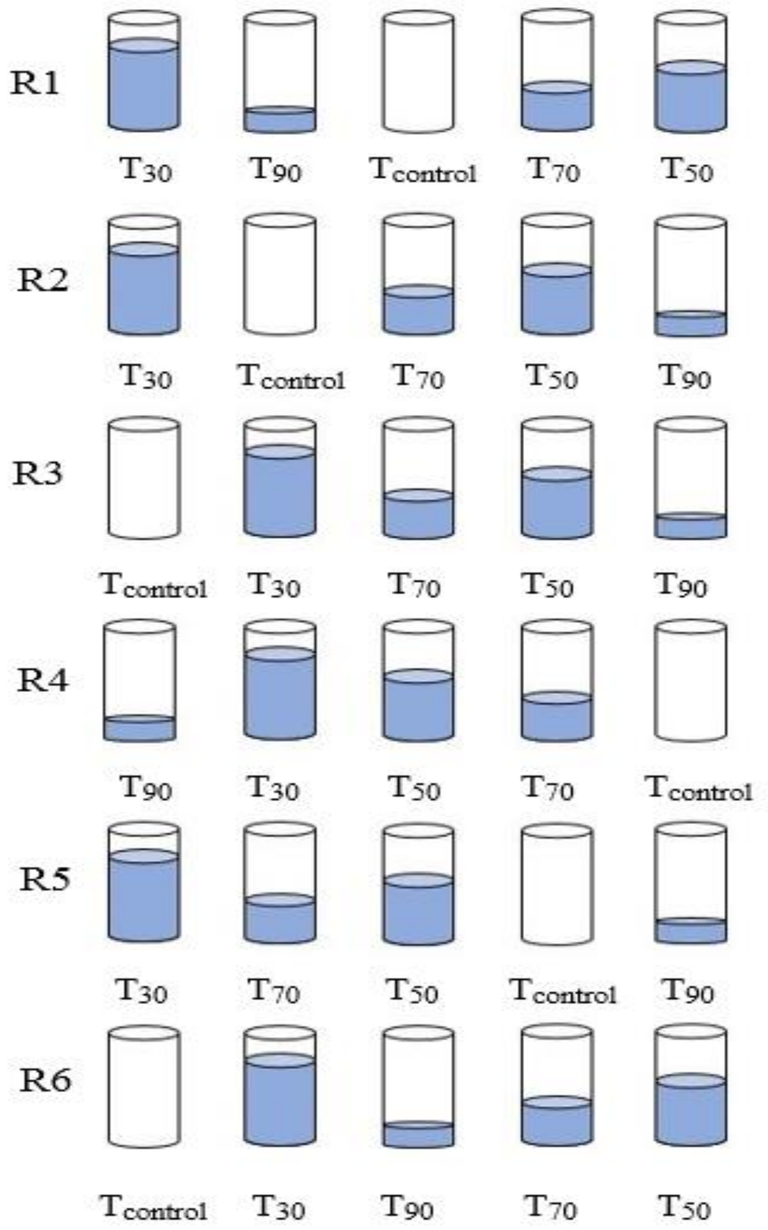

Figure 3.1. Schematics of randomized complete block design using 30 lysimeters. R1, R2, R3, R4, R5, and R6 are the replications for any particular treatment as shown $T_{control}$, T_{30}, T_{50}, T_{70}, and T_{90}.

All the lysimeters were packed using bulk soil samples collected from an agricultural field near Fergus Falls, MN. The soil physical properties of the packed lysimeters are presented in Table 3.1. The soil texture was a loam used on the USDA system. The soil was air-dried and ground to less than 2 mm before the packing of the lysimeters. The soil compaction problem was observed in the lysimeters during a preliminary experiment. Therefore, the textural characteristics of the soil were altered by adding 300 g of sand to each 1 kg of soil. The soil texture and distribution in the lysimeters from bottom to top was designed as 12 cm gravel, 12 cm sand and 96 cm loam soil (Figure 3.2). All the packing in the lysimeters were applied uniformly using the necessary tools.

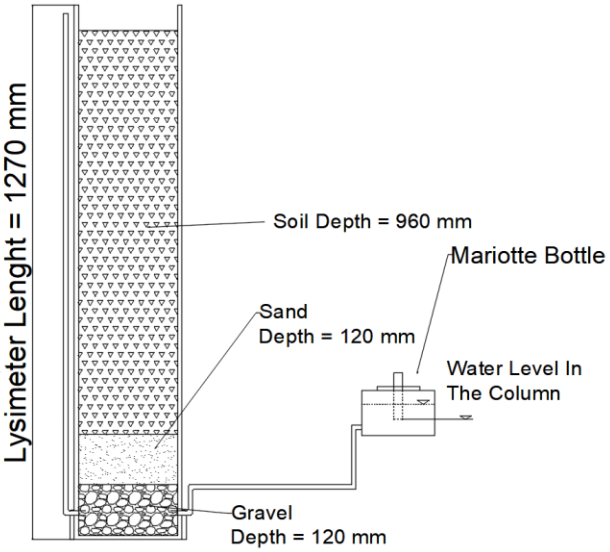

Figure 3.2. Schematic diagram of a lysimeter and Marriotte bottle system.

The lysimeters were made of Schedule-40 PVC material with a diameter of 152.8 mm (6 inches) and the wall thickness of 5 mm (0.02 inch). The height of each lysimeter was 127 cm (50 inches). One end of each lysimeter was enclosed by a cap and sealed to hold the water and soil. For the irrigation treatment, in order to determine the timing of irrigation and the amount of water needed for the irrigation, total three soil water potential sensors (TEROS-21, METER Group, Inc.) were placed in one lysimeter of the $T_{control}$ at depths of 15, 45, 75 cm from the top of the soil surface in each lysimeter. Sensors were placed horizontally in the lysimeters to provide an appropriate hydraulic contact with the surrounding soil. Data was logged using an Em50G datalogger at 10-minute intervals (Decagon Inc). A soil-water release curve was determined by using a HYPROP® (Version 10/2011, UMS GmbH München) instrument. Wet range (0 to -100 kPa) soil moisture release curve was measured with HYPROP, and dry range (-100 to -1500 kPa) was predicted through traditional constrained van Genuchten – Mualem model (Van Genuchten, 1980) by HYPROP-FIT software.

A humidity and air-temperature sensor (VP-4, Decagon Devices, Inc., Pullman, WA) was positioned at the middle of the greenhouse. Three sets of ETgage model E atmometers (C&M Meteorological Supply, Colorado Springs, CO, USA) were set up in the middle of the lysimeters, but one ETgage was worked properly throughout the experiment. Daily ET_0 data were collected from March 1st (seedling) to July 4th (harvesting). Readings from the ETgage were automatically recorded with a datalogger on a daily basis.

Chlorophyll fluorescence (Fv/Fm) measurements were carried out periodically (6 times) using OS1p Chlorophyll Fluorometer (Opti-Sciences Inc., Hudson, NH). Fv/Fm was measured on 41, 50, 56, 64, 74 and 82 days after planting in the growing period. On each measurement date, total of 9 readings per lysimeter (3 readings per plant) were taken for a total of 54 readings (6*9=54) were collected for each treatment.

3.3.2. Soybean Planting

ND Bison soybean (RFP-279) variety was used in this study. ND Bison is a conventional type crop released by the North Dakota Agricultural Experiment Station in 2016. Seeds were sowed on March 1st and soybean was harvested on different dates between July 5th and July 22nd. Plants were not got out of the lysimeters until they reach full maturity stage (Kandel 2010).

According to visual observations, all plants did not reach harvesting stage at the same time so that harvesting time differences occurred in the experiment (Table A5.). At the beginning of the experiment, to aim of preparing proper conditions for seedling bed, the water tables were fixed at the top of each lysimeter. Then, lysimeters were drained for 36 hours so that soils remained sufficiently wet for germination. Eight seeds were planted 1.5 inches depth as stated by Kandel (2010) in each lysimeter. Once the seedlings emerged, three healthy plants were kept in each lysimeter and other five seeds were removed from the lysimeters. The plants were sprayed weekly with beneficial nematodes for the thrips control. Additionally, several chemicals [Botanigard Maxx (on April 5th), Azatin O (on April 16th), and Mainspring on (May 7th)] were applied in order to inhibit growth of aphids, thrips and spider mites in the greenhouse during the study. The germination rate of the soybean seeds was also tested and reported in the Appendix section (Figure A1).

3.3.3. Plant Root Measurements and Crop Water Use Determination

At the end of the experiment (after harvesting the soybean), the plant root sampling was carried out to determine root dry mass of each treatment. Since 15 lysimeters was projected to use for another experiment, root sampling, was examined with remaining 15 lysimeters. For those 15 lysimeters, the replications of 2nd, 3rd, and 4th were selected and were cut vertically, and soil cores were taken out from the soil profile. Rather than taking out the whole roots from the soil profile, roots in the three depth intervals (0-20, 20-40, and 40-75 cm) from the top of the lysimeters were extracted. Sampling depth interval was changed from 20 cm to 35 cm just for the 3rd layers because capillary roots in the 3rd layers were easily disrupted during the extracting process. Each soil layer was placed over a screen then soil cores were gently washed out, so that roots in the soil core were left on the screen. Root mass was determined after 24-48 hours of air drying. Dry roots were weighed using a standard analytical balance.

$$(\Delta S) \quad = (P + I + Cr) - (R + Dp + ET) \qquad \text{(Eq. 3.1)}$$

Where, Cr is capillary rise; P is precipitation; I is irrigation; Dp is deep percolation; R is runoff; ET is evapotranspiration, and ΔS is the change in storage in the soil profile. Since, the experiment was carried out in a controlled environment, irrigation, precipitation, runoff, and deep percolation did not occur in the lysimeters. Considering the controlled environment, the soil water balance equation can be explained using Eq. 3.2.

$$ET= Cr + S_1 – S_2 \qquad \text{(Eq. 3.2)}$$

Soybean crop water use was also calculated with these fifteen lysimeters according to soil water balance equation (Eq. 3.1) (Hillel, 1998). At the beginning of the study, the initial moisture conditions of the lysimeters were determined by using soil water potential sensors. The amount of water stored in the soil of WTD treatments (T_{30}, T_{50}, T_{70}, and T_{90}) and control treatment ($T_{control}$) at the initial condition was approximately 360 mm and 175 mm, respectively. Capillary rise during the experiment was determined every 15 days by measuring the decreases in the volume of the Marriotte bottles.

To determine the final moisture conditions of the soil profile after harvesting in both irrigated and non-irrigated treatments, the lysimeters that were cut (as explained earlier) were sampled and soil water content was measured gravimetrically to determine the final conditions of the soil profile.

3.3.4. Irrigation Scheduling

Based on the soil water release curve (Table 3.1), 50% of the TAM was considered as RAM in the soil profile to apply the irrigation on the irrigated treatment, as mentioned earlier. Equation 3.3 was used to determine the depth of the irrigation to be applied (Majumdar, 2001).

$$d = \sum_{i=1}^{n} \frac{F_{ci} - M_{bi}}{100} x A_{si} x D_i \qquad \text{(Eq. 3.3)}$$

Where, d represents the equivalent depth of water in cm; F_{ci} denotes field capacity of the layer in percent by weight; M_{bi} is current water content of the layer in percent by weight; A_{si} denotes apparent specific gravity (Bulk density); D_i denotes the depth of each layer, and n is the number of layers.

Table 3.1. The summary of soil physical properties

soil fractions				physical properties of soil			
sand	silt	clay	soil texture	field capacity	readily available moisture (50%)	permanent wilting point	bulk density
%	%	%	#	cm^3/cm^3	cm^3/cm^3	cm^3/cm^3	g/cm^3
43	35	22	Loam	0.32	0.27	0.21	1.41

Note: Soil fractions and soil physical properties were determined after mixing the soil with sand.

Once the soil water retention curve was determined (the moisture depleted until the RAM, 50%, at the specified depth) the calculated amount of water was added to the soil in order to reach field capacity (Figure 3.3). Since all the lysimeters were packed at the same condition, all replications of the irrigation treatments were irrigated using the same amount of water according to data collected from the $T_{control}$ lysimeter equipped with sensors.

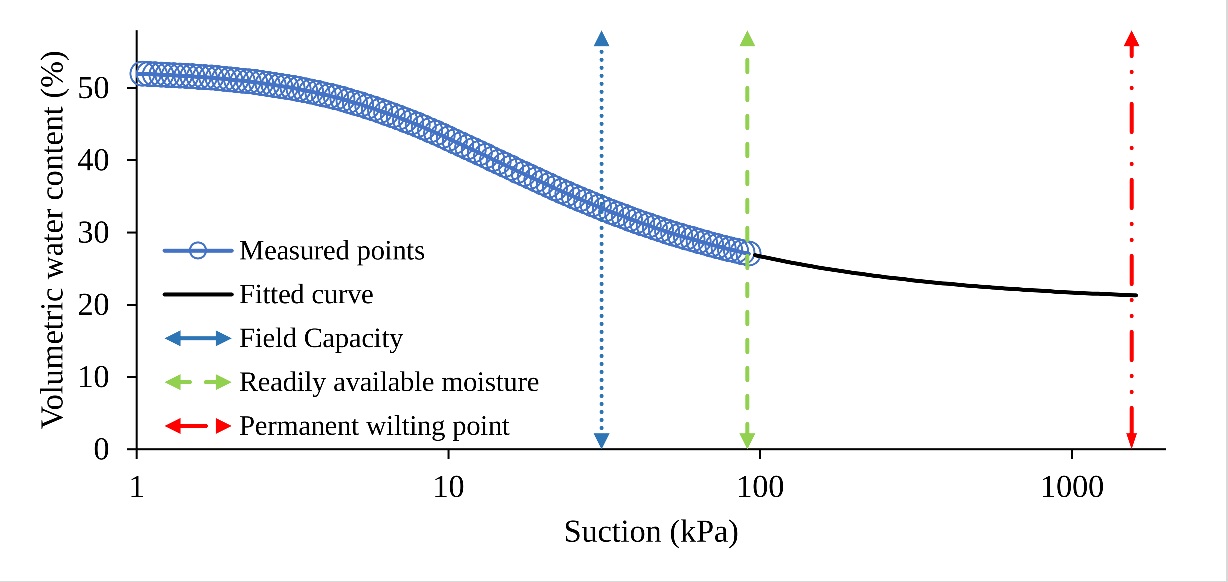

Figure 3.3. The soil moisture release curve

3.3.5. Statistical Analysis

Statistical analysis was performed using standard procedures for a RCBD with six replications for all the treatments (Figure 3.1). One-way analysis of variance (ANOVA) with P ≤0.05 was conducted to interpret the study of the possible effects of groundwater level on soybean growth and yield parameters including crop water use, plant height, Chlorophyll fluorescence, seed weight, pod weight, total biomass, root-shoot ratio, and root distribution obtained from R Studio, (R Core Team 2017).

When the *F* test for treatments was significant (P ≤0.05), mean separation tests on treatments were conducted using Tukey HSD (honestly significant difference) test comparisons at the P ≤0.05 probability level.

3.4. Results and Discussions

3.4.1. ET_0 and Air Temperature in the Greenhouse

Daily average air temperature and ET_0 rates during the soybean growing period of March 1st through July 4th, 2018 were measured continuously. The results showed that average temperatures in the greenhouse were 25±5 °C in March and April and more fluctuated in May, June, and July because of high ambient temperatures (Figure 3.4). Daily ET_0 rates for the growing period were recorded and total (cumulative) ET_0 was measured as 687 mm between March 1st and July 4th. The figure showed that, whenever the room temperature dropped in any time, ET_0 was also reduced proportionally.

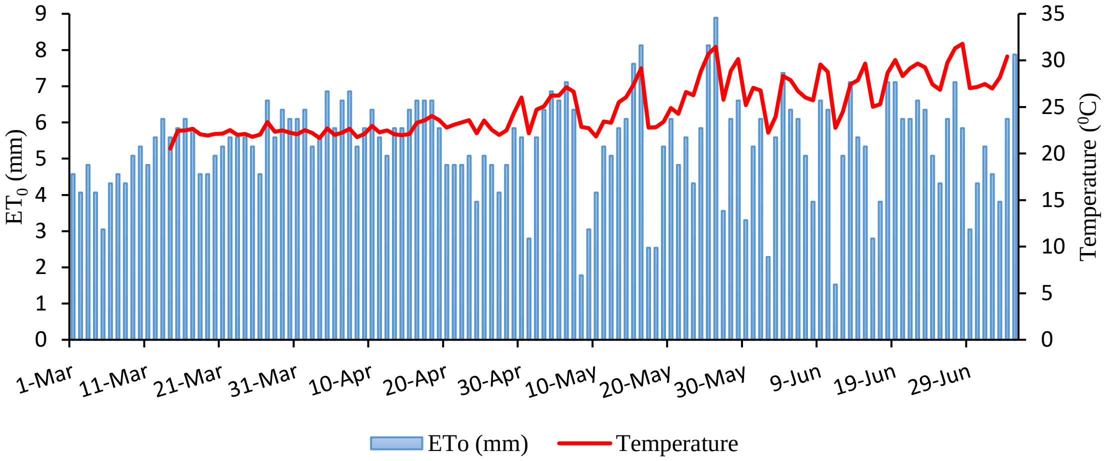

Figure 3.4. Measured daily air temperature (°C) and ET_0 values in the greenhouse.

3.4.2. Crop Water Use

$T_{control}$ was designed to keep soil water content between field capacity and RAM so as to keep plants from water stress (Karam et al., 2005). Crop water requirements computations were carried out considering rooting depth. Rooting depth was assumed as 30 cm between March 1st and April 5th, and it increased to 60 cm on April 5th.After May 10th, crop water requirements were calculated considering 90 cm rooting depth. Figure 3.5.a shows soil moisture distribution throughout the growing period and Figure 3.5b shows time and amount of irrigation applied in irrigated treatment. Additionally, physical properties of the soil such as field capacity, RAM (50% of TAM), and permanent wilting point were presented in Figure 3.5.a.

Available soil moisture in the root zone was always maintained between field capacity and RAM, and it never exceeded 50% total available soil moisture level until May 20th. However, once the 60-90 cm soil profile was included in irrigation scheduling, the available soil moisture level seemed to exceed 50% total available soil moisture level. Soil water content fluctuated between RAM and permanent wilting point after May 30th. The growing period for field soybeans is indicated to be 123 days (Kandel, 2010). Since our current experiment was conducted in the greenhouse, it was assumed to be harvested before the field conditions so that harvest was planned in the last week of June and according to this decision, irrigation was terminated on June 7th. However, plants in the greenhouse were not ready for harvesting until July 5th according to visual observations.

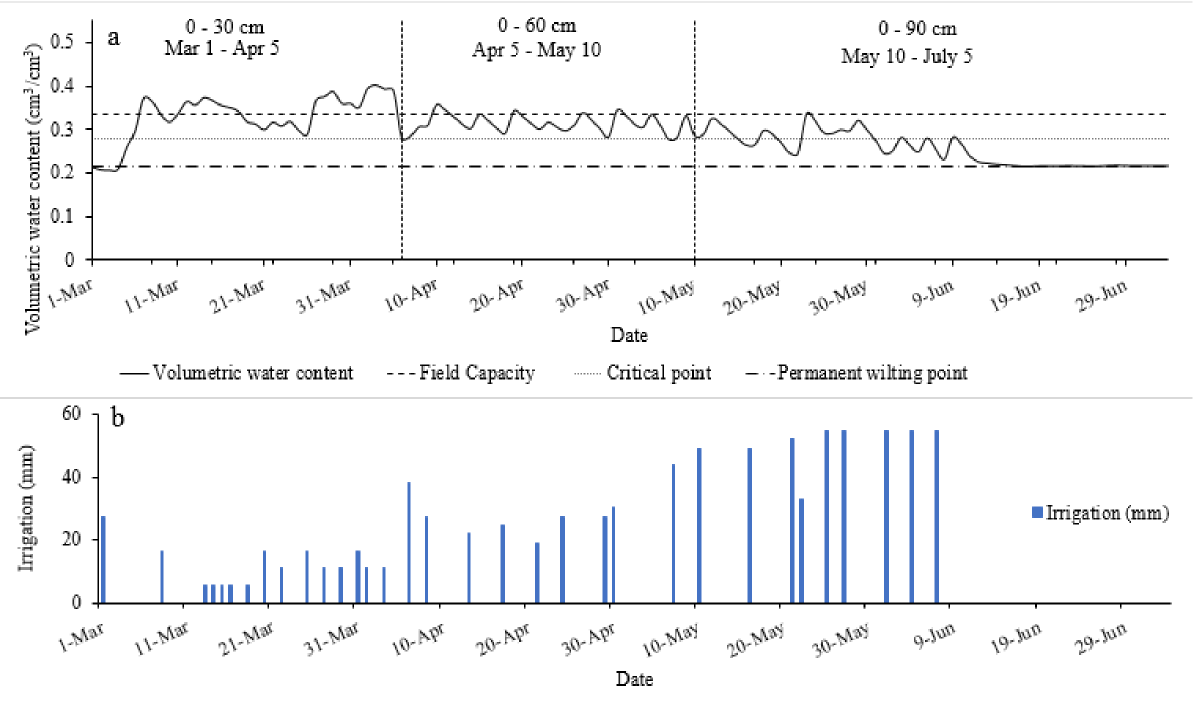

Figure 3.5. (a.) Soil moisture content measurements of $T_{control}$ with soil water potential sensors at the indicated depth of soil profile, and (b.) the amount of irrigation water applied to the lysimeters

Because of the delay on the harvest, stress conditions were occurred in the last growing period for the irrigation treatments ($T_{control}$). After termination of irrigation on June 7th, water content was constant at the permanent wilting point. Karam et al. (2005) pointed out that the highest soybean yield was obtained when optimum environmental and irrigation conditions were provided throughout the growing period. Foroud et al., (1993) reported that significant yield loss was found on soybean due to the water deficiency during the seed enlargement (R5) stage. In the current study, low yield and biomass of irrigated treatment could be explained with moisture stress, which occurred after the last irrigation application. On the other hand, when considering at the depth of 60 cm for irrigation scheduling, soil water content was mostly above the RAM so that stress conditions did not occur as much as occurred in 0-90 cm soil profile.

Table 3.2 summarizes the total evapotranspiration from irrigated lysimeters. The same amount of irrigation was applied to all replications of irrigated treatment (R2-$T_{control}$). Results from the soil water balance equation indicated that the sum of soybean crop water use varied from 856 to 886 mm, with a mean value of 873 mm for the irrigated ($T_{control}$) treatment.

Table 3.2. Summary of total crop water use of irrigated ($T_{control}$) treatment (mm)

lysimeter number	initial condition	cumulative irrigation water	final condition	cumulative ETc	mean ETc
#	mm	mm	mm	mm	mm
R2-$T_{control}$	175	891	190	876	873
R3-$T_{control}$	175	891	180	886	
R4-$T_{control}$	175	891	211	856	

Note: R and T denote to replication and treatment, respectively. Initial conditions were assumed to be identical for all lysimeters.

Summary of total crop water use and groundwater contribution data for the 15 lysimeters are shown in Table 3.3. Soil water content was calculated using the data obtained from the soil water potential sensors placed in 3rd replication of T_{50} and found to be 360 mm in the 90 cm soil profile. It was assumed that the difference of water content among the lysimeters was minor and all these lysimeters have the same initial condition since all the lysimeters were processed with the same condition.

Soybean crop ET was measured in the lysimeters. Table 3.3 proved that groundwater contribution, as well as total ETc, were influenced by WTD. Compared to total ETc which occurred from different WTD, the highest ETc occurred when the WTD was maintained at 30 cm. Total ETc from deeper water table levels were less than 30 WTD. The difference between 70 and 90 cm depth was minor compared to the difference between 30 vs 50, and 50 vs 70 cm depths. Groundwater contribution and total ETc decreased with increasing WTD from 30 cm to 90 cm, which means there was an inverse relationship between WTD and groundwater contribution.

Table 3.3. Summary of total crop water use from groundwater depths (mm)

lysimeter number	depth	initial condition	water use from GW	final condition	ETc	mean ETc	mean ETc
#	cm	mm	mm	mm	mm	mm	% of $T_{control}$
R2-T_{30}	30	360	573	280	653		
R3-T_{30}	30	360	678	287	751	673	77
R4-T_{30}	30	360	543	289	614		
R2- T_{50}	50	360	605	280	685		
R3-T_{50}	50	360	518	222	656	622	71
R4-T_{50}	50	360	433	268	525		
R2-T_{70}	70	360	431	241	550		
R3- T_{70}	70	360	407	231	536	567	65
R4-T_{70}	70	360	498	244	614		
R2-T_{90}	90	360	437	214	583		
R3-T_{90}	90	360	365	192	533	548	62
R4-T_{90}	90	360	376	207	529		

Note: R and T denote to replication and treatment, respectively. Initial condition was assumed to be identical for all lysimeters.

According to the Tukey HSD test, statistical differences were observed between 30 – 70 and 30 – 90 cm WTDs. These significant differences were indicated with letters in Table 3.4. While the highest proportion of groundwater contributions reached as high as 86, 78, 70 and 66%, the average water-contributions were found as 77, 71, 65 and 63% at 30, 50, 70 and 90 cm WTD, respectively. Similar findings were also reported in previous studies conducted with various plants such as cotton and wheat crops. Namken et al. (1969) proved that groundwater could contribute around 61% of cotton evapotranspiration when the water table was maintained at 91 cm depth. Ayars et al. (2001) found that the contribution of water table reached around 40% for cotton crop when the average WTD maintained less than two-meter depth. Luo and Sophocleous (2010) found that 75% water requirements of wheat crop could be supplied from 1 m WTD.

3.4.3. Growth and Yield Parameters

Differences between treatments, in response to varying WTD were not significant for plant height, pod weight and total biomass, however, for seed weight T_{90} was significantly higher than $T_{control}$ (Table 3.4). The highest mean plant height was 50.1 cm for $T_{control}$ (Irrigated), while the lowest mean plant height was 48.8 cm at T_{90}. There is a negative correlation between the mean plant height and WTD. Although plant height was not statistically significant, some replications clearly showed that higher plant height was observed with the irrigated treatments.

The highest and lowest seed weight was found at the 90 cm WTD (T_{90}) and irrigated ($T_{control}$) treatment with 7.00 and 3.91 g plant^{-1}, respectively. Seed weight for T_{50} increased by 6% compared to T_{30}; by 6% for T_{70} compared to T_{50}, and by 12% for T_{90} compared to T_{70} (Figure A2). Water stress in the late reproductive stage of irrigated lysimeters was likely the reason for low grain yields. Karam et al. (2005) stated that seed filling, along with seed enlargement stage, are known to be the most susceptible periods of soybean growth. Thus, the author reported that moisture stress in R5 stage resulted in around 30% seed yield reduction. Similar results were found for pod weight since correlation between grain yield and pod weight was 98%.

Table 3.4. Soybean growth and yield parameters

treatment	height	total biomass	pod weight	seed weight per plant
#	cm	g/plant	g/plant	g/plant
$T_{control}$	50.1^{a}	9.2^{a}	5.9^{a}	3.91^{a}
T_{30}	49.2^{a}	13.4^{a}	7.9^{a}	5.53^{ab}
T_{50}	48.9^{a}	14.8^{a}	8.5^{a}	5.88^{ab}
T_{70}	49.4^{a}	14.6^{a}	8.7^{a}	6.25^{ab}
T_{90}	48.8^{a}	14.5^{a}	9.7^{a}	7.00^{b}

Results also indicated a linear correlation between biomass and seed weight. Total biomass was the highest at the T_{50} with 14.8 g and the lowest at the $T_{control}$ with 9.8 g. Low soybean total biomass at the $T_{control}$ probably caused by the water stress in the late growing season. A linear trend was particularly observed between WTD treatments. The relationship between 95% of variables of mean soybean grain yield and WTD could be explained by linear regression analysis (Figure A2).

Additionally, chlorophyll fluorescence values were measured, and they did not present any significant difference among the treatments throughout the experiment (Table A4). Since water was appropriately applied to the irrigated treatments during vegetative growth, higher plant growth was measured at the $T_{control}$ treatment; however statistical difference was not observed between the irrigated and water table treatments.

3.4.4. Water Use Efficiency (WUE)

In this study, WUE was calculated for the total biomass (harvested total dry matter) divided by ETc, and total grain yield (harvested seed weight) divided by ETc (Table 3.4). The highest grain yield and biomass were found with the 90 cm WTD treatment, and significant difference occurred between the treatments in terms of grain yield WUE. Mean soybean grain yield WUE varied from 0.031 g lys^{-1} mm^{-1} as highest value at 90 cm WTD (T_{90}) to 0.008 g lys^{-1} mm^{-1} as lowest value at the irrigated treatment ($T_{control}$). $T_{control}$ had extremely low WUE due to higher ETc and lower grain yield values (Figure 3.6). As crop water use decreased with increasing groundwater depth, the highest WUE was found at 90 cm WTD (Table 3.4).

Table 3.5. Soybean grain yield, total biomass, water use and water use efficiency values

treatments	mean grain yield	mean total biomass	mean crop water use	mean grain yield WUE	mean total biomass WUE
	g/lysimeter	g/lysimeter	mm	g/lysimeter*mm	g/lysimeter*mm
$T_{control}$	6.9^{b}	13.8^{b}	873^{a}	0.008^{c}	0.016^{b}
T_{30}	15.1^{a}	33.9^{a}	673^{b}	0.022^{ab}	0.053^{a}
T_{50}	10.5^{ab}	30^{a}	622^{bc}	0.018^{bc}	0.041^{a}
T_{70}	14.1^{ab}	33.8^{a}	566^{c}	0.025^{ab}	0.053^{a}
T_{90}	17.2^{a}	33.9^{a}	548^{c}	0.031^{a}	0.061^{a}

Note: Different letters (a, b, and c) in each column indicate a significant difference occurred at ($P \leq_{0.05}$) level. Water use efficiency calculations were made according to 2nd, 3rd, and 4th replications of the experiment.

As shown in Figure 3.6, biomass WUE has similar trends as grain yield WUE in response to different WTD. The WUE of soybean total biomass gradually increased with the increased WTD. Mean biomass WUE for T_{90} was found highest with 0.062 g lys^{-1} mm^{-1}. Mueller et al. (2005) confirm that higher WUE was found at deeper WTD. The intervals of 60-80 cm WTD has been found to have the highest biomass WUE for winter wheat and maize, 80-130 cm WTD for the alfalfa, and 70-110 cm WTD for red clover (Mueller et al., 2005). There was a rather surprising result that the WUE of T_{30} was higher than T_{50}, which was similar to the WUE of grain yield. This difference resulted from the third replication of T_{30} treatment where both the biomass and grain yield were the greatest among all treatments. In addition, highest ETc and groundwater contribution values were observed at the third replication of theT_{30} treatment.

The relationship between the WUE of soybean biomass and grain yield, the correlation of these parameters was investigated (Figure 3.6). Biomass WUE and grain yield WUE were compared for each treatment. A linear correlation was found between these two parameters that indicates increasing groundwater level increased both the grain yield and biomass WUE.

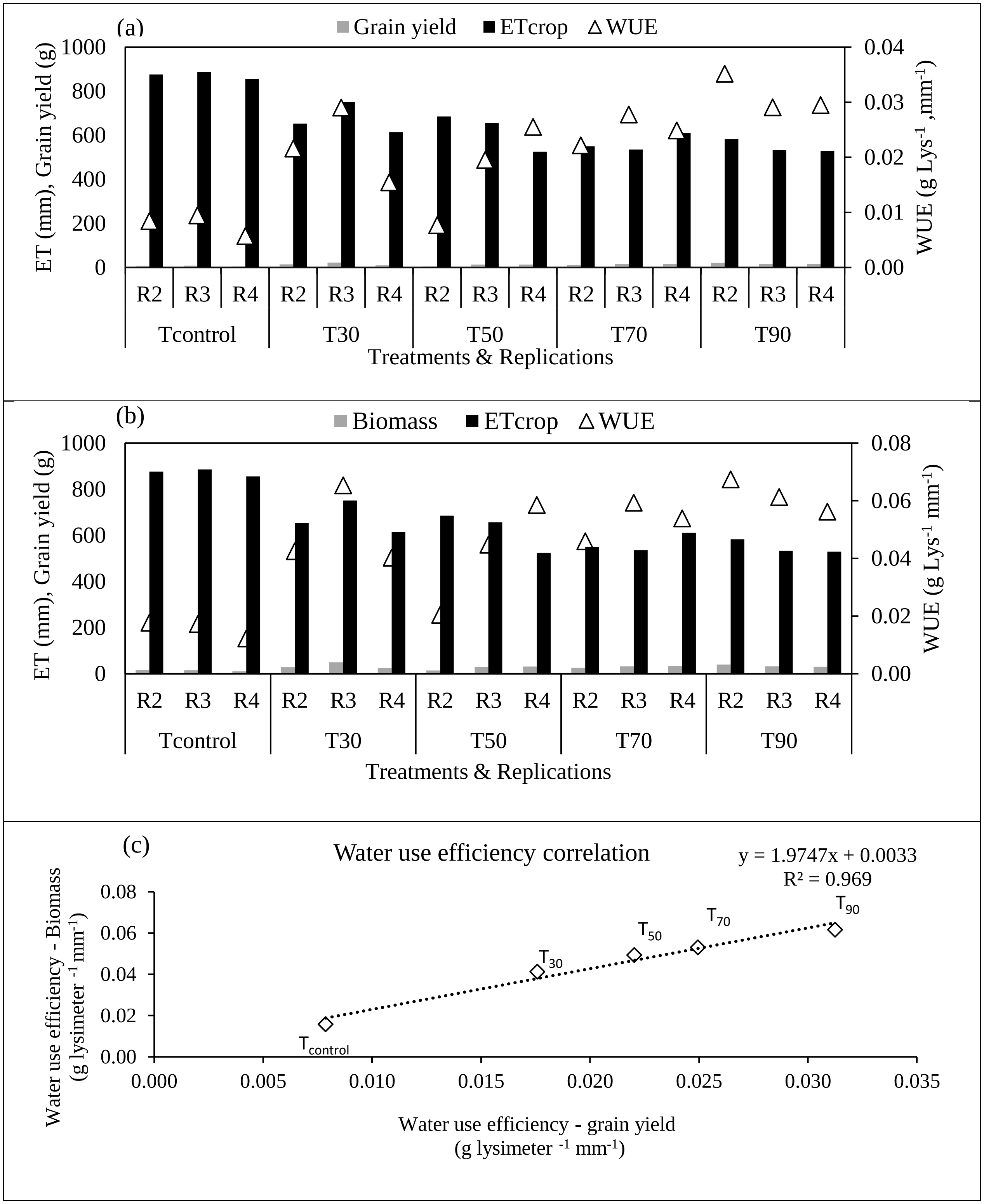

Figure 3.6. Soybean water use efficiency under different groundwater table. (a) grain yield WUE (b) total biomass WUE (c) correlation between grain yield and total biomass / R denotes to replication number.

3.4.5. Dry Root Mass

Dry root mass distribution in response to WTD is presented in Table 3.5. As explained earlier, total 15 lysimeters (3 lysimeters from each treatment) were cut and soil profiles were extracted to analyze root mass distribution. The average of three lysimeters of $T_{control}$ treatment (irrigation) was found as 4.37 g in the 0-20 cm depth. This value was recorded as the highest value in the 0-20 cm depth among all five treatments (Table 3.5). Meanwhile, comparatively lower root mass was observed in the deeper soil layers with irrigation applications. Mostly 0-60 cm of soil depth was wetted by irrigation, and available water existed in the 0-20 and 20-40 cm depth soil so that roots were mostly developed in the top 40 cm depth. When the proportion of root mass of irrigation treatment was considered, it was found that around 71% of root mass occurred in the top 20 cm, and 90% of root mass was in the top 40 cm. The mean total mass of $T_{control}$ in the soil profile was determined as 6.17 g, which was the lowest among all treatments and significantly lower than T_{70} and T_{90} treatments.

Table 3.6. Average root mass and proportions of roots.

Layers	Depth	Average root mass and percentage									
		$T_{control}$		T_{30}		T_{50}		T_{70}		T_{90}	
	cm	g	%	g	%	g	%	g	%	g	%
1^{th}	0-20	4.37^A	71	3.53^A	41	2.40^B	27	2.30^B	20	3.10^B	24
2^{nd}	20-40	1.17^B	19	2.23^A	26	1.73^B	19	1.10^B	10	1.30^B	10
3^{rd}	40-75	0.63^B	10	2.90^A	33	4.80^A	54	8.00^A	70	8.43^A	66
TOTAL		6.17^b	100	8.67^{ab}	100	8.93^{ab}	100	11.40^a	100	12.83^a	100

Note: Uppercase letters indicate statistically significant differences ($P \leq_{0.05}$) between depths within a given treatment, and lowercase letters indicate statistically significant differences between treatments.

Similarly, at the 30 cm WTD treatment (T_{30}), the highest root mass values were found in the 1st layer, with an average mass of three lysimeters is 3.53 g (Table 3.5). Soybean root mass lessened to an average of 2.23 g in the 2nd layer. However, root mass that was observed at 40-75 cm depth increased to 2.9 g. Proportional root mass in three soil layers (0-20, 20-40, and 40-75 cm) of 30 cm WTD accounted for 41, 26, and 33%, respectively. Mean total root mass of T_{30} in the soil profile was found as 8.67 g, which was higher than average for the control treatment. However, there was no significant difference between $T_{control}$ and T_{30} treatments in terms of their mean total root mass.

In contrast to irrigation and the 30 cm WTD treatments, a significant part of the root mass for the 50 cm WTD treatment was concentrated in the 3rd layer (40-75 cm soil depth) where it meets the water table. Mean root mass of 1st, 2nd, and 3rd layers were averages of 2.4, 1.7 and 4.7 g, respectively. Proportional root mass in three soil layers accounted for 27, 19, and 54%, respectively. In comparison with 1st and 2nd layers, the 3rd layer was significantly higher, and likewise, in terms of their total mass, there was no significant difference between $T_{control}$, T_{30}, and T_{50} treatments.

A similarity across the replications of T_{70} and T_{90} treatments was observed in root mass development. (Figure 3.7). Mean total root mass of T_{90} treatment was found the highest among all treatments with 12.83 g, and T_{70} was found to be 11.40 g. Comparing proportional root mass distribution of T_{70} and T_{90} treatments in 1st, 2nd, and 3rd layers (Table 3.5), percentages of root mass in each layer was quite similar. However, T_{90} was consistently higher than T_{70} in all the layers. Compared to T_{70}, T_{90} had 12% higher total root mass. However, T_{90} did not differ significantly from T_{70} ($p<0.05$). It was clear that stress occurred in the upper layers, stimulating roots to develop at deeper layers, and resulted in root development near the water table.

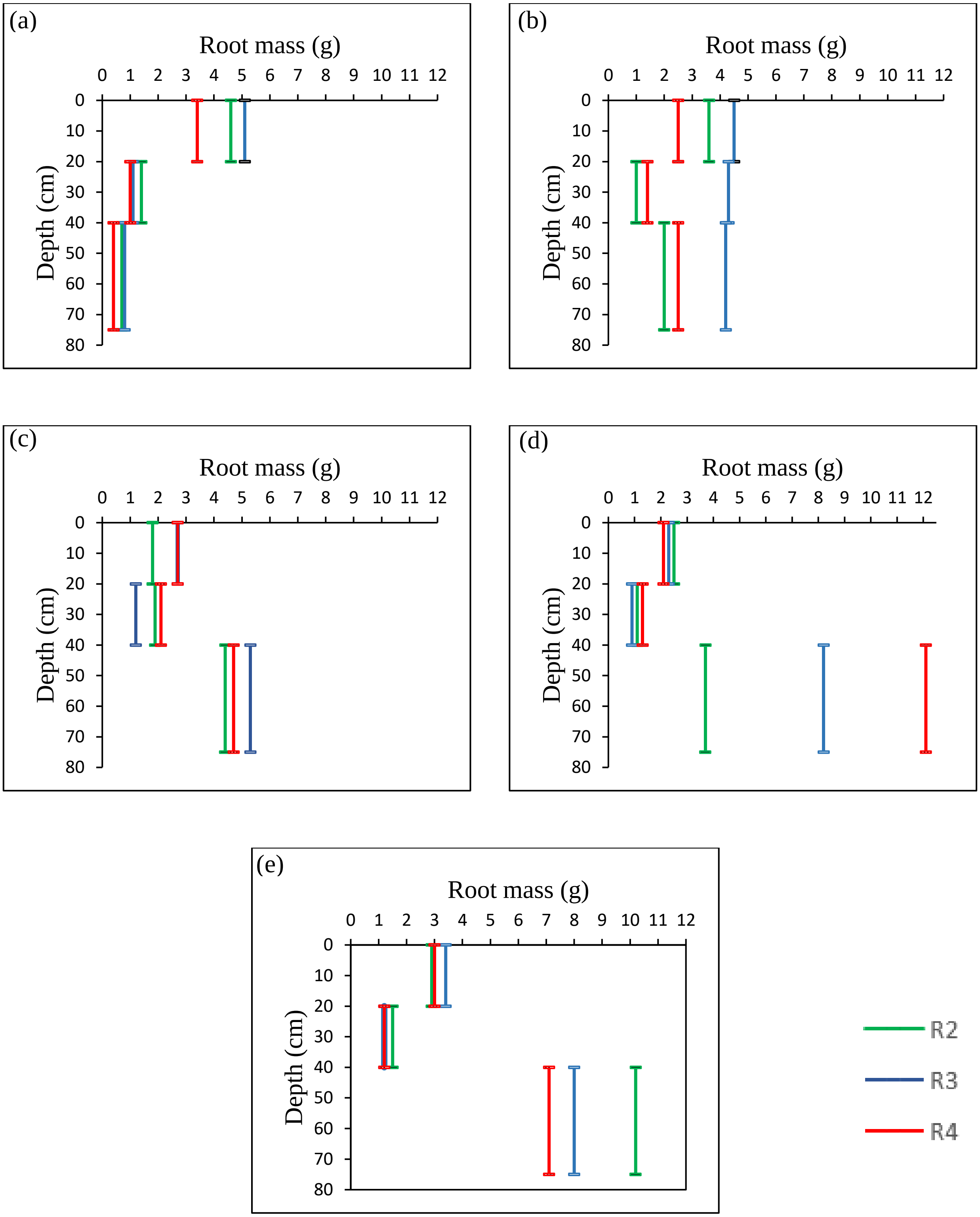

Figure 3.7. Root mass distribution of soybean as influenced by water table depth (WTD). (a) irrigated, (b) 30 cm WTD, (c) 50 cm WTD, (d) 70 cm WTD, (e) 90 cm WTD. Data at 20 cm represent root mass from 0 to 20 cm depth interval; 40 cm represents 20-40 cm; and 75 cm represents 40-75 cm.

Comparatively, very low dry root mass was found at the 1st, and 2nd layers of the T_{70} and T_{90} treatments, most probably because the plants roots did not spend energy to increase root density in the upper two layers. Similar findings were found by Imada et al. (2008) that they observed higher fine-root length just above the deeper WTD versus the upper layers.

Total mean root mass and root mass per layer varied with WTD. The total mean dry root mass for irrigation treatments was lowest compared to all other treatments. Increasing root development was observed in deeper layers in response to increasing WTD, and proportion of root mass in the layers varied significantly. While 90 and 67% of the root mass was present at the 1st and 2nd layer of the $T_{control}$ and T_{30} treatments, roots in the 3rd layer for T_{90} accounts for approximately 66%.

3.4.6. Root-Shoot Ratio

To determine plant response to WTD, the relationship between total biomass and roots were analyzed. Root-shoot ratios (total root mass per total plant biomass in each lysimeter) were calculated for 15 lysimeters. Root mass, shoot mass and root-shoot ratio data are shown in Figure 3.8.

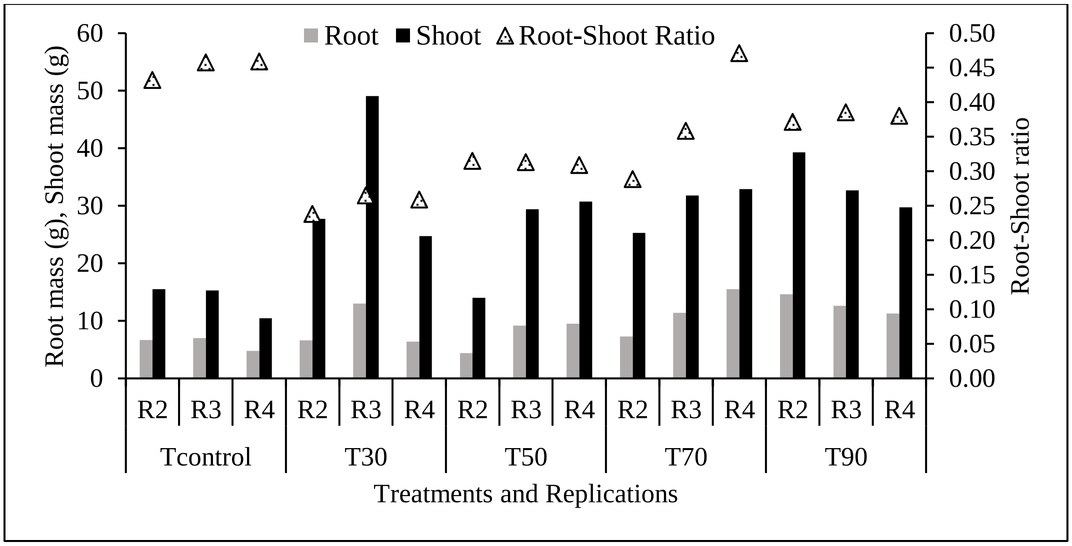

Figure 3.8. Root-shoot ratio in response to shallow groundwater table

The average highest and lowest root-shoot ratio were observed in the irrigated ($T_{control}$) and 30 cm WTD (T_{30}) treatments. $T_{control}$ and T_{30} showed the ratio of roots to shoots ranged from 0.43 to 0.46 for $T_{control}$ and 0.24 to 0.26 for T_{30}. Similarly, an ANOVA test showed significant differences between the treatments. Further analysis with the Tukey HSD test indicated that mean root-shoot ratio of 30 cm WTD was significantly lower than all treatments except for the 50 cm WTD treatment. Furthermore, the mean root-shoot ratio for the irrigated treatment was shown to be significantly higher than all other treatments with the exception of the 90 cm WTD treatment. Although the highest root-shoot ratio was found in the irrigated treatment, considering the root and shoot mass, T_{70} and T_{90} treatments reached the highest values.

4. CONCLUSIONS AND FUTURE WORK RECOMMENDATION

4.1. Conclusions

Parameters of soybean growth, yield, crop water use, WUE along with root mass distribution in response to different WTD were investigated by conducting lysimeter study in greenhouse conditions. ND Bison Soybean (RFP-279) variety was found to be tolerant to shallow water table in a vegetative growth period since there was no statistical difference observed among the treatments at the measured above ground parameters such as plant height. Similarly, yield parameters such as total biomass and seed weight did not show any significant difference among the treatments. Considering crop water use from different WTD, the highest groundwater contributions to crop water use was found at the T_{30} treatment and it was significantly higher than T_{70} and T_{90} treatments. Meanwhile, the lowest groundwater contribution to crop water use was found at the T_{90} treatment. These results showed that the depth of water table is the main determinant factor for crop water use. Although significant differences did not occur for the total biomass and seed weight in all the WTD treatments, higher WUE values were observed at deeper WTD because of the lower crop water use at the deeper WTD treatments.

The roots response to different WTD strongly indicated an effect between root development and WTD. Roots were developed near the water table to be compatible in using groundwater. Significant root developments were found in the 40-75 cm depth of the T_{70} and T_{90}. When roots reach to the water table, they become capable of providing water to plants so that higher water uptake by roots from the groundwater can be possible with the plants root system. Considering root mass distributions, it was clearly shown that root mass of T_{70} and T_{90} treatments was higher than shallower water table treatments (T_{30} and T_{50}) and also significantly higher than irrigated treatment ($T_{control}$). It is most probable that developed roots in deeper layers enabled plants to use water from groundwater. In terms of root-shoot ratio, total water use, and WUE; it was found that 70-90 cm WTD was found to be optimum depth interval for soybean in this lysimeter study.

4.2. Recommendations for Future Work

- Shallow groundwater quality is one of the critical factors affecting crop water use. In this experiment, groundwater salinity was not included. The combined effect of groundwater depth and the impact of salinity is needed for future studies.
- This study quantified the total crop water uptake from shallow groundwater. However, water requirements of soybean for each growing stage were not explained. The effect of groundwater depth and quality could be different for each growing period. It is recommended to extend this study to focus on the effect of water table on the different stage of plant growth.
- In this study, the highest yield parameters, root distribution and WUE values were obtained from 90 cm WTD. Deeper WTD treatments could be studied for future studies.
- The effect of water table on other local crops in North Dakota could be studied to determine the water table contributions on crop evapotranspiration.

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APPENDIX A. SOYBEAN GROWTH AND YIELD PARAMETERS

A.1. Germination Rate

For determining seed germination rate, four petri dishes that each petri dish containing 25 seeds were used in the plant chamber. Each day, the germination rates of the seeds were measured. Total germination rate was calculated by using the formula (Eq. 2), and the results of the germination rate were presented below.

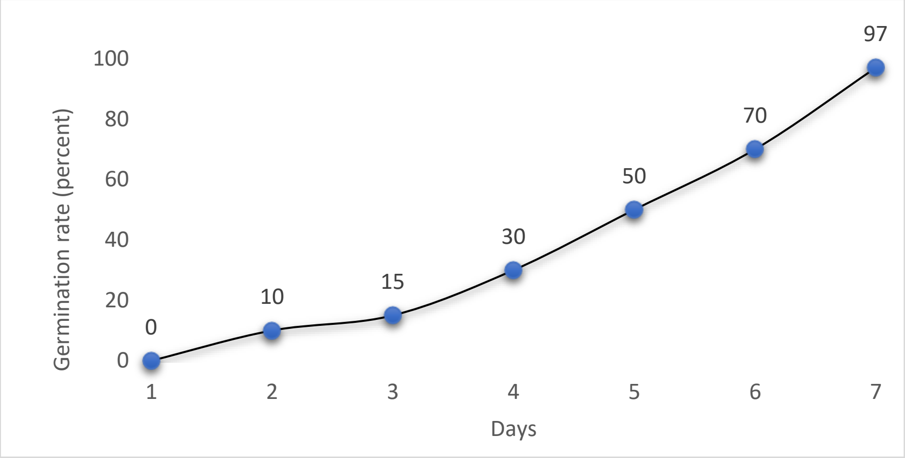

Figure A1. Germination rate of soybean

$$GP = \frac{Seeds\ germinated}{Total\ seeds} x100 \qquad \text{(Eq. A1)}$$

Seeds accepted germinated once the roots became visible. Germination started on the second day, and only 3 seeds did not germinate at the end of 7th day. The experiment was terminated at the end of 7th day, and 97% seed germination was detected. In summary, ND Bison soybean variety was found to have very high germination rate.

A.2. Plant Growth and Yield Parameters

Table A1. Summary of ANOVA of the soybean growth and yield parameters

parameter	d*f*	sum sq	mean sq	F value	Pr(>F)
Plant Height	4	6.50	1.63	0.03	0.998
Grain yield	4	31.55	7.89	2.40	0.077
Pod Weight	4	48.41	12.10	1.88	0.146
Total Biomass	4	135.3	33.83	1.74	0.173

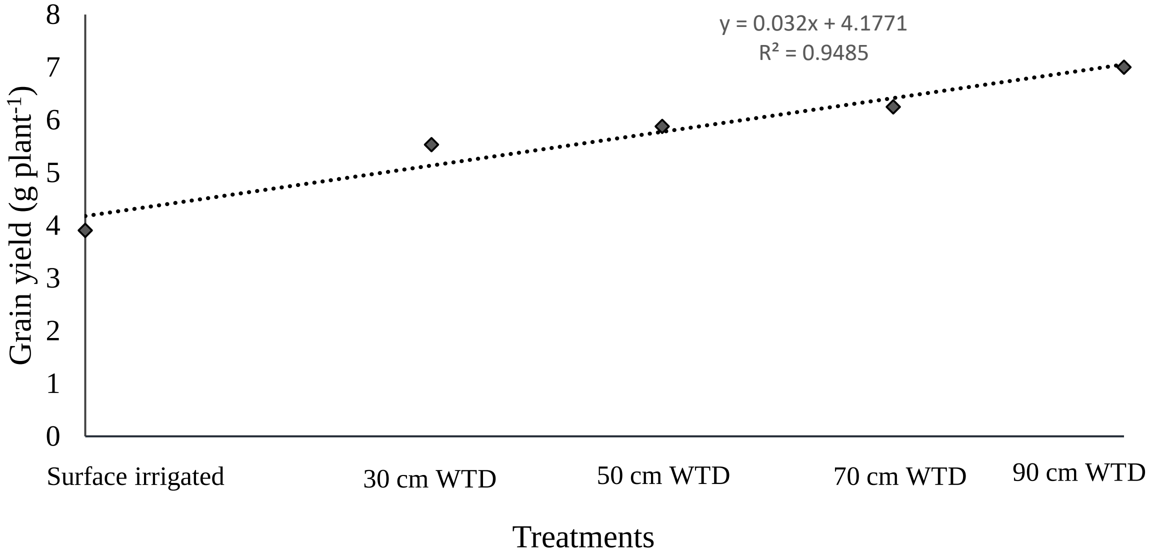

Figure A2. Linear regression analysis of the grain yield of the treatments

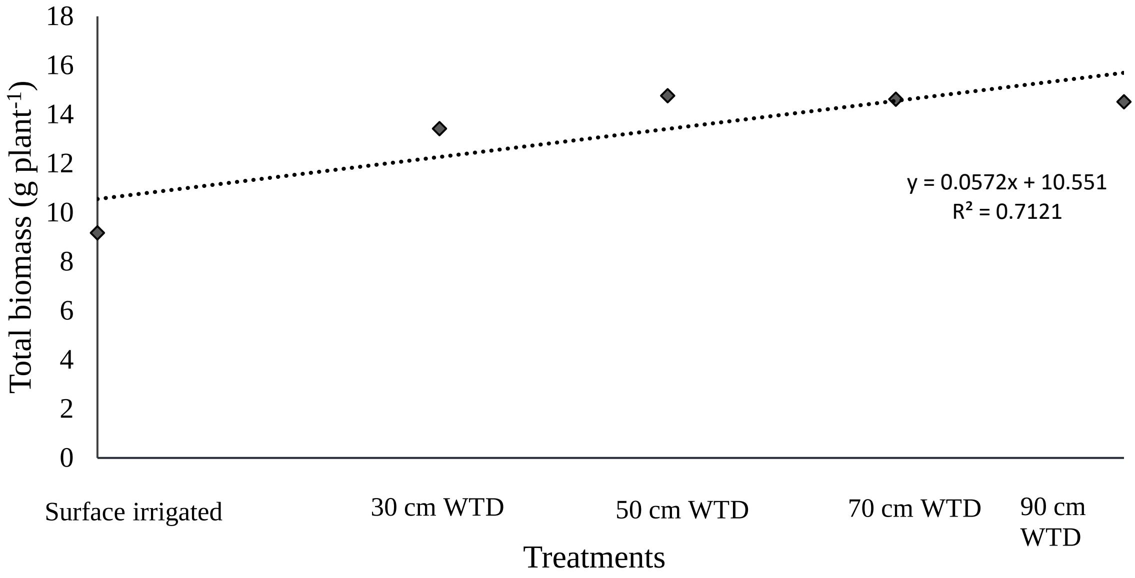

Figure A3. Linear regression analysis of the total biomass of the treatments

Table A2. Plant height measurements during the experiment

	date	$T_{control}$	T_{30}	T_{50}	T_{70}	T_{90}		date	$T_{control}$	T_{30}	T_{50}	T_{70}	T_{90}
replication 1	21-Mar	18	16	15	14	12	replication 4	21-Mar	12	10	14	13	12
	28-Mar	22	23	20	19.5	19		28-Mar	17	20	18	15	18
	4-Apr	31	29	27	26	24		4-Apr	21	26	22	21	20
	11-Apr	38	35	32	31	30		11-Apr	27	31	28	27	27
	18-Apr	45	40	38	38	35		18-Apr	29	37	33	33	34
	25-Apr	48	45	40	40	37		25-Apr	30	41	41	39	39
	2-May	53	47	44	45	38		2-May	30	43	42	40	40
	9-May	58	50	50	48	40		9-May	30	43	44	42	44
	16-May	68	53	55	48	42		16-May	31	46	47	46	50
	23-May	68	54	53	52	54		23-May	35	48	50	51	50
	6-Jun	68	54	57	52	55		6-Jun	37	48	51	51	50
replication 2	21-Mar	20	16	22	15	17	replication 5	21-Mar	14	13	17	12	11
	28-Mar	28	22	26	19.5	22		28-Mar	18	19	21	20	17
	4-Apr	33	27	33	24	29		4-Apr	22	23	25	29	21
	11-Apr	39	32	37	36	36		11-Apr	28	28	29	32	24
	18-Apr	45	34	40	42	42		18-Apr	30	35	30	32	31
	25-Apr	48	37	43	42	46		25-Apr	34	40	34	39	35
	2-May	50	40	45	45	49		2-May	35	41	35	39	37
	9-May	53	41	49	46	51		9-May	37	43	35	41	39
	16-May	59	45	53	51	56		16-May	39	46	39	43	41
	23-May	60	45	54	53	56		23-May	39	46	40	45	45
	6-Jun	60	45	54	54	56		6-Jun	39	46	40	45	45
replication 3	21-Mar	11	8	12	8	18	replication 6	21-Mar	13	12	11	12	9.5
	28-Mar	24	19	17	13	20		28-Mar	17	16	17	17	16
	4-Apr	28	27	23	18	26		4-Apr	21	22	21	24	19
	11-Apr	35	30	27	22	31		11-Apr	26	25	27	30	25
	18-Apr	40	38	31	28	36		18-Apr	34	32	31	32	30
	25-Apr	44	46	36	31	39		25-Apr	35	34	38	35	33
	2-May	45	48	39	36	40		2-May	39	37	40	38	36
	9-May	47	52	41	40	42		9-May	41	39	42	42	37
	16-May	50	54	45	45	44		16-May	45	43	45	46	39
	23-May	51	58	45	48	46		23-May	46	43	47	47	42
	6-Jun	51	59	45	48	46		6-Jun	46	43	47	47	42

Measurements terminated June 6th since no more growth observed between last two measurements.

A.3. Cumulative Groundwater Contribution

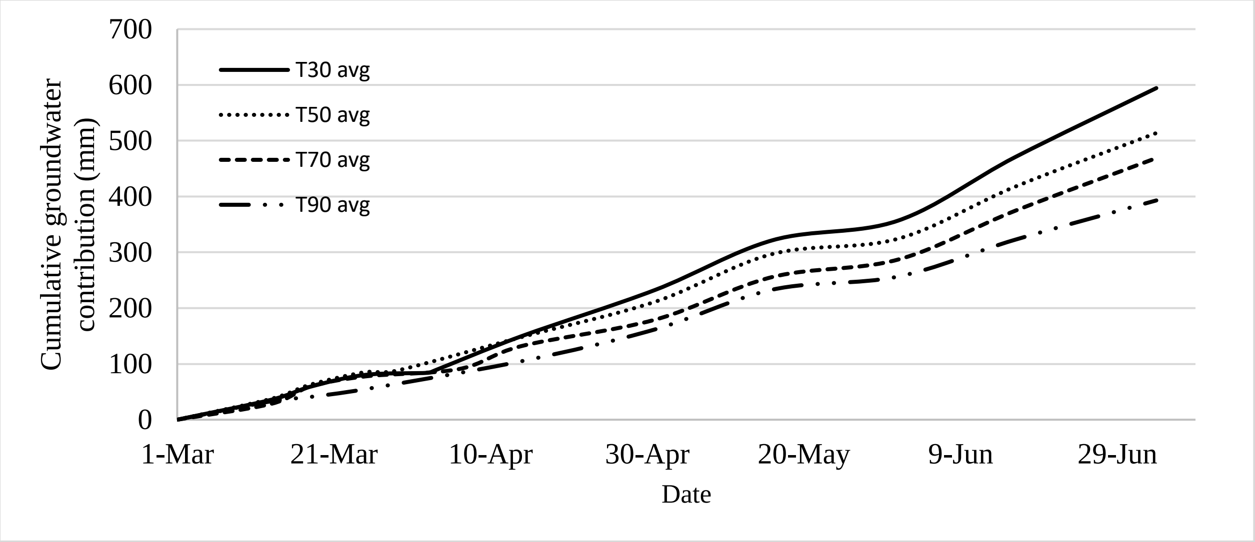

Figure A4. Seasonal capillary rise of WTD treatments measured by Marriotte bottle periodically

A.4. Chlorophyll Fluorescence Measurements

Table A3. Summary of ANOVA of the chlorophyll fluorescence measurements

dates	days after planting	d*f*	sum sq	mean sq	F value	Pr(>F)
10-Apr	41	4	0.00655	0.001637	0.181	0.946
19-Apr	50	4	0.01427	0.003567	0.501	0.735
25-Apr	56	4	0.02042	0.005105	0.823	0.523
3-May	64	4	0.00807	0.002017	1.408	0.26
13-May	74	4	0.03875	0.009688	2.461	0.0715
21-May	82	4	0.03475	0.008688	5.553	0.00243

Table A4. Summary of average chlorophyll fluorescence measurements

date	days after planting	average chlorophyll fluorescence				
		$T_{control}$	T_{30}	T_{50}	T_{70}	T_{90}
10-Apr	41	0.49^{a}	0.53^{a}	0.51^{a}	0.53^{a}	0.52^{a}
19-Apr	50	0.58^{a}	0.53^{a}	0.52^{a}	0.56^{a}	0.55^{a}
25-Apr	56	0.54^{a}	0.57^{a}	0.58^{a}	0.52^{a}	0.52^{a}
3-May	64	0.63^{a}	0.62^{a}	0.61^{a}	0.63^{a}	0.59^{a}
13-May	74	0.61^{a}	0.60^{a}	0.66^{a}	0.68^{a}	0.60^{a}
21-May	82	0.67^{ab}	0.69^{a}	0.69^{a}	0.69^{a}	0.60^{b}

A.5. Harvesting Dates

Table A5. Soybean harvest dates

treatments	replications					
	1	2	3	4	5	6
$T_{control}$	5-Jul	5-Jul	5-Jul	22-Jul	14-Jul	5-Jul
T_{30}	18-Jul	22-Jul	20-Jul	14-Jul	14-Jul	5-Jul
T_{50}	20-Jul	5-Jul	20-Jul	14-Jul	18-Jul	18-Jul
T_{70}	18-Jul	22-Jul	20-Jul	22-Jul	14-Jul	14-Jul
T_{90}	22-Jul	22-Jul	22-Jul	18-Jul	5-Jul	5-Jul

Figure A5. Extracted roots from the soil profiles. Soil profiles were divided into 3 layers (0-20, 20-40, and 40-75). Each layer sorted from left to right in each picture. A. R2-$T_{control}$, B. R3-$T_{control}$, C. R4-$T_{control}$, D. R2-T_{30}, E. R3-T_{30} F. R4-T_{30}, G. R2-T_{50}, H. R3-T_{50}, I. R4-T_{50}, J. R2-T_{70}, K. R3-T_{70}, L. R4-T_{70}, M. R2-T_{90}, N. R3-T_{90}, O. R4-T_{90}

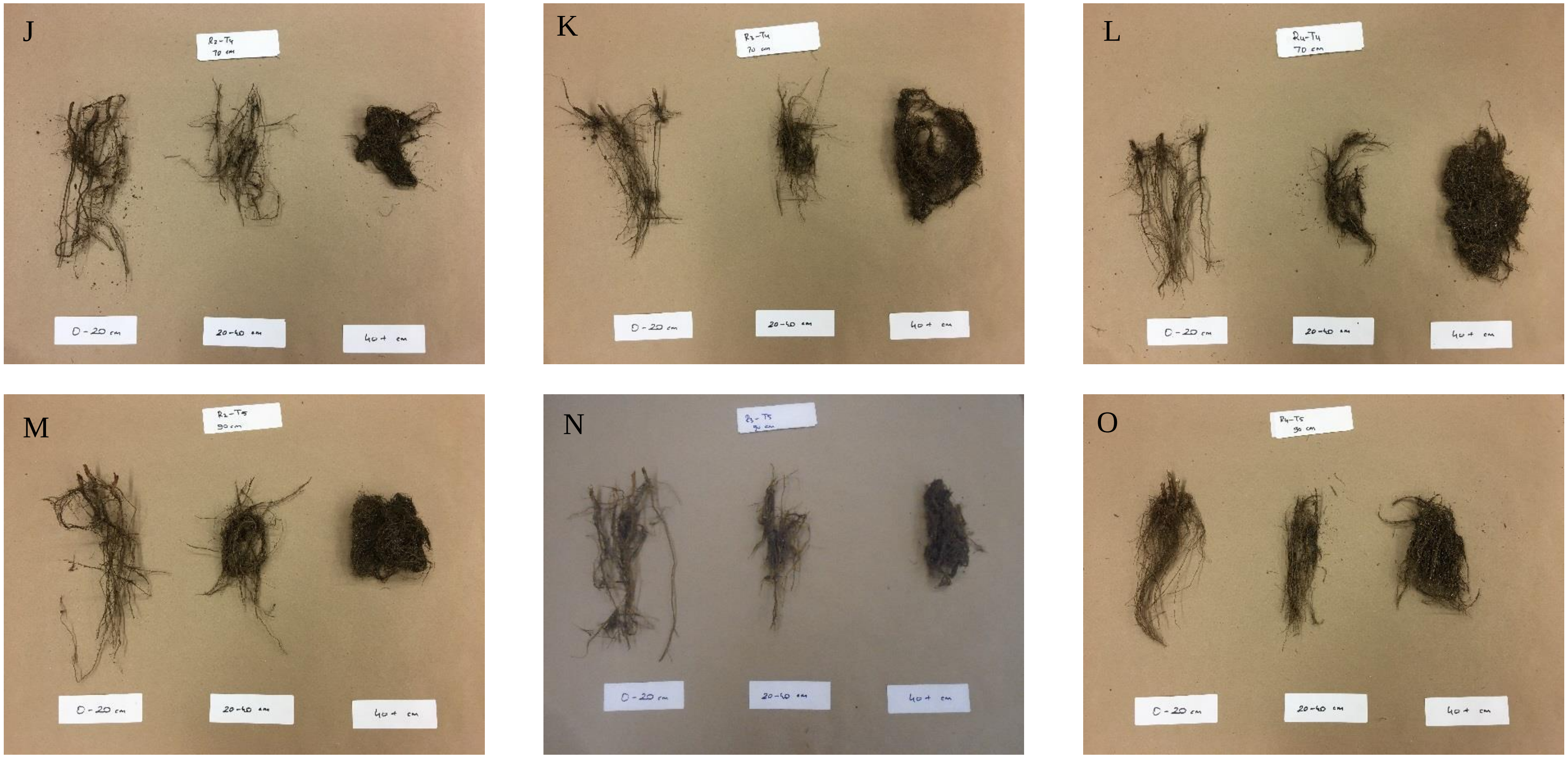

Figure A5. Extracted roots from the soil profiles (continued). Soil profiles were divided into 3 layers (0-20, 20-40, and 40-75). Each layer sorted from left to right in each picture. J. R2-T$_{70}$, K. R3-T$_{70}$, L. R4-T$_{70}$, M. R2-T$_{90}$, N. R3-T$_{90}$, O. R4-T$_{90}$