

# Precision Water Saving Cultivation Focused on Water Retention Zone

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## 学 位 論 文 要 旨

### Precision Water Saving Cultivation Focused on Water Retention Zone

保水領域に着目した精密節水農法の研究

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Water shortage has become a serious problem across the global. And this problem will be worse in the future due to the growth of the world population and the climate change. How to improve water use efficiency (WUE) in agriculture to meet the growing demand for food, feed, fiber and fuel has become an urgent issue. The precision agriculture (PA) approach has shown a great potential in agricultural management to improve the water and fertilizer use efficiency based on the information and measurement technology. To implement the PA approach in irrigation management to improve the WUE in crop production, this study presented a new cultivation method by keeping the minimum moisture necessary for plant growth only in crop rooting zone, and harvested fruits by using only a few percent of normal irrigation water. Also, this study attempted to observe water dynamics in the rooting zone and the plant physiological response to the irrigation water. As a result, it is possible to analyze the irrigation waste against the water requirement of plant organism from the view point of water volume necessary for plant growth. This study analyzed the irrigation water use efficiency which is not clearly understood in the existing studies. The knowledge gained in this study may contribute to the development of water saving agriculture. Furthermore, based on the fact that the water retention can be controlled within plant rooting zone, the morphological feature of root and the root hydrotropic response to the wet soil

condition were able to be precisely observed and analyzed under the controlled condition which cannot be realized in the existing studies.

In order to evaluate the current water saving cultivation system in Japan, this study firstly investigated the spatial variation of soil moisture in a field. In the survey, a sloped citrus field with mulch drip irrigation system was selected and the soil moisture was measured at three points in the depth direction using a capacitance soil moisture sensor. To visualize the results, the measured soil moisture with RTK-GPS location data was used to develop geographical soil moisture map by the ArcGIS tools. And the field moisture variation was shown in both horizontal and vertical direction. As a result, moist moisture distributed in the deeper soil, which confirmed the irrigation water lost due to gravity. This study also attempted to measure the soil moisture and nutrients by spectroscopic methods and evaluated its prediction accuracy towards 24 soil parameters (Chapter 2).

Next, in order to maximize irrigation efficiency to agricultural crops, this study practically verified whether the state that moisture exists only in crop rooting zone can be stably controlled. Experiments were carried out under an artificial climatic environment. Irrigation was done manually through point water source to the rooting zone. Tomatoes were used as cultivars. Homogenous soil was used which was artificially dried and sieved. Temperature, humidity and solar radiation were set artificially, while only the irrigation volume was used as the control parameter. In order to precisely grasp the moisture dynamics in the rooting zone, the moisture condition was measured by higher resolution of centimeter order soil moisture sensor matrix. Cultivation experiment was conducted to stably create water retention in limited and small soil area around crop rooting zone by finely controlling water volume and timing based on the observed soil moisture dynamics. This study quantitative analyzed the plant growth in response to the water to know the relationship between crop growth and the irrigation water volume. In this experiment, the irrigation water was attempted to be saved to a limit for plant growth, and cultivated the plants until first fruit was harvested. An average of less than 50 ml of irrigation water per day was used which was only a few percent of the normal irrigation volume. The water use efficiency and the morphological features of the roots were then analyzed under this extremely water saved condition (Chapter 3).

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# Chapter 1 Introduction

## 1.1 Background

### 1.1.1 Water use crisis

Although nearly 70% of Earth's surface is covered by water, only about 2.5% is fresh water (Oki, 2012; Chai et al., 2016). The majority of water is trapped in glaciers, permanent snow or aquifers. The fresh water in easily used form such as lake and river, are quite limited (Siddique and Bramley, 2014). The limited water resources are unevenly distributed in time and space, which are not always available when demanding it. The transportation and storage of water are much more expensive than water itself, which are economically impractical especially in developing countries (Oki, 2012). Global water shortage has become serious problem, with nearly 800 million people lack access to safe drinking water and 2.5 billion have poor sanitation (Schiermeier, 2014). The situation may get worse in the near future due to the world population will increase to another 30% by 2050 (Shiklomanov, 1999). Climate change may potentially affect the water resources availability for human use. It is estimated one fifth of the global population could suffer severe water shortage of freshwater or quality water in the near future (Girones et al., 2010; Schiermeier, 2014).

Water shortage is becoming a serious issue in arid and semiarid areas. For example, in China, the water shortage not only constrains social and economic developments but also leading to serious environmental problems in some arid regions (e.g. Shiyang river basin and Heihe river basin in the northwest of China) (Akiyama, 2004; Liu et al., 2017). The Various commodities need to be produced to meet the needs of the fast growing economy and the 1.3 billion people's needs for food, feed, fiber and fuel. The rapid urbanization further increased competition for water between agriculture and other sectors (Chai et al., 2016). Consequently, much pressure has been put on agriculture to reduce the water use. And this must be achieved without food production loss if food security is not threatened in these regions.

On the other hand, the water shortage is rare in Japan due to the regular annual rain fall and the advanced infrastructure and facilities to secure fresh water supply (Oki, 2012). However, climate change may affect the water cycle while increasing trend of fluctuation between extremely low rainfall and extremely high rainfall (MLIT, 2008). When water shortage occurs, suspended or reduced water supply would have a serious impact on everyday home life and social activities as it disables people from doing their routine. In agriculture, farmers need to spend additional labor and cost to save water which may result in increase in food price (MLIT, 2008; Oki, 2012). As the consequence, when the whole amount of water becomes insufficient, crop growth is reduced or completely hindered. With the trend of globalization and international food trade, water shortage is becoming a global issue and water saving has become to everyone's responsibility.

#### 1.1.2 Water use in agriculture

Agriculture sector has accounted for more than two thirds of fresh water withdraws. Irrigation land comprises less than 20% of world arable land which produced 40% to 45% of the world's food (Döll and Siebert, 2002; UNESCO, 2012). The irrigation land is still increasing to meet the growing population's requirements (Howell, 2001; Bodner et al., 2015). However, in many parts of the world, irrigation water has been over-exploited and over-used, which has resulted in huge impact on environment and ecosystems (Chai et al., 2016). In contrast to domestic and industrial water use, most of the water withdraw in agriculture is lost from evaporation and transpiration, while a large faction of water consumed in agriculture may not be available from the water cycle in local catchment. In the vital view of water consumption, agricultural water is accounted by nearly 90% of freshwater used by humans (Oki, 2012). Clearly, sustainable development requires reduced water use in agriculture.

Under this circumstance, agricultural water use has generally been recognized as large quantities and inefficiency, with low economic values under extensive management. In terms of public support, overprotection compared with other sectors has also been

criticized. Arguments are also being made that most of world's fresh water use is consumed by agriculture (Ochi and Yamaoka, 2003). The agricultural sector should reduce its requirement so that more water can be diverted to other uses. As the per capita use increases due to changes in lifestyle and as increase of population as well, the proportion of water for human use is still increasing. It can be said that irrigation agriculture holds the future key of humanity for both water and food. And there is growing ask for radical solutions in agricultural production to improve water use efficiency and water productivity.

### 1.1.3 Water conservation in agriculture

How to increase the effectiveness of irrigation and make water use more sustainable is an urgent question (Morison et al., 2008; Bodner et al., 2015). Increasing water use efficiency (WUE) aimed at increasing the crop's use of applied water for growth and production, with minimum non-productive losses (Ali and Talukder, 2008; Agam et al., 2012). The water losses in an agricultural system can be attributed to run-off, deep percolation and evaporation from soil (Burt et al., 1997). Various irrigation systems have been developed to deliver water to plant with different WUE (Camp, 1998; Howell, 2001; Evans et al., 2012; Shukri, 2014). Surface irrigation with various gravity methods has been widely used with the concept to supply water up to the saturated regime of field and to fill the soil reservoir to the maximum field capacity. Due to the water loss and inefficiency of these methods, surface irrigation has been gradually replaced by low pressure irrigation systems (e.g. sprinkler irrigation, Drip/trickle irrigation) (Howell, 2001). Sprinkler irrigation is a method of spraying water through sprinklers to break the water into small drops which fall to the ground. This system is tolerant to variation of soil properties since the rate of application can be controlled (Evans et al., 2012). The disadvantage of this method is quite similar with the surface irrigation due to high water loss by evaporation. Drip or trickle irrigation provide means of irrigating only plant root zone to meet plant water requirement. This method has been confirmed high WUE due to low water loss compared with other methods (Camp, 1998). The low uniformity to distribute water to the field is one of the problems in drip

irrigation system (Camp. 1998; Barth, 1999; Iwama et al., 2006).

Since the crop growth and soil water retention are always not uniform within a field, some fraction of an irrigated field will be under irrigated while the remainder is fully irrigated or over irrigated (Kado and Tejima, 1982; Yabe et al., 1986; Shukri et al., 2014). Capillary irrigation based on negative pressure has the potential to solve this problem. This method uses a porous material as an interface, from where water is automatically and continuous supplied when plant water uptake germinated a negative pressure difference between the porous material and the surrounding soil. Adaptive control of the negative pressure can minimum water loss and improve WUE (Kado and Tejima, 1982; Yabe et al., 1986; Shukri et al., 2014).

One management strategy to improve WUE is utilizing precision agriculture (PA) approach. PA utilizes information technology to record field variation (water, nutrients, grow, yield, etc.) in detail, and utilizes control technology based on the variation to maximize yield while minimizing agriculture input (Shibusawa, 2006). In terms of precision irrigation, increasing WUE is aimed at increasing the crop yield with minimum non-transpiration water loss (e.g. deep percolation, evaporation). This can be achieved by accurate and precise control of timing, frequency, amount and location to meet the specific water requirement of individual plant (Raine et al., 2007). PA approach requires rapid and low cost soil monitoring techniques to quantify spatial and temporal variability of soil properties at fine scale, and model their relationships with the crop production (Viscarra Rossel and Bourn, 2016).

#### 1.1.4 Research issues

Since the conventional irrigation methods are based on uniform rate of water supply while ignoring the spatial and temporal variability of soil properties, the further studies aims to improve WUE based on precision agriculture approach (Nahry et al., 2011). A five years research project entitled water saving system for precision agriculture (WSSPA) has been carried out from 2011 to 2015 under the Core Research Evolutionary for Science and

Technology (CREST) funded by Japan Science and Technology (JST) (Shibusawa, 2016). As the achievements, a capillary subsurface irrigation system has been developed (Ohaba et al., 2011). This system has been proved to be high WUE for precision irrigation by continuously supplying small amount of water to plant root zone based on capillary force, while maintaining appropriate soil moisture to meet spatial and temporal plant water requirement (Shukri et al., 2014a; Shukri et al., 2014b). Based on adaptive control of capillary water flow, the system used 1/10 of irrigation water compared with surface irrigation and achieved higher WUE than the current environmental controlled water saving greenhouse (Shukri, 2014).

Although the advanced irrigation technologies have improved the WUE, the detail of water relation to crop yield has been studied in few related works. This may be due to the non-transpiration water losses are difficult to determine (Burt et al., 1997; Burke et al., 1999). The crop water relation needs to be studied under field conditions to quantify the spatial variability of soil properties and its relation with crop yield for precision management of irrigation water. Advancement of this study is to develop crop yield - water relation function based on water retention control, while no non-productive water losses occurs during an irrigation event. This could help to understand the WUE at the limit of water saving to crop production and can be newly proposed to evaluate WUE of precision irrigation systems.

## **1.2 Literature review**

### **1.2.1 Crop water relation and water use efficiency**

Plant needs water for growth and tissue expansion. The most important factor driving water movement in plants is transpiration. About 90% of water absorbed from soil is used for transpiration, but a small portion of the water absorbed is used during photosynthesis for producing carbohydrates necessary for plant growth (Shioi, et al., 2009). The transpiration rate is depending on the soil moisture condition and photosynthesis activities. Transpiration



will stop when soil moisture decreases to wilting point, a point at which insufficient water left in soil for plant to transpire. The plant available water is defined as the soil moisture between the field capacity and wilting point, at which plant can absorb water from soil for transpiration and growth. The irrigation has the purpose to compensate the depletion volume of soil moisture based on the assumption of no reductive effect on crop yield (Fujioka and Nishide, 1963).

If soil moisture cannot meet the transpiration needs in a given climate condition, plant will start to wilt and show a symptom of water stress. The main consequence of water stress is decreased growth and development caused by reduced photosynthesis. Stomata are plant cells that control movement of water, carbon dioxide (CO<sub>2</sub>), and oxygen into and out of the plant. During moisture stress, stomata close to conserve water. This also closes the pathway for the exchange of water, carbon dioxide, and oxygen resulting in decreases in photosynthesis (Shioi, et al., 2009). Researchers have taken efforts to manage water stress by using drought tolerant species (Morison et al., 2008; Molden et al., 2010), proper irrigation scheduling (Greets et al., 2008; Greets and Raes, 2009) and partial root zone deficit irrigation (Dodd, 2009; Casa and Rouphael, 2014; Chai et al., 2016), based on the concept of improving photosynthesis activity without corresponding increase in transpiration loss that will consequently improve the WUE.

There are many terms to describe the efficiency of water used in plant growth. The WUE is a conceptual term which described the plant growth response to the water consumed. So this term has also been defined as biomass water ratio, which can be used at various scales (Morison et al., 2008). In addition, transpiration efficiency, which defined as the ration of CO<sub>2</sub> uptake to the water loss by transpiration, has also been used to describe the WUE at a leaf scale (Morison et al., 2008). And general defined WUE is the ratio of crop yield to the evapotranspiration (Y/ET) (Zwart and Bastiaanssen, 2004; Greets and Raes, 2009). Due to this term considers much on plant physiological response while taking little account of the irrigation practice, the term of crop water productivity, application efficiency or irrigation efficiency has also been used to evaluate the efficiency of an irrigation system to reduce non-productive water losses in the irrigation practice (Howell, 2001; Hsiao et al., 2007). Generally, the objectives of these terms are to quantitative

analyzing the crop yield response to the water transpired, or to the applied irrigation water. The definition is also depending on how to determine the water loss to meet the needs of an irrigation project (e.g. recharge groundwater or leaching requirement) (Burt et al., 1997; Burke et al., 1999). A concept of virtual water content has recently been introduced to express the amount of water consumed in terms of evapotranspiration (ET) to produce a unit of crop product (Hoekstra and Hung, 2005; Oki, 2012; Lovarelli et al., 2016). The virtual water content is the inverse of WUE. The ET component in the WUE equation is always calculated using the potential evapotranspiration, which is calculated from the FAO's Penman-Monteith equation, and then multiply the crop coefficient (Zwart and Bastiaanssen, 2004; Hoekstra and Hung, 2005). The non-productive water loss from an irrigation event is always ignored.

Methods to increase WUE included improving proportion of photosynthesis per unit of transpiration through crop breeding, increasing proportion of economic yield to total biomass (Harvest index) through varieties selection or crop breeding, and increasing biomass production while minimizing the water loss. The last method can be implemented through precision agriculture approach.

### 1.2.2 Root response to water

Plant root serves as sportive organ for water and nutrient which plays a critical role in determining the yield of crops (Aiken and Smucker, 1996). The formation of root is controlled by internal cues and tropistic response to external stimuli (Hawes et al., 2013). An assumption of hydrotropism suggests that water gradient control the directional growth of root to help them to explore water and avoid drought, which plays an important role in shaping the form of root system (Takahashi, 1997; Hawes et al., 2013). During the past decades, researchers have developed various experimental systems to study hydrotropism in seedling roots and demonstrated the existence of this phenomenon (Jaffe et al., 1985; Takahashi and Scott, 1991; Takahashi and Scott. 1993; Takano et al., 1995; Takahashi et al., 2002; Eapen et al., 2005). These studies have been carried out in air or agar by

eliminating the effect of gravity, and the roots showed different degree of hydrotropic response among different species (Jaffe et al., 1985; Takahashi and Suge, 1991; Takahashi and Scott, 1993; Takano et al., 1995; Takahashi, 1997; Takahashi et al., 1999; Mizuno et al., 2002). The later studies have elucidated the hormones and proteins process which helped to improve the understanding of the mechanism of hydrotropism, and its interaction with gravitropism at the cellular, molecular and genetic level (Takahashi et al., 2009; Iwata et al., 2013; Dietrich et al., 2017). Further researches are expected to develop hydrotropic enhanced species for water saving cultivation in arid land. A combination of precision water saving system and hydrotropic enhanced species can be expected to improve the WUE in agricultural production (Shibusawa, 2016; Tohoku University, 2017).

### 1.2.3 Soil water balance in an irrigation event

In order to improve the WUE in an irrigation event, it is important to understand how water loss from the root zone. Fig. 1.1 shows the soil water balance in conventional irrigation. The water infiltrate into soil matrix is in transit. As part of the water will enter the plant, while another fraction of water will temporarily store in soil, evaporate from the soil surface or move down below the root zone. The soil pore volume is a reservoir to hold water. Not all of the water in the pore is available for plant use. Saturation means all the soil pores are filled with water. Gravity will pull some of this water down through the soil below the crop's root zone. The water that redistributed below the root zone due to the gravity force is called deep percolation. Deep percolation is generally considered as a loss due to that it cannot be directly used by plant (Burt et al., 1997). After the redistribution process is completed, the soil is filled with water at field capacity. The water held against the force of gravity by capillary forces and is called capillary water. This form of water is most important to plant and constitutes the only available source of water to plant (William and Robert, 2006). Since the soil pores are always not uniformly distributed within a field, some fraction may be under irrigated while others are fully or over irrigated (English et al., 2002).

Although evaporation is a portion of ET, it has been considered as water loss due to

that it is not directly consumed by the crop and has little effects on the formation of crop yield (Mellouli et al., 2000; Agam et al., 2012). Previous researches use the ET to calculate WUE probably because of the difficulty to separate the evaporation and transpiration in a real field. A tradeoff between transpiration and evaporation is therefore becoming important in irrigation management to improve WUE (Burt et al., 1997).

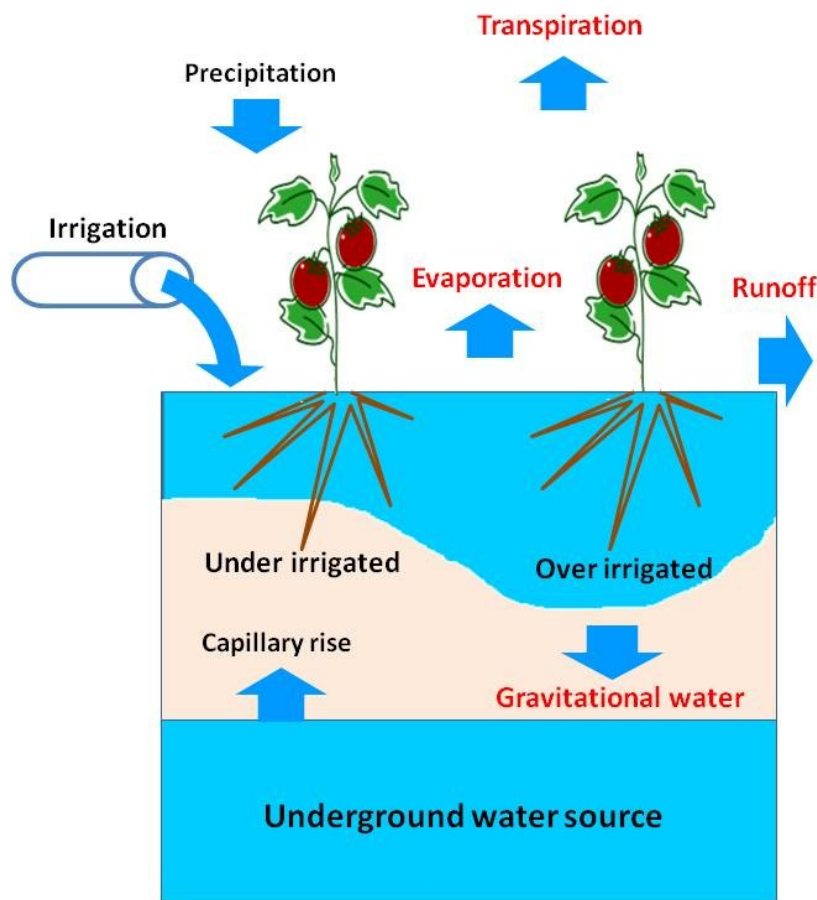


Fig. 1.1 Soil water balance in conventional irrigation

Since the WUE is independent of irrigation system which does not take into account the non-productive water losses, engineers have long characterized irrigation performance using various efficiency and uniformity terms (Burt et al., 1997; Howell, 2001). Want et al. (1996) proposed a general efficiency ( $E_g$ ) term based on the ratio of transpiration to the sum of the volume of applied water and the volume of the deficit, which is expressed as:

$$E_g = \frac{\alpha E_a E_s}{(E_a + E_s - E_a E_s)} \quad (1.1)$$

Where  $E_g$  is the general efficiency,  $\alpha$  is the transpiration fraction of ET.  $E_a$  is the application efficiency which is defined as volume of water stored in the root zone per unit of water volume delivered to the field, and  $E_s$  is the storage efficiency which is defined as volume of water stored in the root zone per unit of water needed in the crop root zone. This equation emphasized the need to maximize transpiration while minimizing application losses and meeting the water needs of crop. For example, when irrigation water is excessive, the efficiency is depending on  $E_a$ . If there are no evaporation and deep percolation losses, the equation can be written as  $E_g = E_s$ . This equation is closely to crop yield since it considers both the deep percolation losses and crop water requirement, while excluding the evaporation loss that may not directly contribute to crop yield. However, the water components in the equation are still practically difficult to measure in a real field (Howell, 2001).

#### 1.2.4 Water productivity function

A water productivity function is a curve to quantitatively express the relationship between crop yield and the applied irrigation water (Fig. 1.2). Many authors have showed that the curve has a logistic shape (Mannocchi and Mecarelli, 1994; English et al., 2002; Geerts and Raes, 2009). The maximum WUE may always occur at the point before maximum yield is reached. Which indicates reducing a fraction of irrigation water may improve WUE by reducing water loss from an irrigation event (English et al., 2002). The irrigation managements are usually depending on the availability of water resources. If water resources are sufficient, the irrigation management aims to meet the full water requirement of a field to gain the maximum production. However, this method is lack in precision and WUE due to the water loss and stochastic distribution of soil properties across a field (English et al., 2002). When water is insufficient, deficit irrigation becomes

increasingly significant. The limited water availability cannot only fulfill crop water requirement based on one single field. The saved water need to irrigate additional fields. The optimizing approach is preferred to maximize the net production per unit of water instead of per unit of field (English et al., 2002). Various crop functions have been developed for best planning of irrigation management (Mannocchi and Mecarelli, 1994; Geerts and Raes, 2009). However, the lower limit of this function has been studied in little previous works. That means little work has been conducted to study the limit of water saving and the yield response to the limit level of the irrigation water.

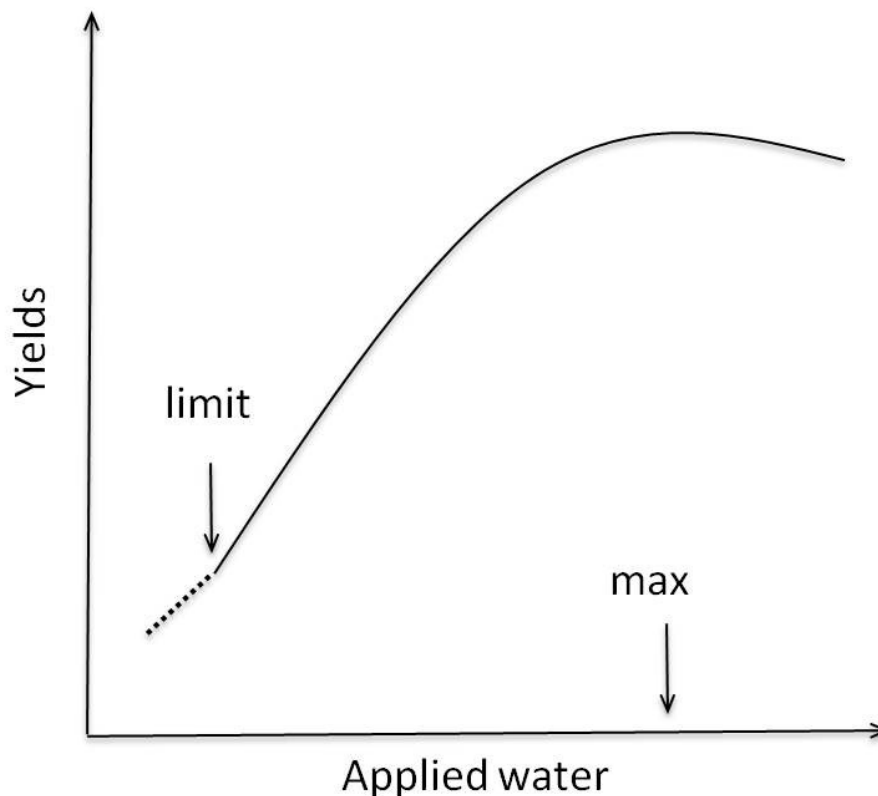


Fig. 1.2 General form of relationship between applied water and crop yields

#### 1.2.5 Precision agriculture (PA)

The traditional agricultural practices used to consider that field is homogeneous in nature, and management practices determine a uniform input rate based on what is best for

the field as a whole (Nahry et al., 2011). The traditional agriculture is hard to meet the growing demand for food and water (Hashimoto et al., 2002). With the development of information and communication technology (ICT), PA concept has come out and became an innovative strategy in the management of field variability (Shibusawa, 2006). PA is a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production (Shibusawa, 2006). It involves studying and managing of the within field variability which may affect the crop yield. The implementation of precision agriculture practices depends on the development of three fundamental technologies: the first is sensing technology to describe the within field variability (e.g. yield, soil properties, pest and weeds), which is fundamentally important for PA. The second is variable rate technology to precisely apply the inputs based on specific crop needs indentified in each part of the field. The third is decision support system which integrates various models and optimization algorithms to help farmers with the trade-off problems, such as the balance between fertilizer cost, yields and environmental impact (Shibusawa, 2006). In terms of precision irrigation, the timing, placement and amount of water should meet the plant water need resulting in reduced non-transpiration water losses and optimized crop production responses (Raine et al., 2007). A new development of precision agriculture is plant factory technology. In which crop growth environment is artificially controlled to optimize the growth process. A plant-based method called speaking plant approach (SPA) is a new management paradigm in plant factory that enables the system to adapt to the variability in crop-water demand according to the individual crop-water response (Hashimoto et al., 2002; Jones, 2004; Shibusawa, 1995, 2006).

#### 1.2.6 Vis-NIR spectroscopy for soil characterization

To implement site-specific irrigation management in precision agriculture, a large number of soil samples are needed to achieve statistical significance among samples to describe the within field variability (Shibusawa, 2006). Point soil moisture can be obtained using many techniques such as time domain reflectrometry (TDR), capacitance sensors, or

volumetric sampling. But applying these techniques is restricted in small area, and is generally too expensive to provide high resolution data (Weihermüller et al., 2007). Therefore, simple and low cost soil testing techniques are needed in the laboratory and in the field. Visible and near infrared (Vis-NIR) spectroscopy, which relies on chemometrics, is a popular analytical technique to characterize soil physical, chemical and biological properties. In previous researches, this technique has shown great potential in prediction of soil moisture and some other parameters (Ben-Dor and Banin, 1995; Shibusawa and Hirako, 2001; Chang et al., 2001; Islam et al., 2003; Viscarra Rossel et al., 2006; Kodaira, 2012, 2016). The energy of IR depends on the wavelength, which corresponds to the energy level difference between different rotational and vibration states of a molecule. And the energy of NIR light corresponds to the overtones and combination bands of fundamental of molecular vibrations (e.g. O-H, C-H, and N-H) from the mid-IR (Chang et al., 2001; Viscarra Rossel et al., 2006).

Due to the broad and overlapping nature of absorption bands in the NIR region, complicated approach is needed to correlate the reflectance spectra to a soil property. This approach generally includes data pretreatment, multivariate calibration and prediction, and validation steps. In addition, the variation of soil physical properties such as soil moisture content, particle size, soil color, surface roughness may affect the reflectance measurement. Therefore, when measuring reflectance data based on fresh soil, a robust approach is needed to minimize the influence of the soil physical properties.

### **1.3 Objectives**

Abundant of researchers studied the relationship between crop yield and applied irrigation water based on field level while the spatial variability of soil properties has been ignored. The climate change and improved environmental standard requires improved WUE in agriculture based on PA approach, while the crop water relation needs to be researched based on individual crop. The aim of this study is to investigate the relationship between crop yield and soil water for best design of precision irrigation system. The studies



have been carried out in both field and laboratory cases. In the field case, a portable spectrophotometer was used to map the spatial distribution of soil water and nutrients, and then investigates their relations to crop yield. In the laboratory case, the crop water relation was studied in an artificially controlled environment. And a zone of water retention was formed and controlled in root zone during the plant growth. The limit of irrigation water for plant growth was investigated using this approach. Specifically, this study intended to achieve the following objectives:

1. To investigate the feasibility of a portable spectral photometer for rapid mapping of soil water and nutrients for tree-based management.
2. To reduce water use to a minimal level of plant growth based on water retention control.
3. To investigate the response of crop yield and rooting to the water volume applied in the water retention zone

#### **1.4 Dissertation organization**

This thesis is divided into four chapters. The first chapter is the Introduction which described the background issues, motivation and objective of this study. This chapter also includes literature review which reviewed the water and crop yield relations and some approaches and concepts to improve WUE. The second chapter is the mapping of soil parameters using Vis-NIR spectroscopy in a sloped citrus field. The third chapter introduced the concept and methodology to control the water retention in rooting zone. The WUE was also introduced at a limit irrigation level based on water retention control. And the root hydrotropic behavior was then studied in response to the water retention zone. And the last chapter is general conclusion.

## Chapter 2

### Soil parameter mapping using Vis-NIR spectroscopy

#### Abstract

Japanese citrus field are most located on sloped field with good sunshine and natural drainage system. Drip fertilization system with year-round mulching is introduced to citrus field to maintain proper soil moisture for good quality management, and it was a typical case of water saving cultivation in Japan (Morinaga, 2005, 2013). The within field variability of fruit yield and quality is the present problem due to the uneven distribution of soil water retention (Morinaga, 2013). In order to study the relationship between yield and soil water, and nutrients for tree based management, soil properties are expected to be quantified for each tree. In this study, a portable spectrophotometer was used to predict 24 soil parameters based on fresh soil sample spectra collected in a sloped citrus field. One hundred soil samples were collected randomly from the field for a training set (75 samples) and a test set (25 samples). The partial least squares regression (PLSR) analysis was used to develop regression models. Evaluation was conducted based on the values of the coefficient of determination ( $R^2$ ) and the residue prediction deviation (RPD). The results showed that 13 soil parameters were predicted with  $R^2 > 0.5$  and  $RPD > 1.4$ . Soil parameter maps and yield maps were developed with height change in the sloped field based on the location information collected by a real-time kinematic GPS (RTK-GPS) system.

## 2.1 Introduction

Water and nutrients are closely related, and both are essential for plant growth and crop production. The advent of precision agriculture method and enhanced environment and quality standards require improved nutrient and water use efficiency (Shibusawa, 2006). These objectives have led to the development of rapid soil monitoring methods (Shibusawa and Hirako, 2001; Viscarra Rossel and Bourn, 2016). The current guidelines for citrus fertilization are based on soil and leaf analysis and yield expectancy, which are commonly used to monitor the nutrient status of citrus fields and modify fertilizer management (Takatsuji, 1987). Soil analysis is an important procedure but is not used as often as leaf analysis. Soil analysis uses laboratory analysis of representative soil sampling within a block or field. The result is then correlated to one uniform rate of fertilizer application and yield (Zaman and Schumann, 2006; Mann et al., 2011). Laboratory soil analysis is an important reference for fertilization, but this method is quite labor intensive and time consuming, and the representative values cannot be used to interpret the grower's observations of within-field citrus variation.

Visible and near-infrared (Vis-NIR) soil spectroscopy is an appropriate method for rapid and low-cost soil status determination. A single spectrum may contain comprehensive information including chemical, physical, and biological soil properties, which can be simultaneously quantified (Islam et al., 2003). This technology has been successfully used based on laboratory soil spectral measurement (Chang et al., 2001; Islam et al., 2003; Viscarra Rossel et al., 2006; Wetterlind et al., 2010). Its use under in-situ, field conditions, however, is limited (Udelhoven et al., 2003; Mouazen et al., 2007; Kodaira and Shibusawa, 2013; Ji et al., 2014). An important task for in-situ Vis-NIR spectroscopy is to control the influence of environmental factors, such as moisture content (MC), color, surface roughness, type and texture of fresh soils, all of which could be sources of error that affect the prediction performance (Udelhoven et al., 2003; Kuang et al., 2011). Calibration scale can also affect the prediction accuracy of NIR spectroscopy under field condition, and best accuracy was obtained from field-scale modeling (Stenberg et al., 2010). Since large-scale data cover a wide range of soil structure and MC, their influence on soil spectra is difficult to

control (Mouazen et al., 2007).

To remove the effect of MC from wet sample spectra, Bogrecki and Lee (2005) reconstructed dry spectra from wet sample spectra to improve the prediction accuracy of phosphorous. Ji et al. (2016) transferred field spectra into laboratory spectra to increase the prediction ability of total nitrogen, organic matter, and pH using the Chinese spectra library. However, these methods required laboratory measurement of dry sample spectra, and the transformation destroyed the original shape of the spectra, leading to the loss of important information of other parameters to be quantified (Mouazen et al., 2006).

Quantitative analysis of soil information from spectra wavelengths requires multivariate regression techniques. Principle component regression (PCR) and partial least square regression (PLSR) have been extensively used. Both of them extract factors (components) from predictors before prediction. Unlike PCR, PLSR considers both predictors (wavelengths) and response variables (soil parameters) as independent multiple dimensional spaces and models their relation by means of a score vector (Hasegawa, 2005). The PLSR algorithm extracts eigenvectors to maximize the covariance between the predictors and the response variables. A few PLSR factors can explain most of the variation in both predictors and response variables. Due to such characteristics, it can be assumed that the errors contained in the wavelengths and soil parameters have little impact on the calibration process. Thus, performing the PLSR algorithm can minimize the effect of MC while predicting other parameters.

To provide soil information in a timely manner, in-situ measurement is more appropriate than laboratory spectra measurement. In this study, we tested the ability of a portable spectrophotometer (ASD FieldSpec 4 Hi-Res) to predict multiple soil parameters in a sloped citrus field under field condition. The use of this instrument for soil measurement based on laboratory spectra can be found in previous papers (Shepherd and Walsh, 2002; Wetterlind et al., 2010). However, few researches investigated the ability of this device to measure multiple soil parameters under field condition. Also, few papers studied the within-field variation of Japanese sloped citrus fields. The parameters investigated in this study are considered to be important contributors to citrus growth and production (Takatsuji, 1978), and the knowledge of interaction between these soil parameters is also important

when providing soil maps to growers for soil management practice (Uwasawa, 1992).

The objectives of this study were to: (1) Investigate the potential ability of FieldSpec4 Hi Res (ASD Inc.) to predict soil water and other parameters in a sloped citrus field. (2) Compare our results with the results in previous papers, including papers using both laboratory and field-based methods. (3) Produce soil water and other parameter maps and yield maps with height changes in the sloped field. (4) Visualize the spatial variation of soil parameters and yield based on height change, and identify which parameters contribute to the spatial pattern of yield.

## **2.2 Materials and methods**

### **2.1.1 Experimental site and soil sampling**

The experimental site was a sloped citrus field located on Iwagi Island, Ochi District, Ehime Prefecture, Japan (Fig. 2.1). The field was triangular in shape with a total area of 0.12 ha and a height difference of about 5 m (slope=10°). The bottom margin was on the hill side while the vertex was on the valley side. According to the soil analysis center, the soil type was alluvial. The texture was described as 43 % coarse sand, 25 % fine sand, 19 % silt, and 13 % clay. Eighty-nine “Harehime” citrus trees were planted in seven rows within the field (Fig. 2.2) at intervals of 4 m between rows and 2 m between trees. A drip fertilization system with year-round mulching was adopted in the field. This system aims to achieve premium quality of fruit by maintaining proper soil moisture during the fruiting season (Morinaga, 2005). The irrigation tube was placed at a distance of 75 cm at the valley side from the growing rows. Manuring in spring (March), summer (June), and autumn (December) was recommended based on nitrogen (N), phosphorous (P<sub>2</sub>O<sub>5</sub>) and potassium (K<sub>2</sub>O) fertilization. The input rate of fertilizer (N-P-K) varies with each growing row as follows: I: 16.6-8.3-12.3 kg/10 a, II: 21.6-11.0-16.3 kg/10 a, III: 27.3-14.0-20.8 kg/10 a, IV: 20.4-10.4-15.4 kg/10 a, V: 25.5-13.1-19.4 kg/10 a, VI and VII: 24.0-24.0-16.0 kg/10 a. Liquid fertilizer (Kumiai ekihi 1 go, 12-5-7) and (OK special, 15-8-12) were applied to I~V.

Chemical fertilizer (15-15-10) were applied to VI and VII. Organic and micronutrient fertilizer had not been used. The yield for all citrus trees in the test field was measured by the growers every year. In this study, the yield data in H22 (2010), H23 (2011), H24 (2012) and H25 (2013) were used for the analysis.

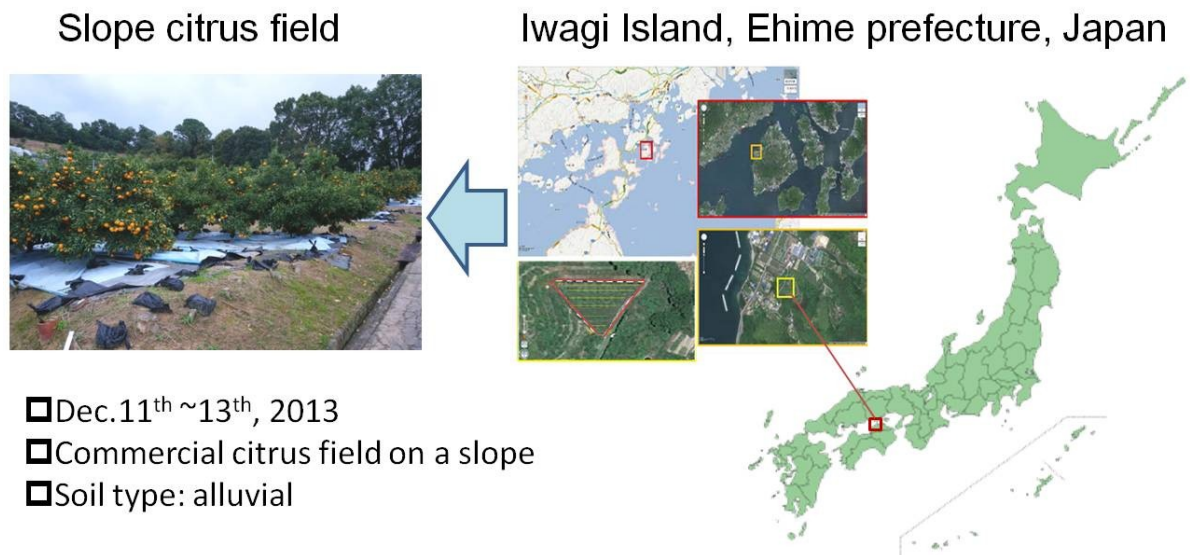


Fig. 2.1 Experimental site

This experiment was conducted on December 12 and 13, 2013 before the autumn manuring. For the purpose of tree-based management, the soil sampling points were determined based on the distance from the irrigation tube and rhizosphere. Eighty-nine sampling positions were determined at 100 cm from the trunk, 25 cm from the irrigation tube, with a sampling depth of 20 cm. Eleven samples were randomly collected on the work road within the field. As a result, a total of 100 soil samples were collected to develop regression models for the multiple soil parameters.

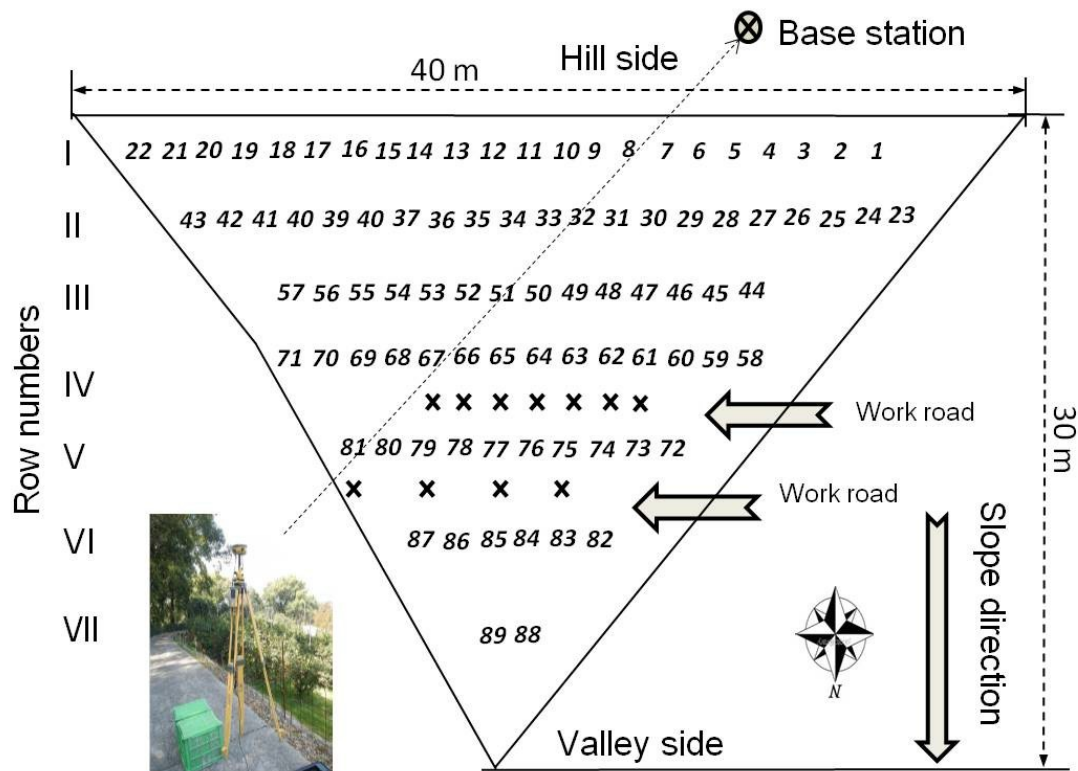


Fig. 2.2 Planting figure of the experimental field. The base station was set on the hill side of the field. “×” refers to the sampling position in the work road.

### 2.1.2 Obtaining location data by RTK-GPS

In order to precisely measure the height difference between each sampling point, a millimeter level Topcon RTK-GPS system was used. This system is composed of a base station and a mobile unit. The base station is a dual-frequency receiver (Hiper II, Topcon) with a data recorder (FC-250, Topcon), which was set at the hill side of the experimental field where the signals were relatively strong (Fig. 2.2). The mobile unit used to measure each sampling position was a GNSS antenna (PG-A1, Topcon) with a data recorder (GRS-1, Topcon). An acrylic flat plate in 5.5 mm thick was placed on the ground to avoid surface roughness. The antenna height was set at the highest level of 2.6 m. The system has horizontal and vertical accuracy of 10 mm +1 ppm and 15 mm +1 ppm, respectively (Hiper II operator’s manual, Topcon).

### 2.1.3 Measurement of soil spectra

Spectra measurement was conducted inside a garage near the experimental site. ASD FieldSpec4 Hi-Res with a contact probe attachment (ASD Inc.) was used for the measurement of reflectance data. This instrument has a 512-channel silicon array (350–1000 nm) and two Graded Index InGaAs detectors (1000–1800 nm and 1801–2500 nm). The sampling interval was 1 nm, which means the output data have 2151 data points. The light source was a halogen bulb inside the contact probe with a 10 mm spot size.

In order to obtain a good signal-to-noise ratio, we designed a measurement tool. It was composed of a probe fixture and a rectangular pedestal container (295 mm in length, 40 mm in width, and 10 mm inside depth). The contact probe was mounted on the fixture and perpendicularly positioned over the sample (Fig. 2.3). The distance between the optical head and soil sample was 0.5 mm. The fresh soil sample was packed into the container with a gentle pressure. Stones and roots were removed from the sample. The excess soil was scraped off by a straight blade to obtain a smooth surface. The pedestal was laterally moved to allow scanning at ten locations of the sample surface. At each location, we collected 5 soil spectra, and an average value of the 50 spectra was used to represent that sample. A light shielding sheet was used to cover the probe to avoid external light.



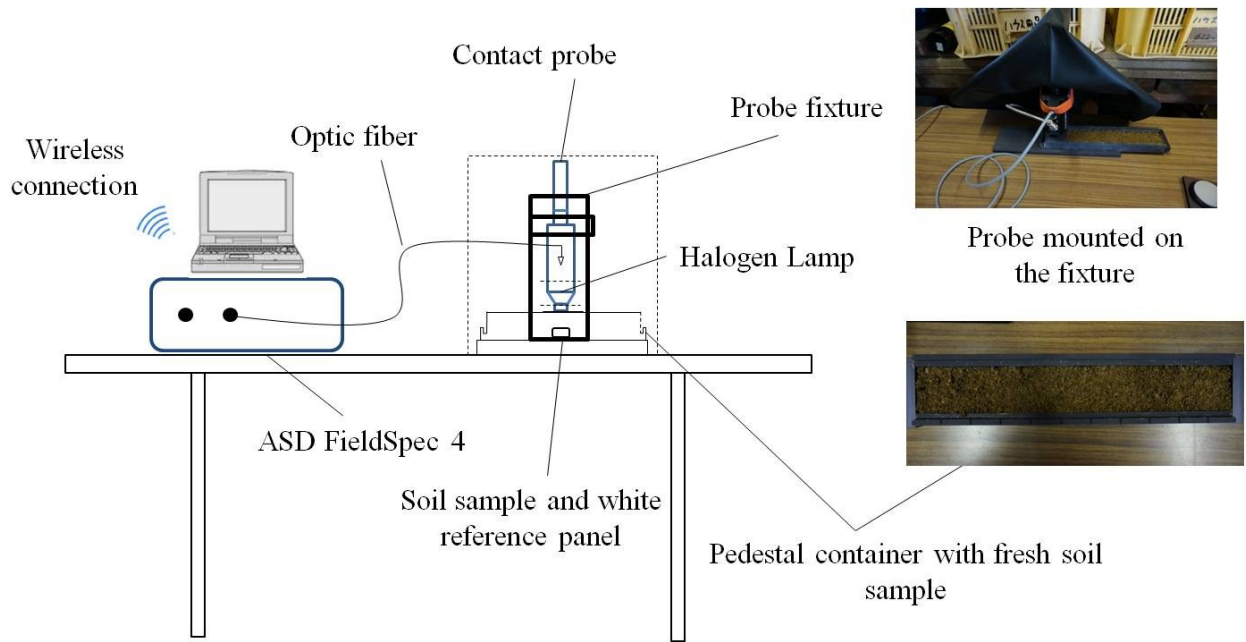


Fig. 2.3 Experimental setup for fresh sample spectra

The spectra were calibrated against a standard reference panel (Labsphere, SRS-40-020) before every sample measurement. When spectral measurement of one sample was finished, the spectral shape was confirmed using ViewSpec Pro<sup>TM</sup> software (version 6.0.11, ASD Inc.). If the shape was abnormal, the spectra of that sample were remeasured. Abnormal spectral shapes were often observed when the soil was rapidly dried out at the scan locations (Fig. 2.4b). It was surmised that the optical head heated the soil scan surface during the scanning action (Fig. 2.4a). This problem was solved by moving the pedestal speedily and by reducing the scan time. Other cases of abnormal spectra were caused by obstacles such as roots, holes and stones. These problems were solved by careful preparation of soil samples.

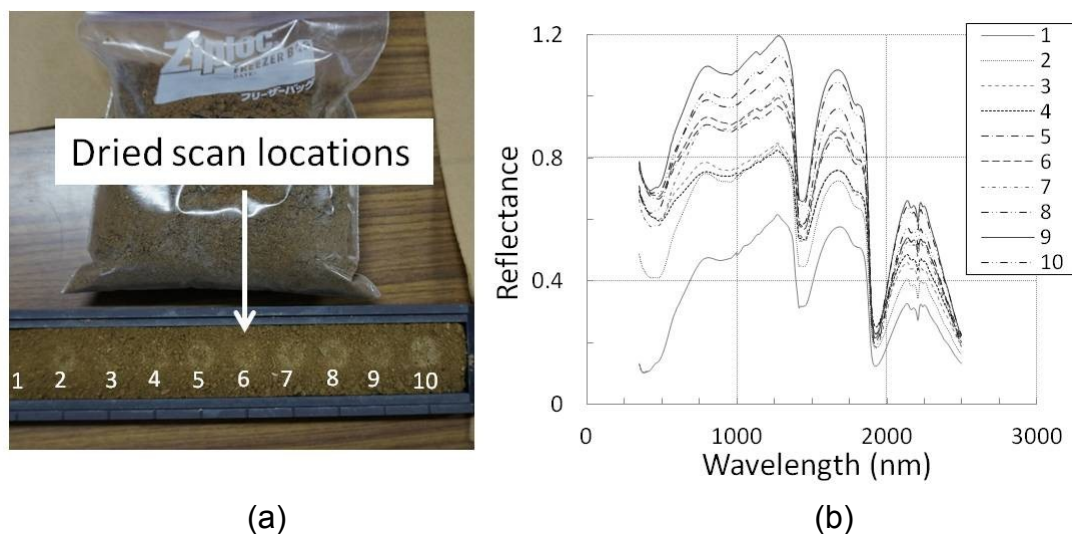


Fig. 2.4 Biases of reflectance spectra caused by drying of scan locations. (a) Dried scan locations by heat with the optical head. (b) Reflectance spectra from the dried locations. The number in this figure represents the spectra data at the scan spot corresponding to (a).

#### 2.1.4 Soil chemical analysis

Twenty four soil parameters were selected and investigated in this study, including MC, pH, EC, available phosphorus (P-a), exchangeable potassium (K), exchangeable magnesium (Mg), exchangeable calcium (Ca), calcium saturation percentage (CSP), base saturation percentage (BSP), soluble copper (Cu), soluble zinc (Zn), easily reducible manganese (Mn), hot water soluble boron (B), hot-water extractable nitrogen (N-h), total nitrogen (N-t), total carbon (C-t), nitrate nitrogen (N-n), ammonium nitrogen (N-a), calcium/magnesium ratio (Ca/Mg), magnesium/potassium ratio (Mg/K), phosphate absorption coefficient (PAC), cation exchange capacity (CEC), bulk density (BD) and exchangeable acidity ( $y_1$ ).

Two sets of the 100 soil samples were collected from the field and sealed into Ziploc bags. One set was transported to Tokyo University of Agriculture and Technology (TUAT) for analysis of MC, and the other set was transported to the Agriculture Product Chemical Research Laboratory (APCRL; Federation of Tokachi Agricultural Cooperative Association, Hokkaido, Japan) for analysis of the other 23 parameters.

The soil samples were transported by a refrigerated courier service at a temperature below 10 °C, and then at TUAT they were stored in a refrigerator at 5 °C. MC was measured for all 100 samples based on dry soil by using the oven-dry method at 110 °C for 24 h. Analysis was repeated three times, and the average value was used in the multivariate statistical analysis.

Soil pH was measured by glass electrodes (F52, Horiba, Ltd.). Soil EC was measured by the AC bipolar method (CM-60R, DKK-TOA CORPORATION). The N-t and C-t were measured by a CN coder (NC-220F, Sumika Chemical Analysis Service, Ltd.). K, Ca, and Mg were measured using the Schollenberger method with atomic absorptiometry (SpectrAA-250FS, Varian, Inc.). Cu, Zn, and Mn were measured using atomic absorptiometry (SpectrAA-220, Varian, Inc.). B was measured using absorptiometry (U3000, Hitachi, Ltd). P-a, N-h, N-n, N-a, PAC, and CEC were measured using absorptiometry (Quaatro, Bran+Luebbe). The y1 was measured using titration method (KCL extraction). Ca/Mg, Mg/K, BSP, and CSP were calculated from the equivalent ratio. BD was determined using the calculation method.

#### 2.1.5 Spectral pretreatment

The measured raw reflectance data were transformed into absorbance ( $\log 1/R$ ) using ViewSpec Pro<sup>TM</sup> (ASD Inc.). Absorbance data in the 350–400 nm and 2450–2500 nm region was removed due to excessive noise (Mouazen et al., 2006; Shepherd and Walsh, 2002; Ji et al., 2016). Therefore, spectral pretreatments were carried out using absorbance data in the 400–2450 nm region. The 1<sup>st</sup> derivative and 2<sup>nd</sup> derivative using the Savitzky and Golay (SG) method were applied in this study. Pretreatment methods for parameters were selected based on their ability to provide the best prediction results compared to other tested methods. The 1st derivative of the SG method was applied for C-t, N-t, N-h, N-n, N-a, Mg, pH, K, Mg/K, Cu, Zn, PAC, and y1, with 2nd polynomial order and 21 smoothing points. For the prediction of P-a, the 1st derivative of the SG method with 2nd polynomial order and 101 smoothing points was used. The other parameters used the 2nd derivative of the SG

method, with 2nd polynomial order and 101 smoothing points. These works were performed using The Unscrambler X software (version 10.2, CAMO Software AS, Norway).

#### 2.1.6 Evaluation of regression model

Cross-validation can be used to evaluate the prediction ability of the regression models. However, it is possible to over or under estimate prediction ability when using the models to predict an unknown data set. To evaluate the utility of the regression models, the data set for validation (test set) should be independent of the set used for calibration (training set) (David et al., 2005). Therefore, this study randomly divided the 100 samples into a training set of 75 samples and a test set of 25 samples. The statistics of each data set are listed in Table 2.1. It includes minimum, maximum, mean and standard deviation.

The PLSR was used to relate the predictors to response variables using The Unscrambler X. Details of the PLSR algorithm can be found in Hasegawa (2005). In order to avoid over fitting, the full cross-validation (leave-one-out) method was performed. The PLSR factors were automatically recommended by The Unscrambler X. Sample outliers can be caused by the noise in the spectra data due to plant residues and stones, and also by measurement errors of the chemical analysis. In this study, the sample outliers were determined by observing a residue variance plot in the cross-validation. One sample with the largest residue variance was determined as the outlier and was removed in the next calculation. This procedure was repeated several times. If excluding a sample results in decreasing the prediction accuracy, the sample was not excluded, and the model before excluding the sample was used. It was reported that water molecules, metal-OH, and carbonate groups have absorption bands near the 1450 nm, 1950 nm, and 2300 nm in the NIR region (Chang et al., 2001; Udelhoven et al., 2003; Stenberg et al., 2010). Thus, the full Vis-NIR wavelengths range (400–2450 nm) and only the NIR region (1000–2450 nm) were tested. The results showed that pH, K, Ca, BSP, CSP, and Ca/Mg gave the best results when only the NIR region was used. Other soil parameters showed best results when using the full Vis-NIR wavelengths range.

Table 2.1 Statistics of chemical analysis data of soil samples collected (All: n=100, Training: n=75, Test: n=25).

Parameter	Dataset	Min	Max	Mean	S.D.	Parameter	Dataset	Min	Max	Mean	S.D.
pH (H <sub>2</sub> O)	All	4.10	7.70	5.30	0.86	B (mg/100g)	All	0.37	1.33	0.73	0.23
	Training	4.30	7.70	5.30	0.86		Training	0.37	1.32	0.74	0.23
	Test	4.10	7.40	5.31	0.90		Test	0.41	1.33	0.75	0.24
P-a (mg/100g)	All	24.70	162.80	77.80	27.77	N-h (mg/100g)	All	1.28	5.98	2.87	1.01
	Training	24.70	154.10	77.10	27.38		Training	1.28	5.97	2.85	0.99
	Test	33.90	162.80	79.83	29.37		Test	1.50	5.98	2.94	1.07
K (mg/100g)	All	7.30	36.20	16.01	4.72	N-t (%)	All	0.02	0.13	0.06	0.02
	Training	7.30	31.30	16.80	4.73		Training	0.02	0.11	0.06	0.02
	Test	10.70	36.20	17.52	4.81		Test	0.02	0.13	0.06	0.03
Mg (mg/100g)	All	5.10	34.10	16.50	5.71	N-n (mg/100g)	All	0.01	3.89	0.61	0.70
	Training	5.10	33.80	16.31	5.64		Training	0.01	3.06	0.63	0.71
	Test	7.70	34.10	16.90	6.12		Test	0.02	3.89	0.57	0.66
Ca (mg/100g)	All	49.40	906.50	180.70	139.86	N-a (mg/100g)	All	0.27	7.24	0.78	0.92
	Training	49.40	826.00	159.12	129.23		Training	0.27	6.18	0.74	0.73
	Test	64.90	906.50	179.11	187.34		Test	0.92	7.24	0.92	1.35
Mg/K	All	0.60	42.00	3.20	6.44	PAC	All	16.00	2001.00	221.30	313.16
	Training	0.60	41.00	2.89	5.84		Training	16.00	2001.00	244.91	357.17
	Test	1.60	42.00	3.97	8.09		Test	18.70	312.00	150.47	65.11
Ca/Mg	All	2.90	39.70	7.60	5.60	CEC (me/100g)	All	5.70	13.30	8.76	1.28
	Training	2.90	33.90	7.41	4.59		Training	5.70	13.00	8.89	1.26
	Test	4.50	39.70	8.32	7.99		Test	7.00	13.30	9.04	1.36
CSP (%)	All	22.10	248.90	63.21	40.32	BD	All	0.95	1.18	1.05	0.04
	Training	22.10	222.00	61.76	33.83		Training	0.95	1.18	1.05	0.04
	Test	26.40	248.90	67.54	53.61		Test	0.98	1.13	1.05	0.04
BSP (%)	All	29.10	260.30	76.50	40.89	EC (mS/cm)	All	0.04	0.24	0.07	0.03
	Training	29.10	234.30	75.08	17.75		Training	0.04	0.24	0.07	0.03
	Test	35.20	260.30	80.83	49.77		Test	0.04	0.17	0.07	0.03
Cu (ppm)	All	0.71	19.78	5.44	3.44	MC (%)	All	11.50	24.40	17.50	2.79
	Training	0.71	18.91	4.90	3.27		Training	11.50	24.40	17.60	2.97
	Test	1.06	19.78	5.29	3.96		Test	12.70	23.70	17.00	2.86
Zn (ppm)	All	1.90	77.91	10.84	11.85	C-t (%)	All	0.12	1.33	0.51	0.26
	Training	1.90	63.77	10.40	10.55		Training	0.17	1.33	0.52	0.20
	Test	2.25	77.91	12.15	15.30		Test	0.12	0.75	0.47	0.18
Mn (ppm)	All	6.74	588.64	73.55	78.49	yl	All	0.80	15.90	7.60	2.75
	Training	6.74	384.84	69.87	63.79		Training	0.80	14.90	7.60	2.74
	Test	13.28	588.64	84.59	112.67		Test	2.40	15.90	7.90	2.83

### 2.1.7 Mapping of soil parameters and yield

The soil parameter maps and yield maps were drawn using the ArcScene software (version 10.2) from the ArcGIS 10.2 (ESRI Inc., USA). In order to show the topography in the sloped field, the maps provided in this study were in the x, y and z coordinate system, where the height change can be visualized. The grid was interpolated with soil parameters and yield data using the inverse distance weighing (IDW) algorithm with a triangle polyline feature. The conditions to use IDW interpolation include sufficient sampling density and uniformly distributed sampling points. This study meets these conditions with 100 sampling points that were uniformly distributed within the field. Thus, the IDW interpolation is proper for the mapping. The default settings of IDW interpolation were used, including grid size: 0.16 m, search radius: Variable (12 points) and power value: 2. Each data range was divided into 3 classes. In order to compare predicted maps with measured maps, the classes in the two maps were made identical.

### 2.1.8 Mapping of soil water at three depths

In the above experiment, only one point was measured in the depth direction. As additional experiments to investigate soil water distribution in both horizontal and vertical direction, and verify whether similar maps can be used for cultivation management, three points in the depth direction at each sampling point were acquired and a 3 dimensional soil water map was developed. The experiment was carried out on December 12, 2013 at the same day as before. The number of sampling points was set to 153 points, at 46 positions (1 position/2 trees) around the tree trunk within the field and 5 positions at the bare place, and 3 points at each position. The sampling depth was 0 cm, 20 cm and 40 cm from the soil surface, as shown in Fig. 2.5.

Regarding the sampling position, the position information (longitude, latitude, elevation) was obtained in the before experiment. In this investigation, soil was not sampled and analyzed. The soil water content was directly measured using Soil moisture,

Temperature and EC Sensor (GS3, Decagon). The measured volumetric water content (VWC) was produced in this study.

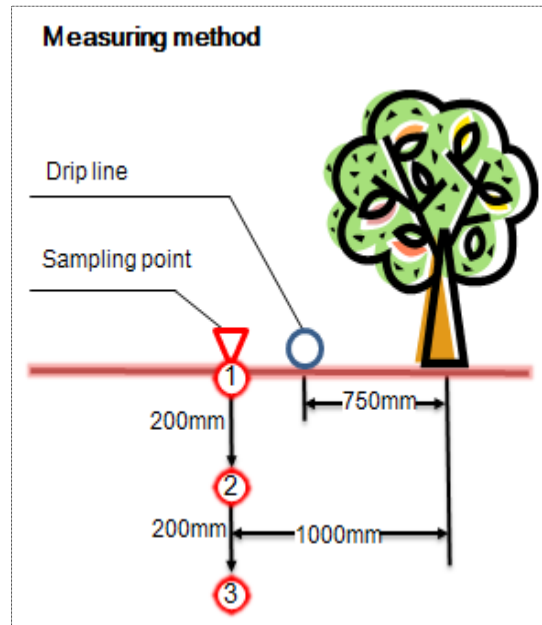


Fig. 2.5 Soil moisture measurement at three depths

## 2.2 Results and discussion

### 2.2.1 Calibration and validation

The PLSR analysis was used to establish regression models on the training set ( $n=75$ ), while full-cross validation was simultaneously performed. These models were then used to predict the multiple soil parameters in the test set ( $n=25$ ). Table 2.2 shows the PLSR results for both validation and prediction for the parameters listed in Table 1. The results included the coefficient of determination ( $R^2$ ), root mean square error (RMSE), and residual prediction deviation (RPD). The RPD is typically employed to compare the prediction accuracy between different data sizes, which is determined by the ratio of standard deviation of the laboratory measured values to RMSE of the test set. The criteria to classify the prediction ability according to the  $R^2$  and RPD values were as follows: Class A ( $R^2>0.8$  and  $RPD>2.0$ ) indicates an excellent model; Class B ( $R^2=0.5-0.8$  and

RPD=1.4–2.0) indicates a good model; Class C ( $R^2<0.5$  and  $RPD<1.4$ ) indicates an unreliable model (Chang et al., 2001).

Table 2.2 PLSR results of validation and prediction of the investigated soil parameters

Parameter	Wavelength (nm)	Cross validation				Prediction (n=25)			Class <sup>c</sup>	
		N <sup>a</sup>	nF <sup>b</sup>	$R_{cv}^2$	RMSE <sub>cv</sub>	$R_p^2$	RMSE <sub>p</sub>	RPD <sub>p</sub>	This paper	Previous
pH	1000-2450	74	11	0.82	0.37	0.85	0.36	2.53	A	C-B
P-a	400-2450	75	11	0.52	19.68	0.59	17.2	1.59	B	C
K	1000-2450	74	9	0.58	3.01	0.44	3.54	1.36	C	C-A
Mg	400-2450	71	8	0.45	3.73	0.43	3.75	1.29	C	-
Ca	1000-2450	74	10	0.68	85.35	0.65	64.36	1.69	B	-
Mg/K	400-2450	73	11	0.19	0.98	0.25	0.88	1.16	C	-
Ca/Mg	1000-2450	74	11	0.61	4.32	0.64	3.25	1.6	B	-
CSP	1000-2450	74	11	0.74	17.27	0.66	21.92	1.7	B	-
BSP	1000-2450	74	10	0.7	23.14	0.67	22.13	1.72	B	-
Cu	400-2450	74	3	0.34	2.85	0.53	1.34	1.42	B	-
Zn	400-2450	74	5	0.29	7.55	0.1	11.41	1.06	C	-
Mn	400-2450	69	10	0.66	23.2	0.8	17.15	2.16	A	-
B	400-2450	74	3	0.66	0.13	0.04	0.26	0.95	C	-
N-h	400-2450	75	4	0.64	0.64	0.39	0.71	1.29	C	-
N-t	400-2450	75	5	0.77	0.01	0.74	0.01	1.93	B	C-A
N-n	400-2450	75	11	0.12	0.67	0.35	0.57	1.17	C	-
N-a	400-2450	75	1	0.03	0.82	0.08	1.12	1.15	C	-
PAC	400-2450	70	9	0.27	47.17	0.31	59.45	1.1	C	-
CEC	400-2450	74	12	0.56	0.9	0.8	0.56	1.89	B	-
BD	400-2450	74	11	0.53	0.03	0.5	0.03	1.44	B	-
EC	400-2450	73	13	0.52	0.02	0.25	0.03	1.14	C	-
MC	400-2450	73	3	0.73	1.53	0.82	1.22	2.34	A	
C-t	400-2450	72	5	0.83	0.1	0.74	0.09	1.92	B	A
y1	400-2450	75	1	NA	NA	-	-	-	-	-

<sup>a</sup> Number of samples used in the model.

<sup>b</sup> Number of PLSR factors used in the model.

<sup>c</sup> Class of the prediction performance. A:  $R^2>0.8$  and  $RPD>2.0$ , B:  $R^2=0.5-0.8$  and  $RPD=1.4-2.0$ , C:  $R^2<0.5$  and  $RPD<1.4$  (Chang et al., 2001).

In this study, the excellent models (class A) included pH, Mn, and MC, with  $R^2$  between 0.80–0.85 and RPD value between 2.16–2.53. The good models (class B) included P-a, Ca, Ca/Mg, CSP, BSP, Cu, N-t, CEC, BD, and C-t, with  $R^2$  between 0.50–0.74 and RPD value between 1.42–1.93. Other models were not reliable for prediction (class C) with  $R^2$  between 0.04–0.44 and PRD value between 0.95–1.36. y1 was unable to be



predicted using the Vis-NIR spectroscopy since the result was not available (NA) in validation. The scatter plots of the measured versus predicted soil parameters for the 25 samples in the test set are shown in Fig. 2.6.

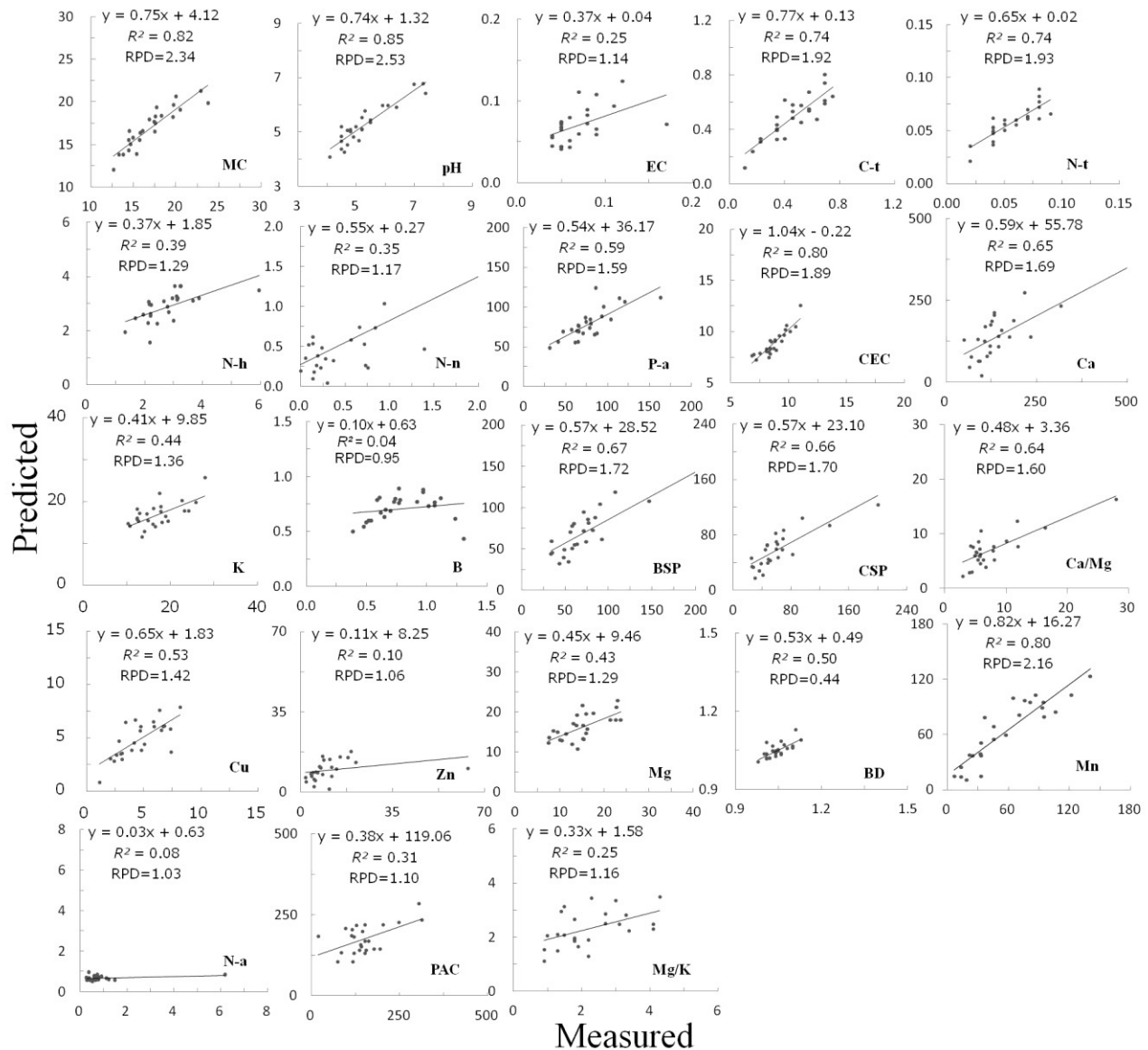


Fig. 2.6 Scatter plot of measured versus predicted multiple soil parameters using the 25 sample spectra in the test set

Generally, spectral active parameters such as MC, N-t, and C-t can always be predicted because they have direct absorption bands in the NIR region (Viscarra Rossel et al., 2006; Kuang et al., 2012; Kodaira and Shibusawa, 2013). Other parameters that are

predicted through indirect correlation are dependent on the correlation structure of the field (Chang et al., 2001). The prediction accuracy of these models is not generalizable, so these models can only be used as local models. The prediction accuracy of these parameters can be improved by enhancing data size, stability of spectral data, and calibration techniques.

A correlation matrix between parameters and yield is shown in Table 2.3. The correlation was determined based on significant levels of 5% and 1%. Because the significant level alone cannot show the strength of a correlation, a simple classification standard was used in this study to interpret the strength of a correlation coefficient ( $R$ ) as shown in Table 2.3 (Hatano et al., 2005). In this study, two groups can be distinguished according to the  $R$ . The first group included Cu, Zn, B, N-h, P-a, and CEC, which were correlated with N-t and C-t ( $R>0.4$ ). The second group included pH, K, P-a, BSP, CSP, Ca/Mg, Zn, PAC and CEC correlated with Ca ( $R>0.4$ ). P-a, Zn, and CEC had correlation with both groups. The second group did not have a direct response in the Vis-NIR region, and the prediction of these parameters depends on the correlation with spectra active elements such as clay minerals (Stenberg et al., 2010).

In this study, pH was best predicted, followed by MC and Mn (class A). The high prediction accuracy of pH may be because of the wide-range and uniformly distributed data set. The prediction accuracy of pH in this study is similar to or better than the previous results (Viscarra Rossel et al., 2006; Kuang et al., 2012; Kodaira and Shibusawa, 2013). Mn was not strongly correlated with spectral active parameters of MC, N-t, and C-t, but it can be predicted with good accuracy (class A). This may be because of its correlation with other spectral active materials that were not investigated in this study. The spectral active parameters of N-t and C-t were not excellently predicted (class B), which may be due to the narrow range of the data set for N-t and C-t ( $SD=0.02$  and  $0.2$ , respectively). N-h, Zn, and B had correlation with N-t ( $R=0.81$ ,  $0.47$  and  $0.64$ , respectively). But the prediction of these parameters was poor (class C). One method to improve the accuracy of these models is to select wide-range and uniform data sets for the calibration. On the other hand, it can be noticed that there is a distinct outlier for N-h, Zn, and B (Fig. 2.6). Accuracy can be improved if the outlier is removed.

Table 2.3 Correlation coefficients (*R*) between yield and measured soil parameters

	Z	pH	P-a	K	Mg	Ca	Mg/K	Ca/Mg	CSP	BSP	Cu	Zn	Mn	B	N-h	N-t	N-n	N-a	PAC	CEC	BD	C-t	EC	yl	MC	2010 yield	2011 yield	2012 yield	2013 yield
Z	1																												
pH	-0.13	1																											
P-a	0.12	0.29	1																										
K	0.01	0.35	0.34	1																									
Mg	0.18	0.18	-0.04	-0.16	1																								
Ca	-0.03	0.77	0.41	0.61	0.09	1																							
Mg/K	0.18	0.07	0.06	-0.13	0.46	-0.04	1																						
Ca/Mg	-0.08	0.7	0.4	0.64	-0.21	0.94	-0.16	1																					
CSP	-0.08	0.87	0.33	0.54	0.1	0.97	-0.02	0.93	1																				
BSP	-0.07	0.88	0.3	0.53	0.17	0.97	0.01	0.9	1	1																			
Cu	-0.09	0.11	0.29	0.09	-0.22	0.02	-0.07	0.09	0.04	0.02	1																		
Zn	0.01	0.45	0.44	0.32	0.01	0.41	-0.03	0.38	0.4	0.39	0.44	1																	
Mn	0.15	0.19	-0.01	-0.05	-0.06	0.08	0.08	0.09	0.12	0.12	0.52	0.24	1																
B	0.12	-0.03	0.52	0.29	-0.29	0.14	-0.13	0.22	0.05	0.02	0.39	0.29	0	1															
N-h	0.14	-0.1	0.53	0.28	-0.22	0.17	-0.04	0.23	0.06	0.03	0.49	0.26	0.11	0.69	1														
N-t	0.22	0.09	0.62	0.33	-0.12	0.29	-0.1	0.32	0.2	0.17	0.66	0.47	0.28	0.64	0.81	1													
N-n	0.37	-0.04	0.23	0.22	0.09	0.18	-0.02	0.16	0.11	0.1	0.08	0.08	-0.01	0.27	0.27	0.24	1												
N-a	-0.25	-0.31	0.05	0.15	-0.21	-0.18	-0.06	-0.11	-0.22	-0.23	0.05	-0.12	-0.17	0.1	0.44	0.14	-0.04	1											
PAC	-0.03	0.54	0.24	0.41	0.01	0.78	-0.06	0.78	0.76	0.74	-0.01	0.33	0.06	0.13	0.14	0.21	0.04	-0.1	1										
CEC	0.2	0.16	0.63	0.54	0.21	0.58	-0.03	0.5	0.42	0.4	0.03	0.28	-0.2	0.39	0.47	0.55	0.43	0.04	0.46	1									
BD	0.14	-0.16	-0.4	-0.2	0.02	-0.31	0.1	-0.31	-0.26	-0.24	-0.33	-0.32	-0.03	-0.26	-0.44	-0.57	-0.02	-0.05	-0.26	-0.43	1								
C-t	0.13	0.14	0.55	0.36	-0.16	0.36	-0.1	0.39	0.26	0.23	0.64	0.45	0.31	0.69	0.79	0.95	0.21	0.1	0.27	0.54	-0.53	1							
EC	-0.03	0.06	0.43	0.47	-0.06	0.38	-0.07	0.39	0.29	0.27	0.08	0.15	-0.1	0.28	0.56	0.37	0.53	0.61	0.3	0.56	-0.2	0.35	1						
yl	0.03	-0.07	-0.11	0.07	-0.24	-0.03	-0.19	0.06	-0.04	-0.06	0.01	-0.04	0.03	-0.05	-0.01	0	0.05	-0.13	0.05	0.01	0.1	0.01	-0.02	1					
MC	0.23	0.3	0.01	0.2	0.15	0.27	-0.04	0.21	0.26	0.26	0.04	0.28	0.06	0.2	0.01	0.11	0.2	-0.26	0.26	0.2	0.02	0.17	-0.11	-0.07	1				
2010 yield	-0.38	0.09	0.03	0.07	-0.06	0.12	-0.15	0.14	0.11	0.11	0.37	0.25	0.19	0.14	0.21	0.3	-0.06	-0.03	0.13	0.07	-0.26	0.3	0	-0.07	0.04	1			
2011 yield	0.37	-0.06	0.05	-0.03	0.03	0.03	0.03	0.03	0.02	0.02	-0.15	-0.05	0.01	-0.06	-0.08	-0.07	0.41	-0.06	0.1	0.06	0.29	-0.16	0.13	0.09	0.11	-0.06	1		
2012 yield	-0.36	0.29	0.03	0.13	0.01	0.25	-0.06	0.26	0.29	0.29	0.39	0.26	0.31	0	0.15	0.29	-0.11	0.05	0.25	0.03	-0.24	0.25	0.14	-0.04	-0.08	0.68	-0.1	1	
2013 yield	0.08	0.15	0.01	0.06	0.02	0.15	-0.01	0.16	0.17	0.17	0.15	-0.01	0.18	-0.11	0.04	0.05	0.29	0.03	0.13	0.05	0.12	0	0.29	0.03	-0.08	0.1	0.48	0.49	1

5% level of significance:  $|R| > 0.197$ , 1% level of significance:  $|R| > 0.232$

Full correlation = 1

High correlation  $1 \geq |R| > 0.7$  (Bold type + gray highlight)

Correlation  $0.7 \geq |R| > 0.4$  (Gray highlight; Negative correlation ( $R < -0.4$ ): Framed)

Low correlation  $0.4 \geq |R| > 0.2$

Almost no correlation  $0.2 \geq |R| > 0$

No correlation  $|R| = 0$

### 2.2.2 Comparison with previous studies using the FieldSpec instrument

Table 2.4 shows the soil parameter prediction results from previous studies that used the FieldSpec instrument. Compared with the previous results, the prediction of pH, Mn, and P-a in this study was the same or better. The prediction of C-t, N-t, Mg, and Ca was poorer in this study. This is probably because the data set used in this study was narrower or skewed. The CEC results were only slightly poorer compared with the previous results.

As shown in Table 2.4, most of the previous studies used the laboratory-based method. The fresh sample based method using the FieldSpec instrument is found in only a few papers (Ji et al., 2014; Ji et al., 2016). Compared with their studies, the prediction of pH, P-a, and K was better in this study, and the prediction of N-t was poorer. Udelhoven et al. (2003) conducted NIR measurement of Fe, Mn, Ca, Mg, and K in laboratory and under field conditions. However, they only obtained predictable results for Ca and Mg ( $R^2 = 0.67$  and  $0.69$ , respectively) under field conditions.

Compared with previous studies, the main improvement in this study was the fresh sample preparation. In our method, the noise from soil surface variation, external light, soil texture, and human error could be minimized. Also, this study was conducted based on a single field with a small variation in soil moisture and structure. Thus, the influence of these factors could be well controlled. On the other hand, the poorer results for the prediction of C-t, N-t, Ca, and K indicated that a wider-range and uniformly distributed data set needs to be used to develop robust regression models.

Table 2.4 A review of the literature for the quantitative analysis of soil parameters using the ASD FieldSpec instrument.

Parameter	Wavelength (nm)	Multivariate method <sup>a</sup>	Based	Range <sup>b</sup>	N <sub>cal</sub>  N <sub>val</sub> <sup>c</sup>	R <sup>2</sup>	RMSE	RPD	Class	Instrument	Author
C-t (%)	430-2500	PLSR (4)	Lab	1.3-4.1	122 31	0.89	0.16	3.4	A	FieldSpec Pro FR	Wetterlind et al. (2010)
N-t (%)	430-2500	PLSR (5)	Lab	0.13-0.55	122 31	0.85	0.024	2.7	A	FieldSpec Pro FR	Wetterlind et al. (2010)
N-t (%)	400-2450	LWR	Field	0.34-4.70	2955 255	0.66	0.39	1.81	B	FieldSpec Pro FR	Ji et al. (2016)
N-t (%)	400-2500	PLSR	Lab	-	114 CV	0.62	0.1	-	-	FieldSpec II	Udelhoven et al. (2003)
N-t (%)	400-2450	LS-SVM	Field	0.03-0.37	78 26	0.88	0.03	3.05	A	FieldSpec Pro FR	Ji et al. (2014)
P-a (mg/100g)	430-2500	PLSR (7)	Lab	2-39	122 31	0.48	3.3	1.7	B	FieldSpec Pro FR	Wetterlind et al. (2010)
P-a (mg/kg)	400-2450	LWR	Field	0.70-108	78 26	0.36	14.33	1.27	C	FieldSpec Pro FR	Ji et al. (2014)
Mg (mg/100g)	400-2450	PLSR (7)	Lab	11-65	122 31	0.83	5.8	2.3	A	FieldSpec Pro FR	Wetterlind et al. (2010)
Mg (mg/100g)	390-2450	MARS	Lab	-	739 369	0.81	1.1	-	-	FieldSpec FR	Shepherd and Walsh (2002)
Mg (mg/100g)	400-2500	PLSR	Lab	-	52 CV	0.91	0.38	-	-	FieldSpec II	Udelhoven et al. (2003)
pH	430-2500	PLSR (8)	Lab	5.9-7.6	122 31	0.65	0.1	1.6	B	FieldSpec Pro FR	Wetterlind et al. (2010)
pH	390-2450	MARS	Lab	-	758 378	0.7	0.43	-	-	FieldSpec FR	Shepherd and Walsh (2002)
pH	400-2450	LWR	Field	3.6-8.4	2883 255	0.61	0.73	2.3	A	FieldSpec Pro FR	Ji et al. (2016)
pH	400-2450	LWR	Field	4.6-8.4	78 26	0.8	0.54	2.23	A	FieldSpec Pro FR	Ji et al. (2014)
K (mg/100g)	430-2500	PLSR (7)	Lab	12-39	122 31	0.87	1.9	2.8	A	FieldSpec Pro FR	Wetterlind et al. (2010)
K (mg/100g)	400-2500	PLSR	Lab	-	52 CV	0.85	0.47	-	-	FieldSpec II	Udelhoven et al. (2003)
K (mg/kg)	400-2450	LWR	Field	32.5-105	78 26	0.14	17.66	0.91	C	FieldSpec Pro FR	Ji et al. (2014)
Ca (mg/100g)	390-2450	MARS	Lab	-	740 369	0.88	2.8	-	-	FieldSpec FR	Shepherd and Walsh (2002)
Ca (mg/100g)	400-2500	PLSR	Lab	-	52 CV	0.94	0.53	-	-	FieldSpec II	Udelhoven et al. (2003)
Mn (g kg <sup>-1</sup> )	400-2500	PLSR	Lab	-	52 CV	0.81	0.19	-	-	FieldSpec II	Udelhoven et al. (2003)
CEC (c mol(+) kg <sup>-1</sup> )	390-2450	MARS	Lab	-	740 369	0.88	3.8	-	-	FieldSpec FR	Shepherd and Walsh (2002)

<sup>a</sup> Multivariate method included the Least square vector support machine (LS-SVM), multivariate adaptive regression splines (MARS), Locally weighted regression (LVM), and Partial Least Square Regression (PLSR). Shown in brackets is the number of PLSR factors used in calibration.

<sup>b</sup> Range means the data size used in the calibration and validation.

<sup>c</sup> N<sub>cal</sub>|N<sub>val</sub> shows the number of samples used in the calibration and the number of samples used for validation. CV means cross validation was conducted.

### 2.2.3 Soil parameter mapping of the sloped field

The IDW maps of soil parameters were drawn for both measured and predicted values as shown in Fig. 2.7. The maps were divided into 3 classes according to the accuracy of Chang's standard (Chang et al., 2001). MC, pH, and Mn were in Class A, which means the predicted values of these parameters can explain more than 80% of the measured values ( $R^2 > 0.8$ ). Thus, the predicted maps can be trusted since they are similar to measured maps in both distribution patterns and values. The true values of class B prediction maps may be under 50% (e.g.,  $R^2 = 0.5$ ). But these maps can still give a general idea of the spatial pattern of the field since they have similarity with the measured maps to some extent. The predicted maps in class C may have true values under 40% ( $R^2 < 0.4$ ), which means the spatial patterns were different between the measured and predicted maps, so these prediction maps cannot be trusted.

The maps of pH, Ca, BSP, CSP, and Ca/Mg showed a similar spatial pattern, which is due to positive correlations between these parameters. The pH map showed high spatial variation. The suitable range of soil pH for citrus production is 5.5–6.5 in the rooting zone (Takatsuji, 1978). Excessive values were found in the third growing row. According to the grower, this area was used as work road and high values were caused by mixing the soil with cement. The lower pH values were a result of fertilizer application (Takatsuji, 1978). In addition, the similar distribution pattern was also found for the soil parameter maps of C-t, N-t, CEC, P-a and Cu which had positive correlations. The spatial pattern of CEC was reversed compared with Mn. This was due to the negative correlation between them.

Cu, Zn, Mn, and Mg are important elements for citrus growth. The absorption rate of these elements by citrus may highly depend on soil pH. For example, excessive soil pH values may decrease available Mn and lead to Mn deficiency, while acid soil resulted in over absorption of Mn (Takatsuji, 1978; Taki et al., 2005). Lime fertilization provides soil improvement based on the analysis of soil pH. It has always been used to neutralize toxicity by adjusting soil pH and supplying additional Mg to citrus trees (Takatsuji, 1978). The high spatial variation of soil pH indicates that soil analysis based on one representative soil sample is not sufficient and a uniform rate of fertilization resulted in over- or under- fertilized

areas within the field.

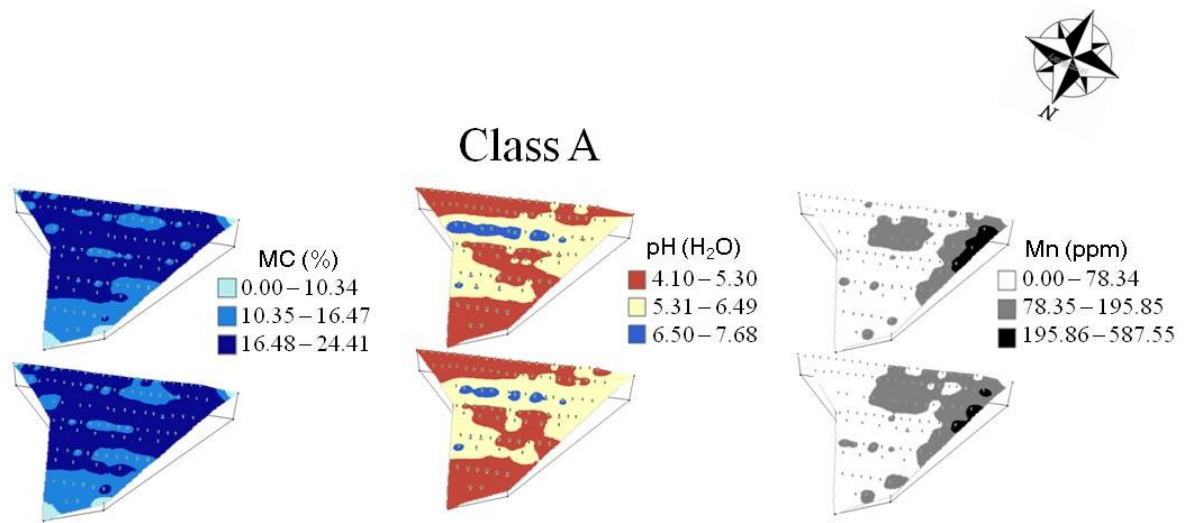


Fig. 2.7 Class A

Fig. 2.7 Measured (up) and predicted (bottom) soil parameter maps. The predicted maps were drawn using the 100 fresh sample spectra and established regression models. The maps were divided into 3 classes based on the accuracy level according to the standard in Chang et al., (2001)

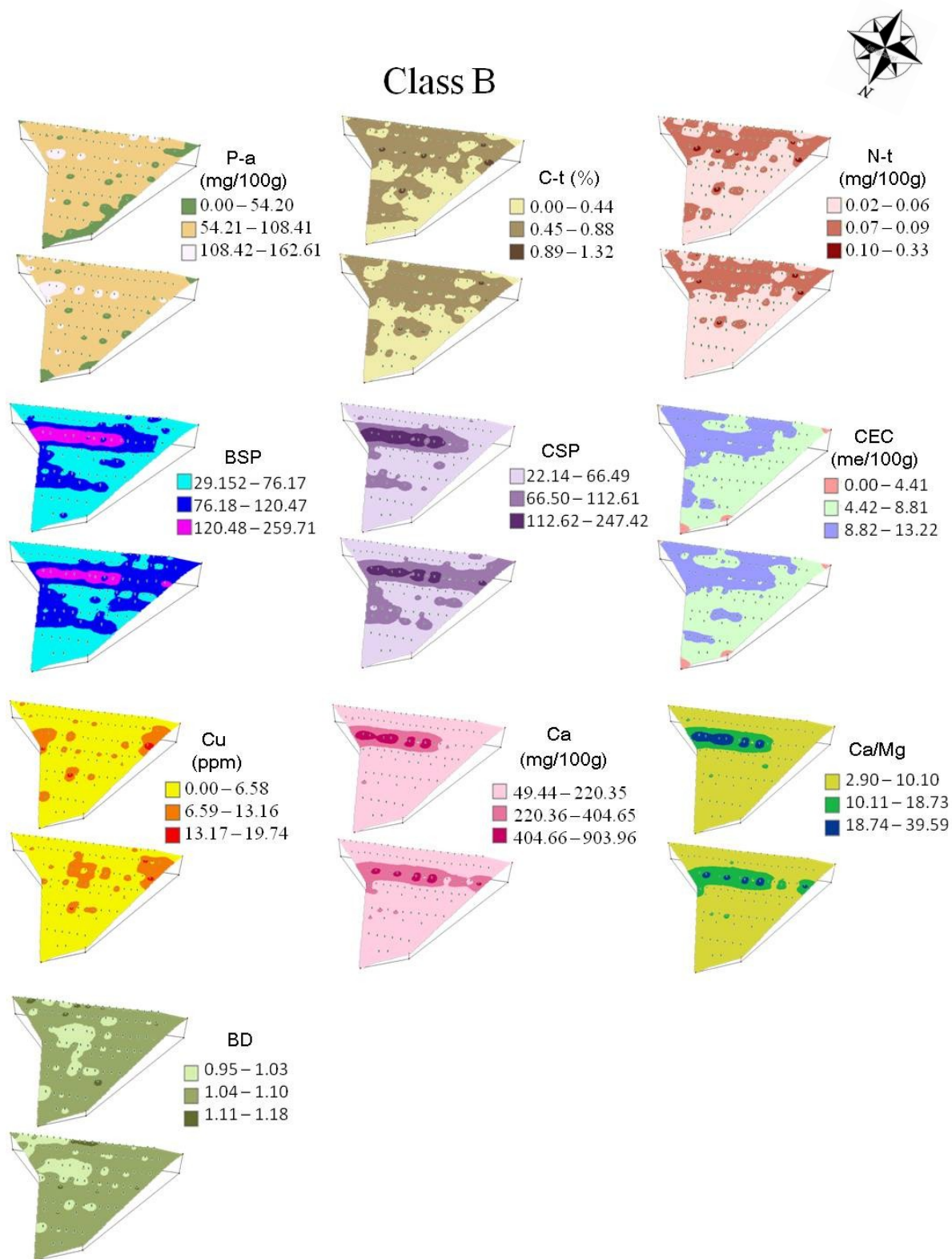


Fig. 2.7 Class B



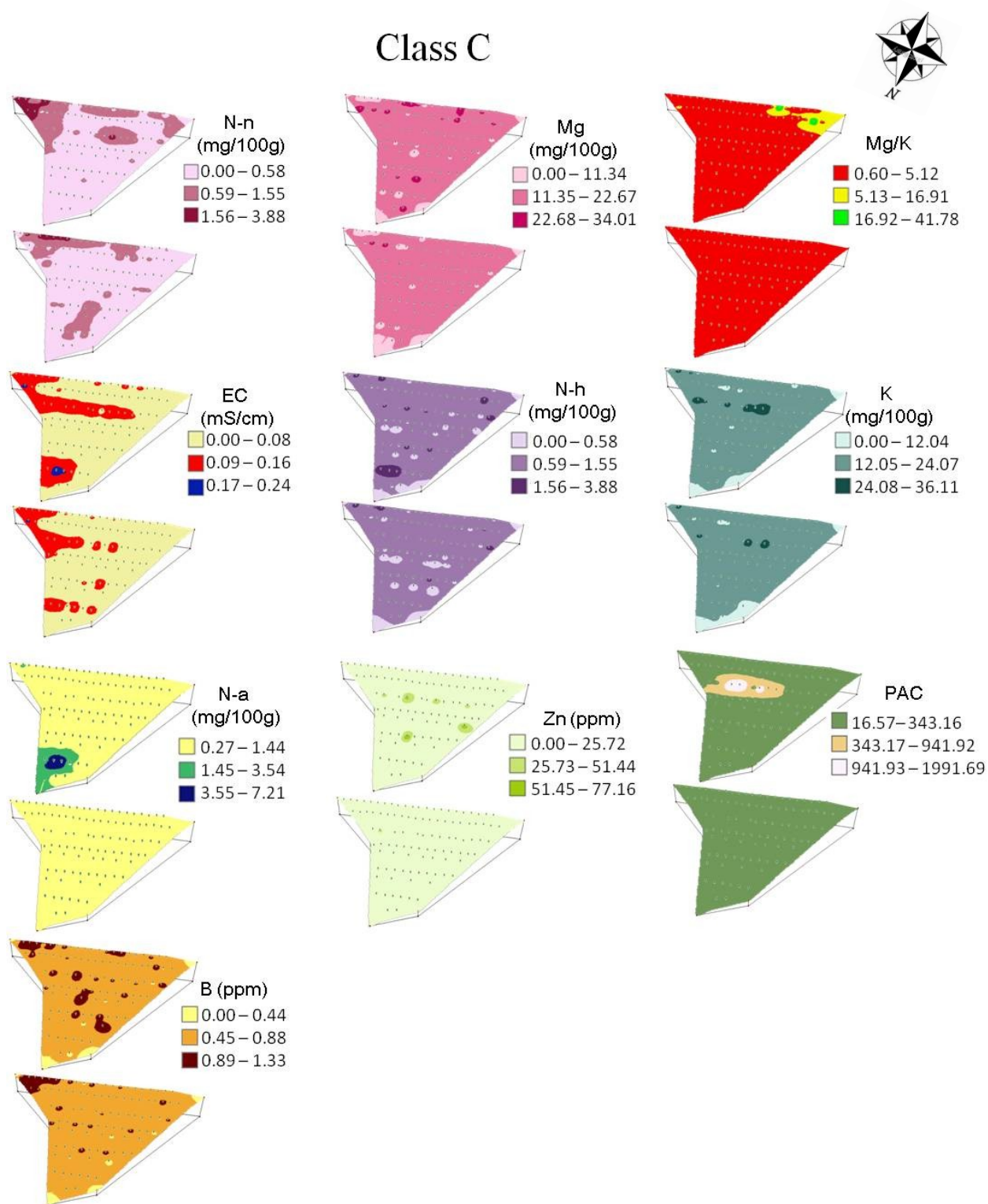


Fig. 2.7 Class C

#### 2.2.4 Correlation between soil parameters and citrus yield

Figure 2.8 shows the yield maps from H22 (2010) to H25 (2013). The phenomenon of alternate bearing was shown in the test field (Shalom et al., 2012). The yield maps of H23 (2011) and H25 had similar spatial patterns where the center of the field showed lower yields and the margin had higher yields. H22 and H24 (2012) were similarly distributed, and the margin on the hill side had lower yields compared to the center of the field. This may be due to the positive correlation between yields in H23 and H25, and between yields in H22 and H24 ( $R=0.48$ ,  $0.68$ , respectively), that is a biennial correlation appeared.

The spatial variation of yield map (H25) showed a similar pattern with the N-n distribution in the soil parameter map. This may be due to the significant correlation between them ( $R=0.3$ ). Nitrogen is the most important soil nutrient for citrus production, and N-n ( $\text{NO}_3\text{-N}$ ) is the available form of nitrogen that can be directly absorbed by the citrus plant. Concerning the impact of environmental pollution on citrus yield, best management of N-n and its relation to crop production has been researched (Alva et al., 2002; Alva et al., 2006).

In this study, the  $R$  between N-n and H25 yield was not high ( $R=0.3$ ), while other soil parameters did not significantly correlate to the yield. On the other hand, significant correlations were found between H24 yield and pH, Ca, Cu, Zn, Mn and N-t. This may be due to the large nutrient reserves in the woody portion of the tree, which suggests that the effect of soil nutrients on yield response needs long-term studies (Takatsuji, 1978). The similarity between N-n distribution and H25 yield map indicates that N-n is still the main contributing factor to the spatial pattern of the yield, which may depend on fertilizer management. However, quantitative determination of a fertilizer application rate to yield response is difficult due to the effect of field and weather conditions. Therefore, site-specific soil and crop detail are needed to quantify the relationships between soil nutrient status, fertilizer application rate, and yield (Reid, 2002).

In this study, H22 and H24 showed negative correlations with the elevation change, while H23 yield had a positive correlation with the elevation. The H25 soil parameters and yield did not show significant correlation with the elevation change except for MC ( $R=0.3$ ).

This indicates the improvement on water and fertilizer management in the test field in H25. Fertilizer is supplied in the irrigation water through the mulch drip irrigation system. The optimal management of this system can improve water and nutrient uptake efficiency, enhance fruit quality and yield, while minimizing underground water pollution (Umemiya, 2004; Morinaga, 2005). Morinaga (2013) mentioned the current challenge is to control within-field variability in fruit yield and quality. Since irrigation water is supplied at a uniform rate to the block or field, the within-field variability of fruit yield and quality may be caused by the variation of water retention. In this study, the Vis-NIR reflectance spectroscopy showed a potential ability to provide site-specific soil data for real-time modeling of soil plant systems in order to adjust water and fertilizer input to different weather and field conditions.

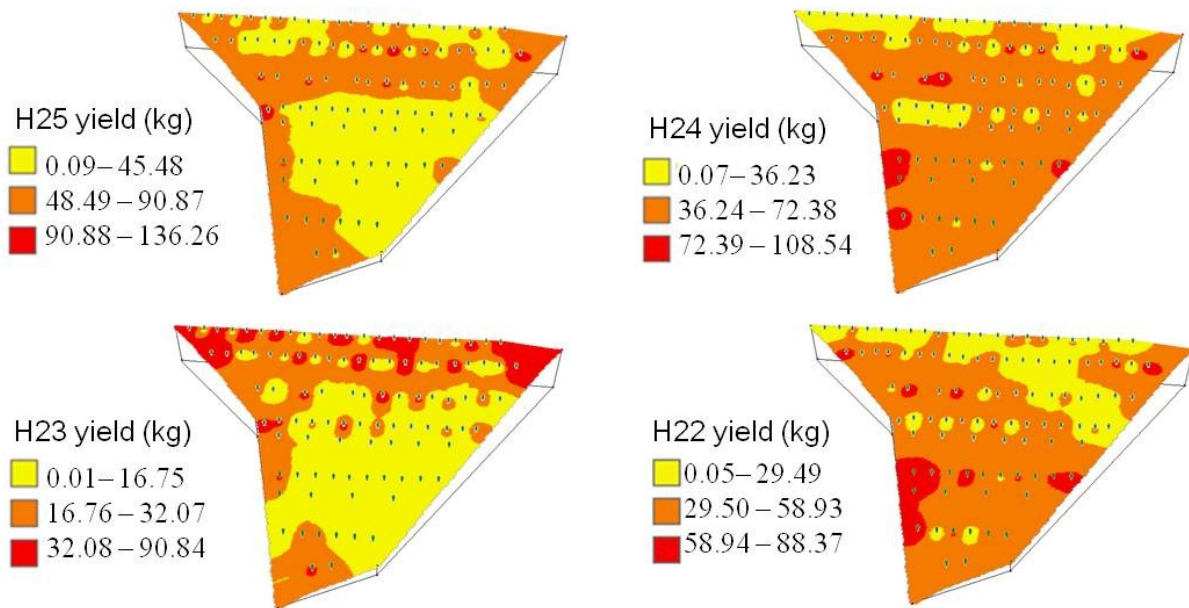


Fig. 2.8 Yield maps of the test field

### 2.2.5 Soil water distribution at three depths

A measured map of volumetric water content (VWC) at three depth using soil moisture sensor (GS3, decagon) was shown in Fig. 2.9. The maps were drawn using ArcScene software (version 10.2) from the ArcGIS 10.2 (ESRI Inc., USA) with IDW interpolation method. A trend can be found in the figure that most soil moisture was distributed in the deeper soil, as the VWC value (min, max and mean) were highest at 40 cm, and was lowest at the surface soil. It can be considered that the gravity may pull down the irrigation water into deeper soil bellow the rooting zone. This portion of water were consider to be waste due to it may not directly contribute to the citrus production. To reduce the waste of irrigation water, it is expected to develop a control method to control soil water retention within the rooting zone.

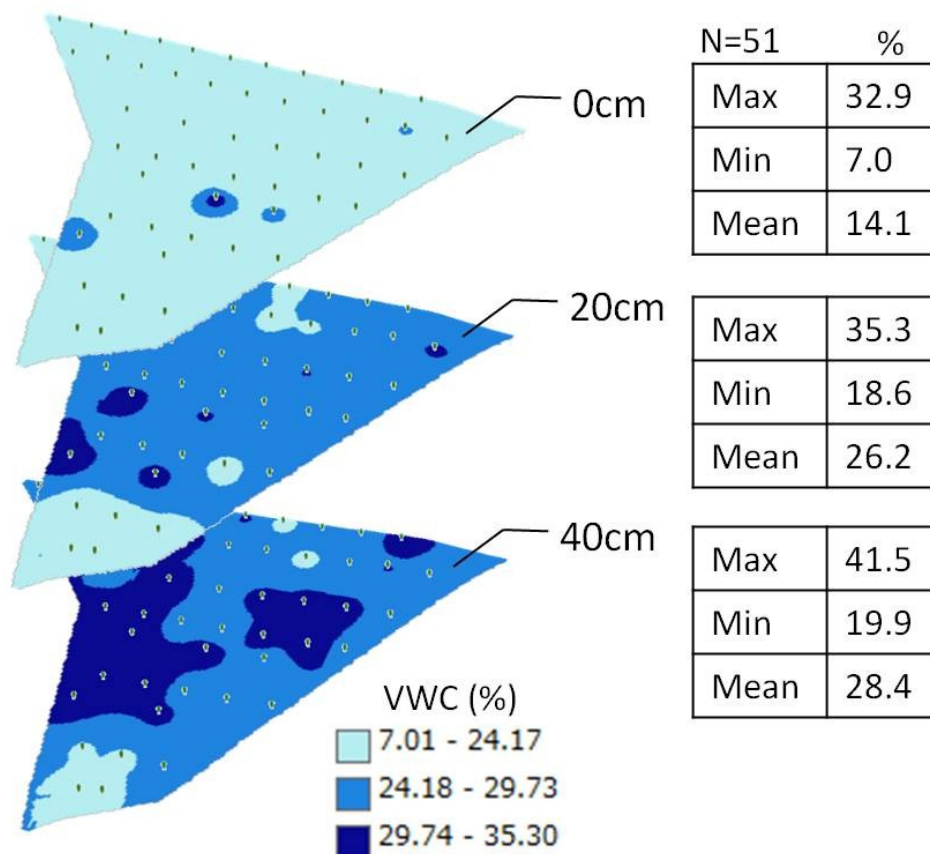


Fig. 2.9 Volumetric water content at three depths

## 2.3 Conclusion

This chapter was the first attempt to test a portable spectrophotometer (FieldSpec4 Hi-Res) to measure 24 soil parameters of a Japanese sloped citrus field based on moist fresh soil sample reflectance spectra, and firstly investigated the spatial distribution of soil water at three depths of citrus field under current mulch drip irrigation system. Soil parameter maps and yield maps with location information measured by an RTK-GPS (longitude, latitude, elevation) were also developed. The investigated soil parameters were MC, pH, EC, N-t, C-t, N-h, N-n, N-a, P-a, Ca, K, Mg, CSP, BSP, Ca/Mg, Mg/K, Cu, Zn, Mn, B, CEC, PAC, BD, and y1.

The result showed that MC, pH, and Mn were best predicted (class A), and the accuracy was similar to or better than previous studies. The spectral active parameters C-t and N-t can be well predicted (class B). This result was attributed to the narrow range of data set. P-a, CEC, Ca, BSP, CSP, and Ca/Mg can be predicted as local models with a medium accuracy (class B). The results were similar to previous studies. It is suggested that a wide-range and uniformly distributed data set is needed to enhance the prediction ability of the regression models. The y1 could not be predicted by the Vis-NIR reflectance spectroscopy. Other parameters showed poor model accuracy (class C). The ability of Vis-NIR spectroscopy to predict these parameters requires further research.

Soil parameter maps were developed for both predicted and measured values. The distribution patterns of measured and predicted maps were compared according to their prediction accuracy, and the correlation between parameters and yield was discussed. The results showed that N-n contributes the most to the spatial variation of crop yield. This indicates the importance of variable rate application of irrigation water and fertilizer to control the within-field variability of citrus yield. The Vis-NIR reflectance spectroscopy has great potential to provide site-specific soil data for adjusting water and fertilizer input.

## **Chapter 3**

### **Observation and analysis of water distribution in rooting zone**

#### **Abstract**

In the previous chapter, a portable spectrophotometer combined with a RTK-GPS system was used to mapping the spatial distribution of soil water and nutrients, and then investigated their relationships with the crop yield for tree based management. Plant yield depends on various factors such as sunlight, temperature, water and nutrients which may affect the carbon assimilation and the interaction of these resources with water stress. Yield also depending on the losses of biomass through maintenance pest and diseases as well as the allocation of biomass within the plant to roots, shoots and the reproductive biomass (fruits and yields). All of these factors are mutually linked and depends on the soil water availability which is one of the most important factors in semi-arid environment (Burke et al., 1999). Due to the complicate system of soil-plant-atmosphere-continuum (SPAC) at the field condition to study the crop yield response to water, this chapter aimed to study the crop water relations under artificially controlled environment. A new water saving technology is proposed in which minimum water required for crop growth existed only in rooting zone. In this study, we confirmed the zone of water retention during the growth of plant through observations of plant growth and soil water retention. This chapter reported the basic concepts and methodology of this technology which control moisture only in root zone, and also reported a case study on the response of crop growth (biomass, yield and root) to a limit level of irrigation water applied in the water retention zone. The results and knowledge obtained from the experiment were then discussed.

### 3.1 Introduction

Water is essential for maintaining the life activity of plants. Plant absorbs water from soil for photosynthesis. The necessary water supplied artificially is called irrigation. In the conventional irrigation method, irrigated water is lost by surface runoff, evaporation from the soil surface, and percolates into the deep underground when the water exceeds the soil water holding capacity. These parts of water are considered to be waste or water losses which will not directly contribute to the crop survival and growth. Only the water existing in the root zone is available for plant growth and survival. Minimizing the water losses and maintaining proper soil moisture in root zone is essential for the design of effective irrigation system in agricultural production (Oeda, 1954). For example, irrigation system such as subsurface irrigation, drip/trickle irrigation have been developed and put into practical use in agricultural field (Kato and Tejima, 1982a; Camp, 1998; Barth, 1999; Mahajan, 2006; Patel, 2008). The drip irrigation method intends to reduce the water losses and improving the application efficiency of irrigation water and fertilizer by continuously supplying a small amount of water to the root zone (Camp, 1998; Barth, 1999; Mahajan, 2006; Patel, 2008). However, even in this method, irrigated water will infiltrate into underground by gravity effect or evaporate from soil surface when a large amount of water is supplied within a short time. In addition, when crop characteristics and soil properties are not evenly distributed within a field, part of the field will be under irrigated while other part is full or over irrigated. In order to solve this problem, a subsurface negative pressure irrigation system has been developed (Kato and Tejima, 1982a, 1982b, 1986; Yabe et al., 1986; Kenji et al., 2006; Nallian and Ranjan, 2010; Oya et al., 2011). In this technique, a porous material was used as a water interface with a water conveying hose buried below soil surface. Water permeates automatically from the porous material to the soil due to negative pressure difference between the interface and the surrounding soil. The system has the characteristics that the amount of water supply can be automatically adjusted according to the negative pressure difference generated by plant water uptake. Therefore, the irrigation substantially reduces water losses and energy inputs compare to the drip or sprinkler system. The analysis and evaluation of the subsurface negative pressure irrigation system



can be seen in many previous researches (Kato and Tejima, 1982a, 1986; Yabe et al., 1986; Iwama et al., 2006). However, most researchers reported experiment under a given irrigation pressure. There is little illustration about the non-transpiration water losses from the root zone.

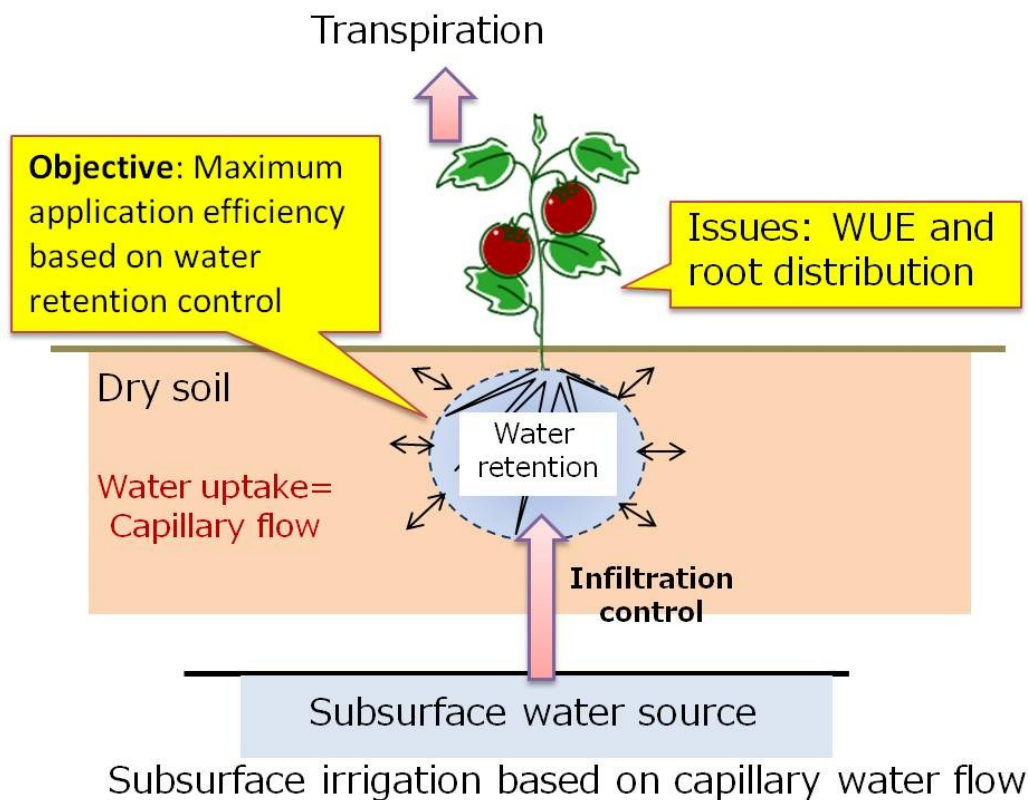


Fig. 3.1 Concept of subsurface capillary irrigation based on water retention control

Priors to this study, the authors involved in a research project in PA field (JST CREST water use area, 2011-2015) (Shibusawa, 2016). A subsurface capillary irrigation system has been developed (Ohaba et al., 2011; Shukri et al., 2014a). We also examined the method to save irrigation water to a limit level (Li et al., 2016). A key technology is to generate an adaptive zone of water retention surrounding the rhizosphere based on water potential gradient as shown in Fig. 3.1 (Shibusawa, 2016). The roots which grow in this area will uptake the water from water retention zone for transpiration. As the water retention decrease, the gradient increase and resume the infiltration again (Shukri, 2014). It can be assumed that the water uptake by plant produced negative pressure which equilibrates with



the capillary force at the wetting front of irrigation water. Consequently, the non productive water losses can be minimized and application efficiency can be maximized. The volume of the water retention zone can be properly controlled according to the plant water requirement. Based on these achievements, this study aims to realize the cultivation technology to control minimal moisture required for plant growth only in rooting zone, and investigate the plant physiological response to the water applied in the water retention zone, such as WUE and root distribution.

To reduce the use of water losses in agricultural production, this study conducted an experiment to verify whether the state of water retention zone can be maintained and controlled during the growth of plant. This study also aimed to obtain the fundamental knowledge to contribute to the implementation of this new water saving technology that to control minimal soil moisture in rooting zone for plant growth.

In soil physics, when water infiltrates into a dry soil, a “wet and solid” zone is formed by the cohesive force of the moist soil particles. This phenomenon can generally be observed in an open field (Yoshida and Iwasaki, 2014). Beside this cohesive force, the negative pressure generated by the plant water uptake can also consolidate the zone of water retention surrounding the rhizosphere. Preceding research can be seen as reference to analyze effect of the size of the water retention zone to the plant growth (Yoshida and Iwasaki, 2014). In this study, we also focused on the soil moisture status surrounding the water retention zone. A boundary between the wet and dry soil can be distinguished, and we defined the soil inside the water retention zone as wet soil region while the soil outside as dry soil region. In the WSSPA, the formation and control of this water retention zone can reduce the water losses, while all the irrigation water applied can be used by the plant for transpiration and photosynthesis. A simulation model has been developed which verified this technique can minimize water losses and meet the water requirement of plant growth (Shukri et al., 2014b).

Based on the context mentioned above, this study proposed a method to observe the water retention formed around the plant root zone with finer resolution at centimeter order than the existing studies, and also proposed a technique to precisely control the water supply according to the moisture response under this resolution, while a zone of

water retention can be formed and controlled in the rooting zone during plant growth. The soil moisture observation method, water supply control to form and maintain the water retention zone, a case study of cultivation experiment using tomato cultivars, and the knowledge or findings obtained from the observed results will be reported in this chapter.

## **3.2 Materials and methods**

### **3.2.1 Formation of water retention zone in soil**

In this study, we aimed to produce a spherical water retention zone in the dry soil and observe the dynamics of the soil moisture in the wet and dry soil region. In order to facilitate the formation and control of the dry and wet soil zone, a homogeneous red soil was used as cultivation substrate which was oven dried and sieved through 1mm sieve to obtain uniform particle size. A point water source was provided which was made by fibrous cloth that installed at a pipette tip and was placed at the center of the assumed spherical water retention zone. The pipette is connected with a plastic tube through which water can be supplied manually into the root zone. The soil packed inside the experimental pots with a gentle compaction to obtain uniform bulk density.

Whether it is possible to form a stable water retention zone in dry soil is pre-requisite to implement this irrigation method. In addition, to obtain the basic data of the size of the water retention zone, we conducted a preliminary experiment to study the size of the water retention zone under a given amount of water supply. In order to grasp the degree of variation caused by the variation of the infiltration rate and the manually error, the experiment was replicated for multiple times.

Figure 3.2 shows the soil particles (water retention zone) which were solidified and agglomerated due to the moisture cohesive force when the amount of water supply was 50 ml, and was dug out from the dry soil. In this experiment, a point water source was set at a pipette tip, water can be supplied into the dry soil through the point water source, and a round water retention zone can be germinated surrounding the water source. Table 3.1

shows the 10 times replication of the measured water supply time, weight and size of the water retention zone when water supply was 50 ml. As shown in this table, it was confirmed that spherical soil water retention with a diameter around 65 mm was formed, which was almost stable in size and shape.

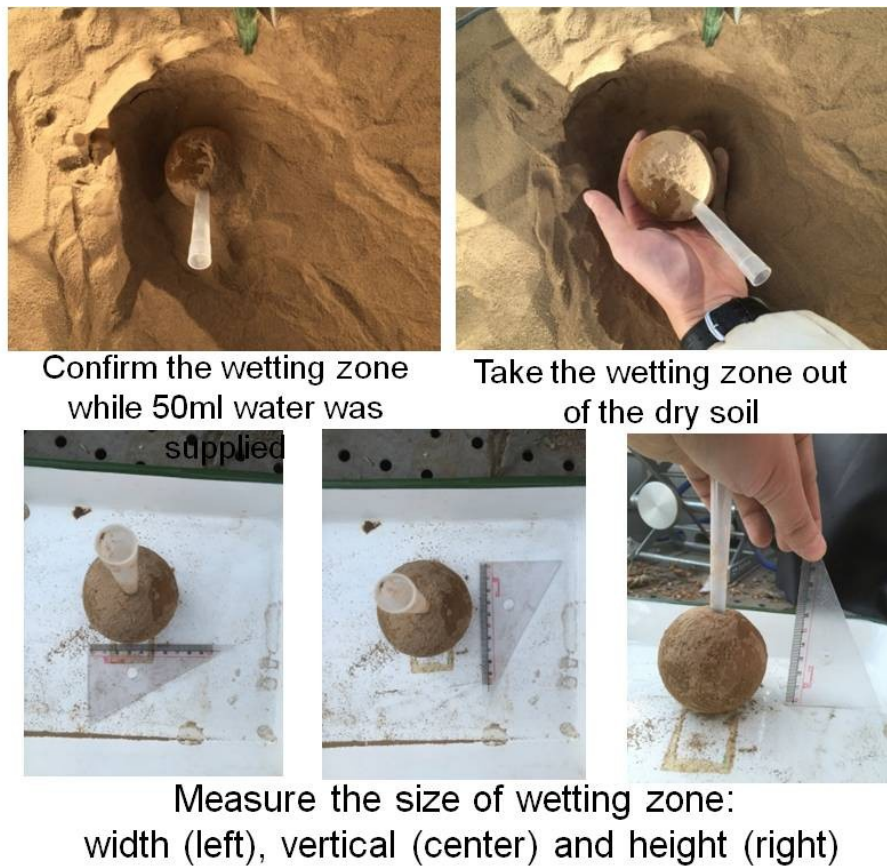


Fig. 3.2 Preliminary experiment to confirm the formation of water retention zone

Table 3.1 Measurement of water retention zone with 50 ml water supply

No.	Water supply time	Wide (cm)	Depth (cm)	Height (cm)	Weight (g)
1	4'32''	7	7	6.5	188.3
2	6'47''	7	7	6.5	185.7
3	6'55''	7	6.5	6.5	179.7
4	10'58''	7	7	6.5	182.5
5	23'03''*	7	7	6.5	187.5
6	2'10''**	7.5*	7	6.5	194.7*
7	6'27''	7	6.5	6**	169.9**
8	3'38''	7.5*	6.5	6.5	187.6
9	3'28''	7	6.5	6.5	182.7
10	7'07''	7	6.5	6.5	180.7
Mean		7.1	6.75	6.45	183.9
S.D.		0.21	0.26	0.15	6.61

\* Max, \*\* Min

### 3.2.2 Experimental system

The experimental system was designed to supply a meager amount of water to plant root zone before they wilt, while avoiding over flow from the water retention into dry soil. Figure 3.3 shows the experimental setup inside a growth chamber (NK-system, KCLP-1500LED-NCS) which is composed of cultivars, environmental control sector (Fig. 3.3 (5)~(8)) and root zone measurement sector (Fig. 3.3 (1)). As shown in Fig. 3.3, two tomato samples (Anemo, Japanese variety) were grown in cylindrical pots with 25 cm in both diameter and height. In order to control the soil physical properties, each pot was filled with homogeneous red soil which was sieved through 1 mm sieve, and was packed into the

pots with a gentle compaction to obtain uniform bulk density. The soil was dried in the oven at 110 °C for 24 hours before the experiment started. Two tomatoes (Anemo, Japanese variety) were planted in the horizontal center of the pots, with 17 cm from the bottom and 7 cm from the surface (Fig. 3.3 (3)). Figure 3.4 shows the actual experiment in the growth chamber. A point water source made by a fibrous cloth was buried at the root zone. After transplanting into the pots, 50 ml distilled water was immediately supplied from the point water source. The initial water supply generated nearly 6 cm diameter spherical water retention surrounding the root zone. After the initial irrigation, water was carefully supplied manually according to visually observed plant status and the soil water retention dynamics. The tomato samples were grown from seeds in a cultivation soil, after two weeks germination they were transplanted to the experimental soil for seedling rising until they were transplanted into the pots (Fig. 3.5).

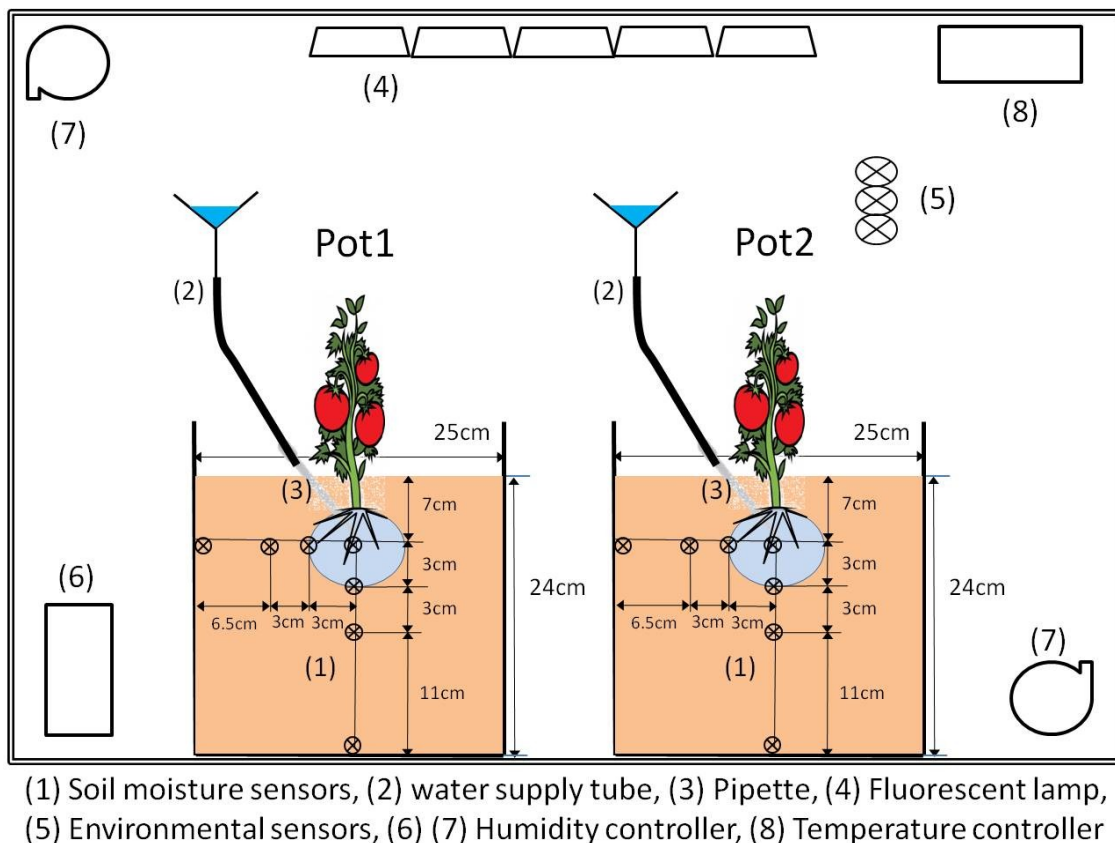


Fig. 3.3 Experimental setup

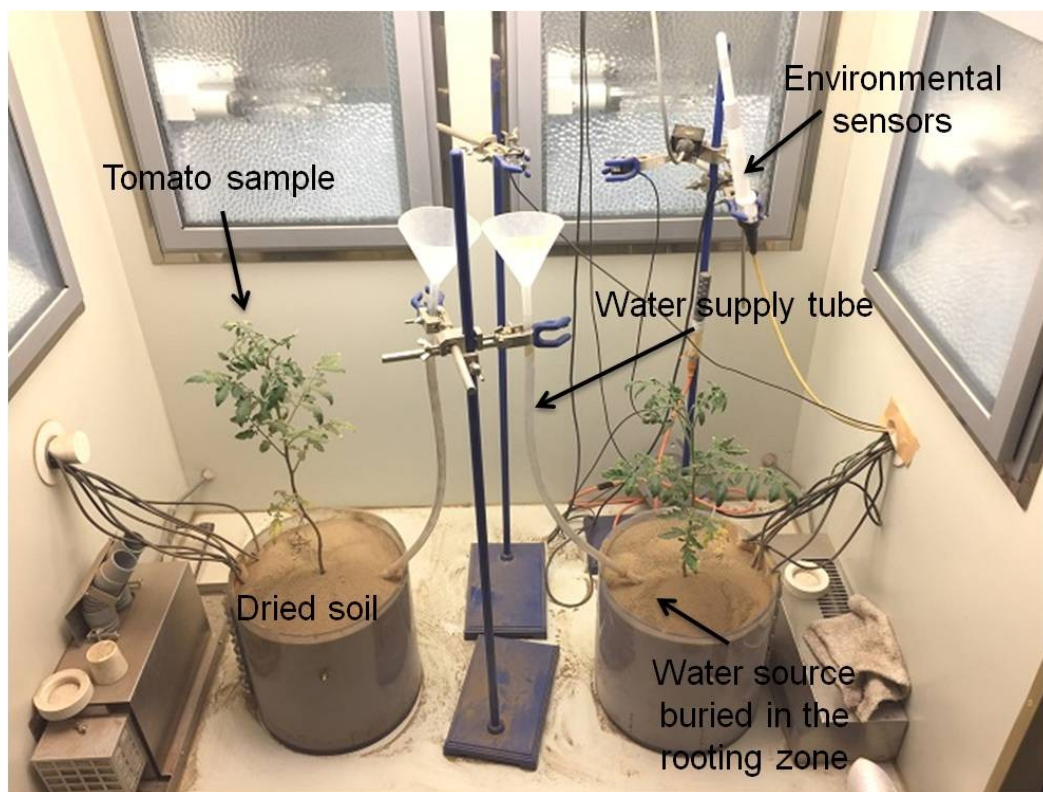


Fig. 3.4 The actual experiment in the growth chamber



Fig. 3.5 Transplanting the samples to the experimental soil

The experiment was started at September 12<sup>th</sup> 2016, and ended at January 23<sup>rd</sup> 2017 at when the first fruit matured. The light density, temperature and humidity was manually setting upped inside the growth chamber was shown in Table 3.2. Two patterns inside the growth chamber were designed that simulated the day time and night time. The plants were illuminated by fluorescent lamps from 8:00 am to 22:00, and the illumination

was stopped at 22:00 until the next 8:00 am. The mean day time photo synthetic photon during the experimental period was 170  $\mu\text{mol}/\text{m}^2/\text{s}$ , which was measured by a quantum sensor (Li-Cor). The corresponding mean temperature was 30°C and the relative humidity was 36% measured by temperature and humidity sensor (HMP-155, Vaisala). The mean night time temperature and relative humidity were 22°C and 60% respectively. The mean CO<sub>2</sub> concentration in both of the patterns was measured by a CO<sub>2</sub> sensor (GMT-222, Vaisala). A data logger (GL820, Graphtec) was used to record the data from the sensors, and the sampling interval was 5 min.

Table 3.2 Program setting inside the growth chamber

	Time	Temperature (°C)	Humidity (%)	Quantum ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	CO <sub>2</sub> (ppm)
Pattern 1	8:00~22:00	30	36	170	2082
Pattern 2	22:00~8:00	22	60	0.3	2069

### 3.2.3 Water supply method

This study focused on water saving cultivation with extremely small amount of water, so the substrate is used to physically support the crops and holding the supplied water. The substrate functioned little in terms of nutrient supply. Similar with the hydroponics, this study used a commercial liquid fertilizer (Hyponex, 5-5-5) which was mixed with distilled water at a ratio of 1:500, and was supplied to the plant with the irrigation water. Due to the soil contains little nutrient, the necessary nutrients for plant growth were all supplied through the liquid fertilizer. That is, both the water and nutrients that required for plant growth are supplied from the irrigation water.

A 10 ml of distilled water was supplied when plant started to wilt, this water supply repeated 4-7 times a day based on confirming there was no excessive water penetrating into the dry soil. The soil moisture level at which plant start to wilt was considered to be the wilting point in this experiment, which was used as an indicator for the timing of water



supply. The frequency was adjusted according the growth stages, and we increased the frequency in order not to hinder the plant growth. However, if the degree of growth was made the same as the ordinary cultivation, it is necessary to increase the daily amount of water supply greatly. If the cultivation is carried out under such condition, the soil in the experimental pot will be saturated with water and the moisture will fall below the root zone due to gravity effect. The water retention zone will also be destroyed. Therefore, water supply was carefully adjusted by confirming the moisture dynamics using soil moisture sensors. As a result, the supplied water generated a limited zone of water retention surrounding the root zone. The daily supplied water was much smaller than the normal cultivation.

In order to control the moisture only in rooting zone, a two dimensional soil moisture sensor (EC-5, Decagon) matrix was designed to measure the soil moisture dynamics. The soil moisture sensors were placed in horizontal and vertical directions from the point water sources. Figure 3.6 shows the placement of the soil moisture sensors which were fixed by plastic sticks. The water source was the same place where the tomato was planted. As shown in Fig. 3.6, the soil moisture sensors were set at an interval in both vertical and horizontal directions, from which the size and position of the water retention zone can be grasped.

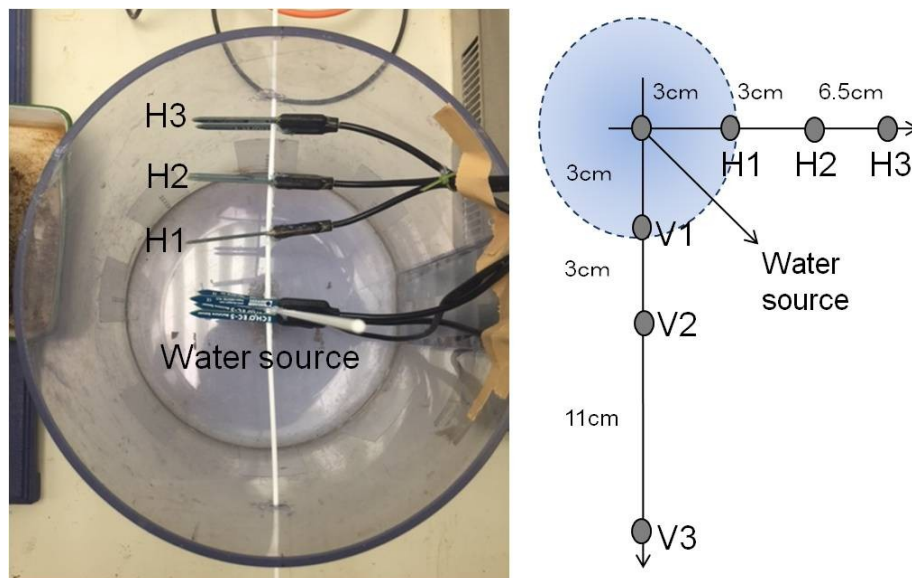


Fig. 3.6 Placement of soil moisture sensors



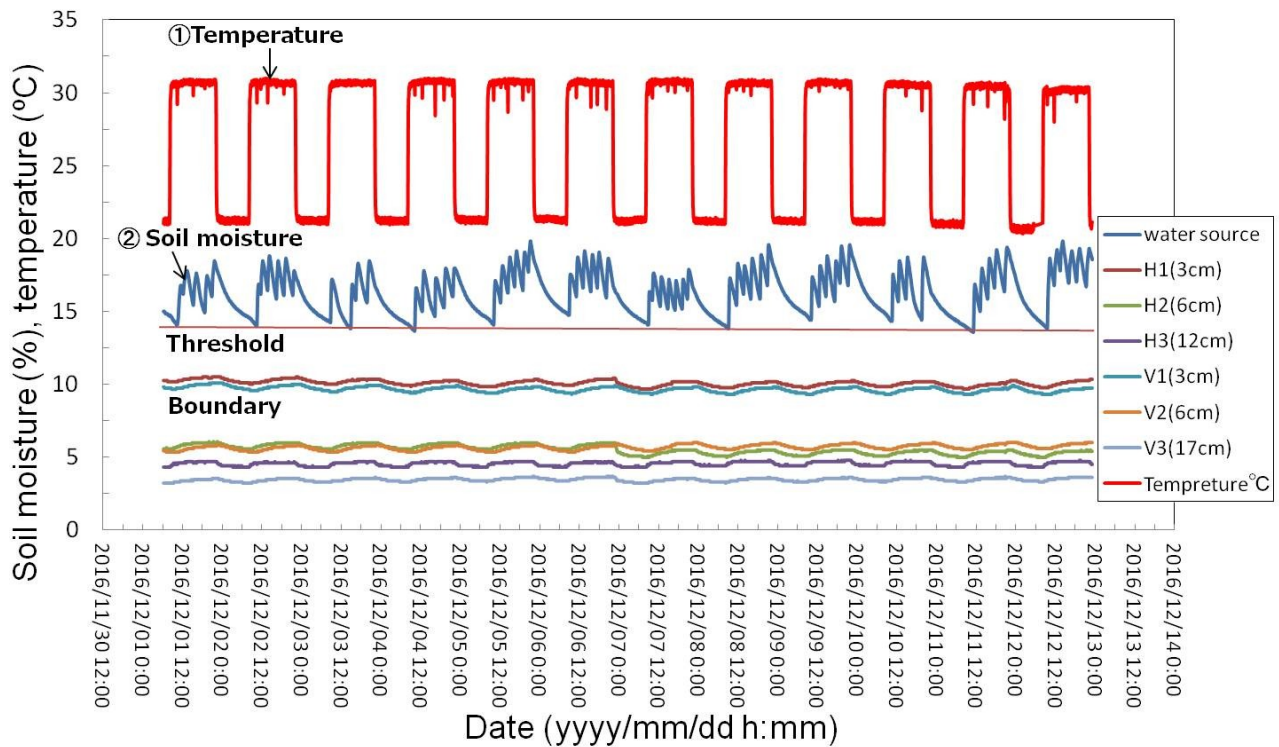


Fig. 3.7 Responses of soil moisture at each position

Figure 3.7 shows the response of soil moisture at each location in a time series. The values expressed the soil moisture at the position close to the root zone and away from the root zone. The red curve at the top (①) is the temperature, which is shown to be synchronous with the growth chamber's setting. The blue line (②) is the volumetric water content (VWC) at the position of the water source. Each peak represented a single water supply event. The decreases of moisture after each peak indicate the water distribution by capillary flow and by the root water uptake. The soil moisture content at which the plant started to wilt is considered as wilting point in the present experiment and is used as the indicator of the water supply. The formation of the water retention zone can be looked from the soil moisture at 3 cm from the water source in both horizontal and vertical directions. As mentioned above, a diameter about 65 mm spherical water volume was generated when 50 ml water was supplied to the soil. And the soil moisture content at this position is considered to be the boundary value between the wet and dry soil. Therefore, the sensors at the H1 and V1 in Fig. 3.7 present the soil moisture value just inside the boundary. In addition, the VWC at the second and third distant locations from the water source is to

confirm the water retention zone was not expended by the water supply. The values in these positions showed a dry state which indicated the water supply was successful due to no excessive water flowed into the dry soil.

In Fig. 3.7, the soil moisture can be distinguished between the wet and dry soil. The moisture content at dry soil indicates the moisture level at which plant cannot survive or extract water from the soil (wilting point). That is, the wet soil region for plant growth and dry soil region below the wilting point were clearly separated in the same substrate. As mentioned before, this study intended to form a zone of water retention in dry soil for plant growth, and this was implemented by supplying a small amount of water (10 ml) for several times per day by confirming the soil moisture responses before and after each water supply event. As shown in Fig. 3.7, the results indicate that the wet and dry soil region was successfully separated in the substrate using this water supply method.

#### 3.2.4 Observation of the water retention zone

In order to visually observe the existence of water retention, a small amount of dry soil was carefully removed from the soil surface to the edge of the water retention, and then recovered to stable soil surface. The moist soil particles adhere to each other and formed a harder part which can be distinguished from the dry soil that is softer. Fig. 3.8 shows the observation of the water retention zone. The boundary of the water retention was visually confirmed and the root distribution at the boundary was also observed.

In order to confirm the water potential gradient generated near the boundary, three soil samples at wet, dry and boundary was collected. The soil samples were then measured for gravimetric water content (GWC) by oven drying at 100 °C for 24 hours. To relate the soil moisture with water potential, we developed retention curve for the experimental soil. The VWC was in the retention curve was calculated using the measured GWC multiplied by the bulk density. The observation was conducted several times according to the changes in physiological symptoms of branches, flowers, and fruits. Due to the changes in growth status represent changing in the root system which may alter the water absorption pattern.

Only Pot 1 was observed during the experimental period. Pot 2 was not disturbed by the observation until the end of the experiment.

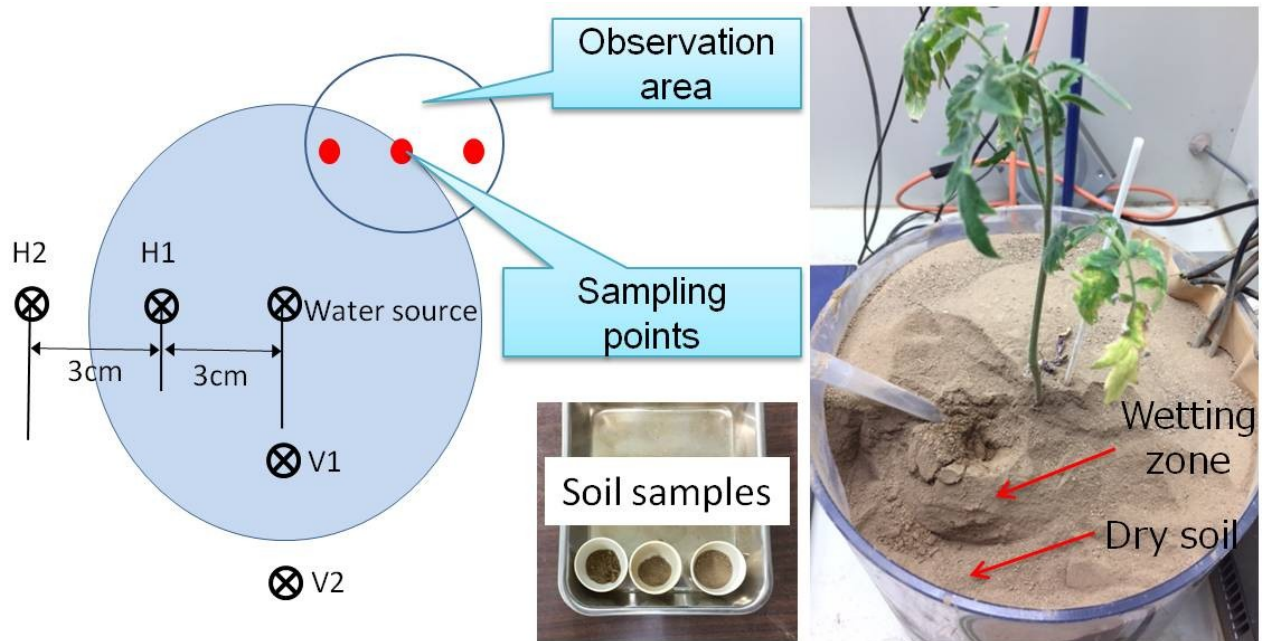


Fig. 3.8 Observation of water retention zone

### 3.2.5 Measurement of plant growth and yield

The aboveground plant growth may be proportional to the growth of the underground part. To quantitatively analyze the response of plant growth to water supply, the plant height, number of fruits and the cumulative water supply were recorded during the plant growth. After the first fruits matured, the experiment was ended. The dry biomass of shoot, and the fruit weight were measured. The shoot was put into the oven at 80 °C for 24 hours to obtain the dry biomass. The WUE was calculated using the ratio of fruit weight to the cumulative water supply.

### 3.2.6 Observation and measurement of root distribution

The root growth inside and outside the water retention zone was analyzed at the end of the experiment. Before the observation, we stopped the water supply for 5 days to equilibrate the soil water content inside the water retention zone. The soil moisture content in the water retention zone decreased to wilting point. The boundary between wet and dry soil can be recognized due to the wet soil is harder than the dry soil. The water retention zone was carefully dug out from the dry soil to measure the root development.

According to the assumption of hydrotropism, the root may elongate towards the wet soil where the water potential is higher (Takahashi, 1994, 1997). The water potential gradient generated near the wetting front of irrigation water may probably induce the hydrotropic behavior (Tusda et al., 2003). In order to analyze this phenomenon, we proposed the ratio of root elongation in the dry soil to the root growth inside the water retention zone. The root growth outside was carefully cut by a scissor across the edge of the water retention zone. The number of root was also recorded. Each of the root length was measured to obtain the total root length outside the water retention zone. The mean root length outside was then calculated by dividing the root number. After the measurement, the water retention zone was sliced by a razor blade at the shoot base to observe the root skeleton inside the spherical water retention zone. The roots were then carefully sieved and washed to separate them from soil, and put into the oven with the shoot at 80 °C for 24 hours to obtain the dry biomass.

## 3.3 Results

### 3.3.1 Relationship between plant growth and cumulative water supply

Plant height was used to express the plant growth status due to it is non-destructive and easy to measure, which has also been widely used by the growers. Fig. 3.9 shows the relationship between the change of cumulative water supply and the plant height for Pot 1.

The plant height at transplanting was 28 cm and increased to 68 cm at the end. The corresponding water supply was about 5.8 L (Fig. 3.9 (a)). The plant increased its height in response to the amount of water supplied in the water retention zone. They had almost a linear relationship ( $R^2=0.97$ ) (Fig. 3.9 (b)). It can be considered that the water supplied into the water retention zone was consumed by the plant for transpiration and accumulating biomass. There were no water losses from evaporation and deep percolation. Excluding the water stored in the water retention zone, all the water supplied was absorbed by the plant.

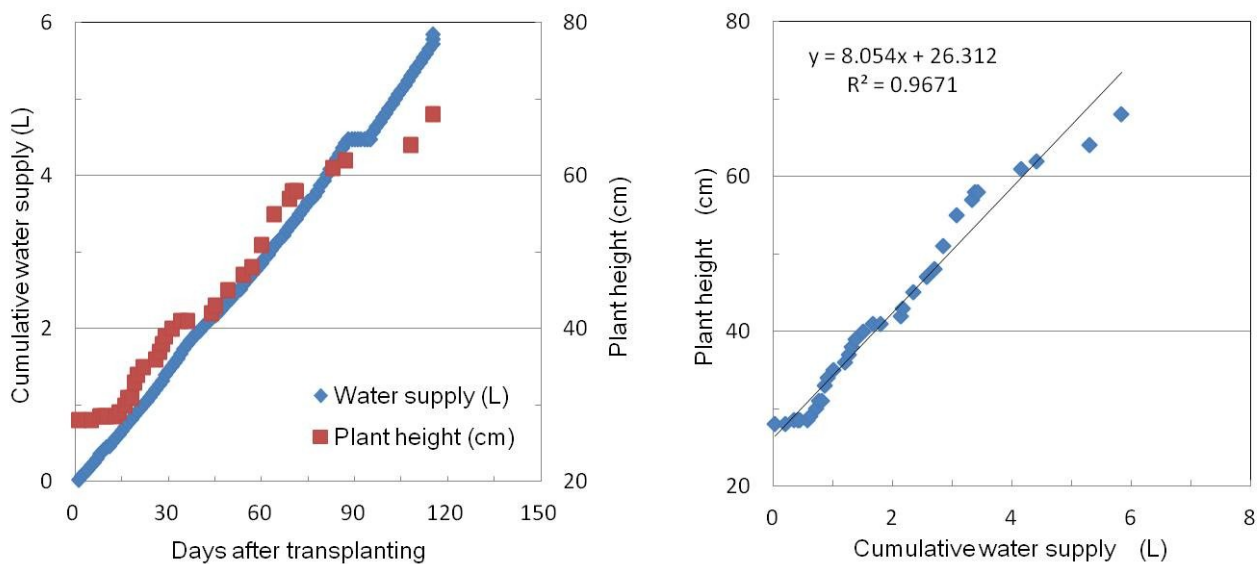


Fig. 3.9 Relationship between plant height and cumulative water supply

### 3.3.2 Observation of plant growth and water retention

The observation of water retention for Pot 1 during the plant growth was shown in Fig. 3.10. From the seedling to flowering and fruiting, the observations were conducted for 8 times by digging the dry soil to the edge of the water retention zone. And the water retention zone was stable in the rooting zone during the entire growth period. The first observation was done at 13 days after transplanting. In this observation, the plant height was 28.5 cm, and the number of branches was 6. The plant increased 0.5 cm in height and

1 branch compare with the initial status at transplanting (28cm in height with 5 branches). In addition, the distribution of roots out of the boundary was not observed at this time, which indicates the root zone remained within the water retention zone. The gravimetric water content at the dry and wet soil was 9% and 19% respectively. It was confirmed that the dry and wet soil was clearly separated in the soil. At the 26 days after transplanting when the first stage bloomed, the plant height was 36 cm and the number of branches was 8. Remarkable growth was found during this period. The total amount of water supply at this time was 1.21 L. At this observation, several root tips distributed at the boundary was observed. At the 74 days, the first tomato fruit was observed at the second stage. The plant height was 59 cm and the number of branches was 13. In the observation of the water retention zone, many root tips were observed at the boundary between the wet and dry soil. However, the roots were not obviously elongated into the dry soil. During the growth period, evaporation from the soil surface was not observed. It can be considered that the supplied water stored inside the water retention zone from where plant can take advantage for growth.



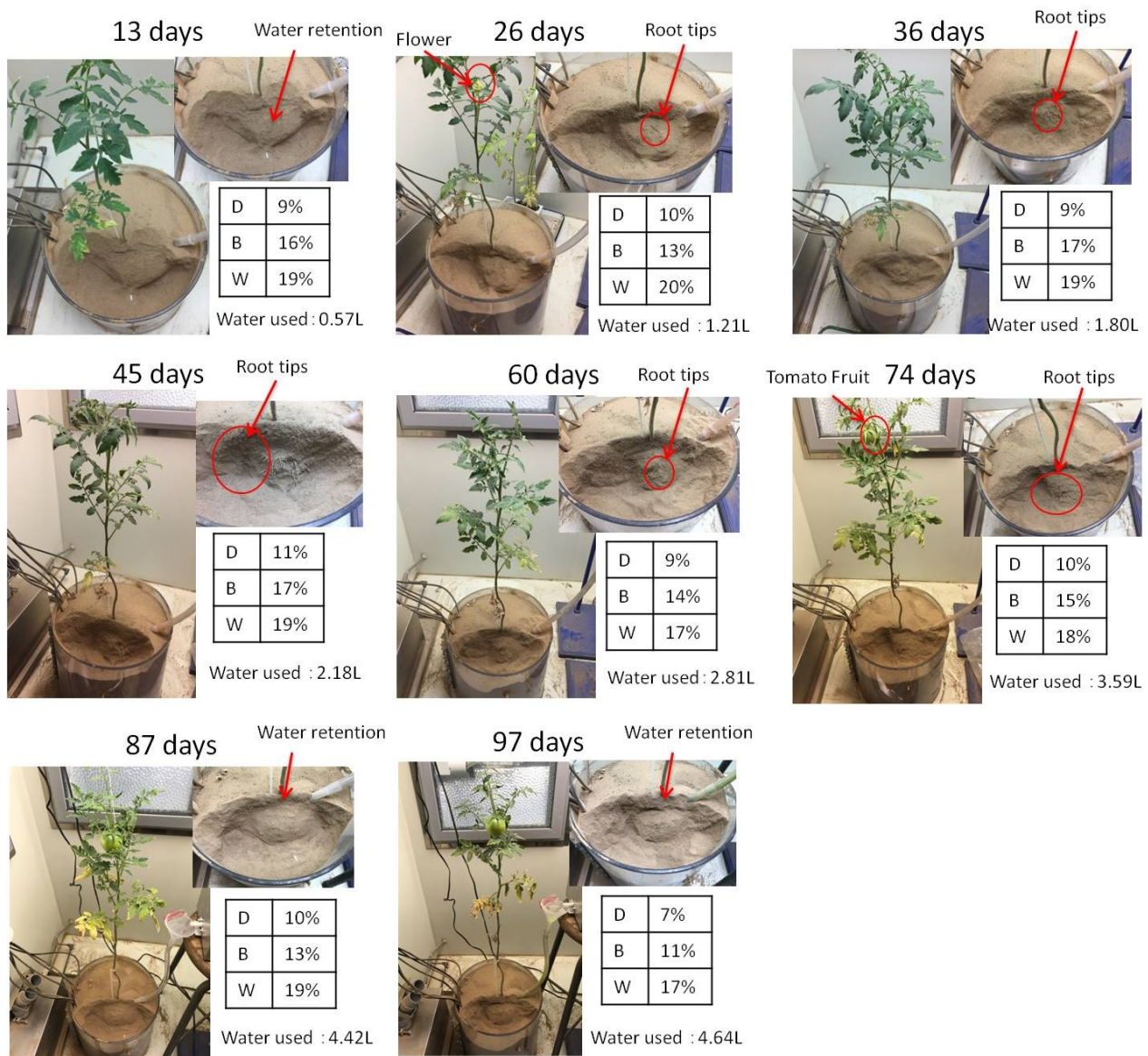


Fig. 3.10 Observation of wet/dry soil boundary

### 3.3.3 Post-observation of water retention after cultivation

After completing the experiment, the pot was left for five days until the substrate was excavated for observation and analysis of the water retention zone. Fig. 3.11 shows the post-observation of water retention zone for Pot 2. Pot 2 and Pot 1 were cultivated under the same water supply condition. But Pot 2 has not been disturbed by observing the water retention during the growth period.



Fig. 3.11 Post-observation of water retention after cultivation

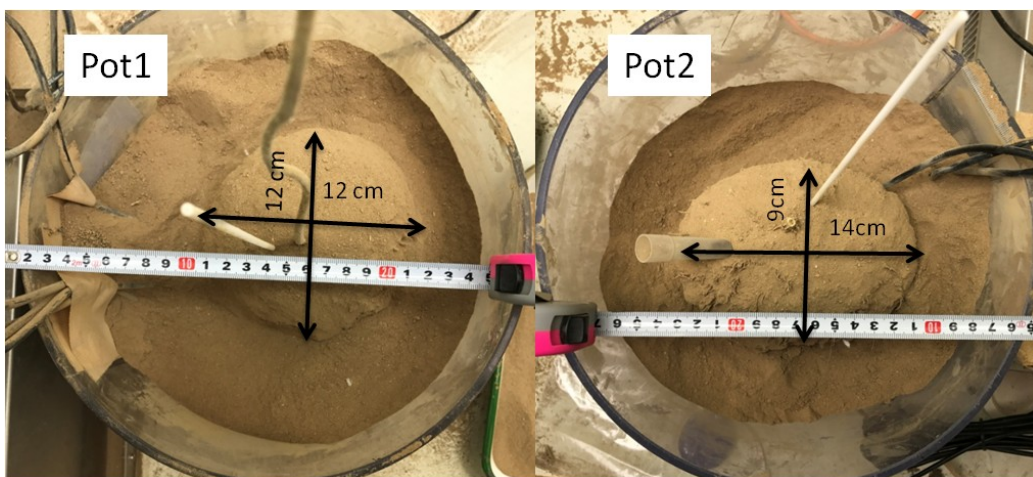


Fig. 3.12 Comparison of water retention between Pot 1 and Pot 2

A comparison of the water retention zone of Pot 1 and Pot 2 at the end of the experiment is shown in Fig. 3.12. The water retention for Pot 1 and Pot 2 were both about 12 cm. When considered this result with the measured value by the soil moisture sensor during the experiment (Fig. 3.7), it can be said that the formation and control of water



retention zone has been realized using the water supply technique presented in this study.

#### 3.3.4 Plant yield and water use efficiency (WUE)

To analyze the WUE quantitatively, the plant dry biomass, yield and total water supply were recorded at the end of the experiment. Then the WUE was calculated as shown in Table 3.3. In this experiment, Pot 1 was wilted at 2 weeks after transplanting. Since the Pot 1 was transplanted again, there was 2 weeks difference of water supply condition between Pot 1 and Pot 2. Excluding this, Pot 1 and Pot 2 were cultivated under the same environmental and water supply conditions. The experiment was ended at the time the first tomato for both Pot 1 and Pot 2 was ripened. At this time, Pot 1 had 2 fruits while Pot 2 had 1 fruit (Fig. 3.13). The difference in the number of fruits under the same cultivation condition is considered to be the effect of different characteristics between individual plant and the presence or absence of pollination.

The calculated WUE was shown in both ratio of yield per unit of water (g/L) and water used to produce 1 kg tomatoes (L/kg). The later has been used in previous published results to evaluate WUE of tomato production in water saving cultivation for both field and greenhouse environmental conditions (Stanghellini et al., 2003; Shukri 2014). Compare to the presented results, the WUE in this study was 2 to 7 times lower than the previous water saving cultivation methods. However, the WUE is difficult to compare due to many factors such as fertilizer management, soil water content, CO<sub>2</sub> concentration and solar intensity which may significantly influence the results. The previous results were based on excellent management of these factors to maximum crop yield while this study researched an extreme condition with extremely lower water supply.

The total water usage in this study was 5 to 6 L. And the amount of water used to produce the first tomato fruit was about 3.6 L (Fig. 3.10), while the daily water supply was around 40 ml to 70 ml. The amount of water supply in this study was 1/10 less than the conventional irrigation. As a result, the plant growth, flowering and fruiting were confirmed under this extreme water saved condition, while the irrigated water was almost absorbed by

the plant due to no distribution losses. The root distribution was also restricted inside the water retention which indicates the root expansion can be controlled by controlling the water retention.

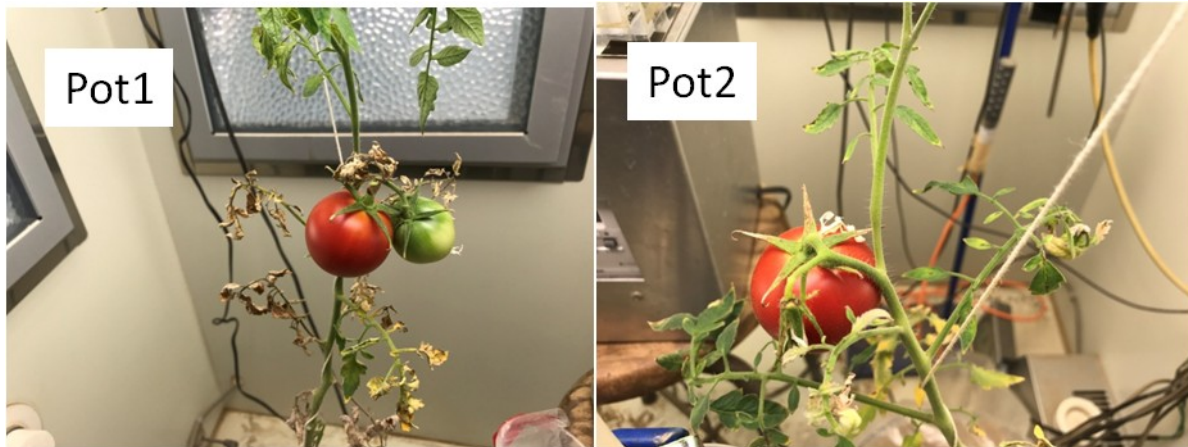


Fig. 3.13 Tomato fruits for Pot 1 and Pot 2, the photos were taken at the end day of the experiment

Table 3.3 Plant yield and WUE

	Total dry biomass (g)	Number of fruits	Fruit weight (g)	Total water usage (L)	WUE (g/L)	Virtual (L/kg)
Pot 1	6.12	2	36.06	5.18	6.96	144
Pot 2	4.71	1	32.14	6.06	5.30	189

### 3.3.5 Root distribution analysis

In order to quantitatively analyze the root hydrotropic distribution, we registered the root weight inside (RWI), root weight outside (RWO), root number outside (RNO), total root length outside (TRLO) and mean root length outside (MRLO) as shown in Table 3.4. We did not measure the total roots number and total roots length due to the technical difficulties. The results showed Pot 1 developed more roots in dry soil than Pot 2. If the assumption of

hydrotropism is dominant in the root distribution, it can be considered that roots may elongate towards the inside of the water retention zone where the water potential is higher. And the root distributed in the dry soil may due to random errors. The result suggests that hydrotropism may probably play a dominant role in root distribution under this limit irrigation case.

Table 3.4 Root growth inside and outside the water retention zone

	Pot 1	Pot 2
RWI (g)	1.48	1.01
RWO (g)	0.04	0.06
Total weight (g)	1.52	1.07
Percentage (%)	2.63	5.61
RNO	82	138
TRLO (cm)	172.2	290.4
MRLO (cm)	2.1	2.1

### 3.3.6 Root skeleton inside the water retention zone

The roots bending back towards the inside of the water retention were observed from the cross section of the water retention zone. Figure 3.14 (a) shows the soil structure inside the water retention which was sliced by a razor blade. While Fig. 3.14 (b) shows the same root which were carefully separated from the soil attached it. The root separated from the soil maintained the initial skeleton. As shown in the figures, the roots concentrated inside the water patch with a circular shape. In Fig. 3.14 (a), the roots were found to turn round at the point water source, bending back towards inside of the water retention zone which formed a vertex shape. These results indicated the root hydrotropic response to the water gradient produced at the boundary between the wet and dry soil can overcome the gravitropism, which play a dominant role in shaping the root skeleton.

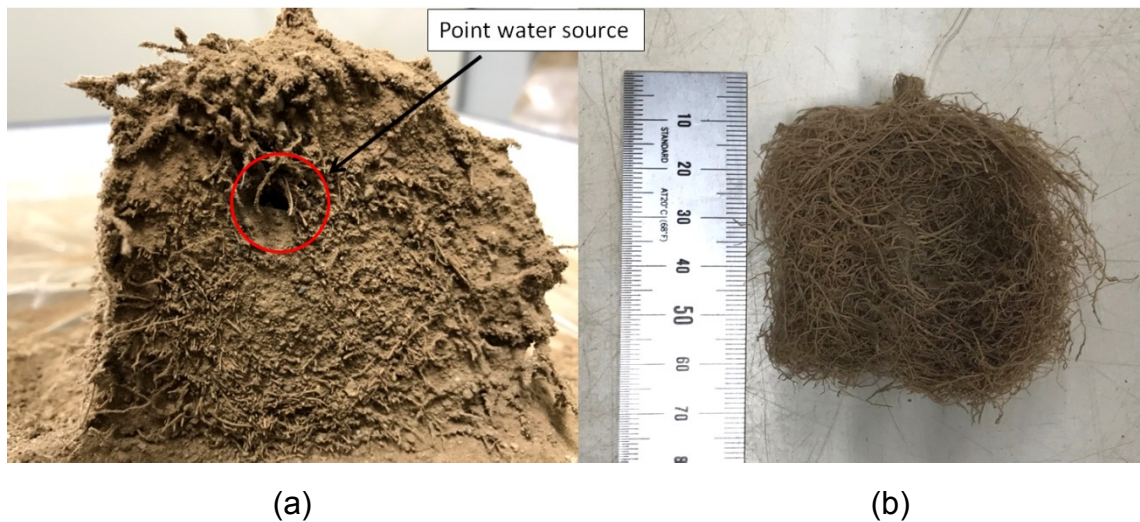


Fig. 3.14 Root skeleton inside the water retention. (a) Root skeleton observed from the cross section of the water retention zone. (b) The root was separated from the soil with the initial form

### 3.4 Discussion

In this study, the purpose is to form and control a water retention in the plant root zone. When water is supplied from the point water source buried in dry soil, a region with moist soil is formed by the cohesive force of the moist soil particles and the pressure difference with the surrounding soil. In soil physics, a limit penetration pressure exists at the boundary between the wet soil and dry soil. When the penetration pressure is lower than the limit pressure, the equilibrium is reached (William and Robert, 2006). As the water supply continues, the water retention zone is further enlarged by the meniscus, and finally reaches a certain size. This is the case only for the soil where plants do not exist. Next, considering the case that when plant is grown. Since plant absorbs water from the root, a negative pressure difference is generated between the root and the surrounding soil. And the water retention zone formed may be narrower than the state when the plants are not present. This narrowed region is considered to be the available water that used by the plant. If this volume of the available water is controlled through the irrigation to balance the

moisture flow between plant and the surrounding soil, the penetration pressure may not exceed the limit and the water retention zone can be maintained at a constant volume. The mathematical expression of the three dimensional unsteady water flow is described by the following Richards' equation which also considered the root water uptake (William and Robert, 2006).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K(h) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K(h) \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K(h) \left( \frac{\partial h}{\partial z} + 1 \right) \right] - S_w \quad (4.1)$$

**$\theta$** : volumetric water content;  **$t$** : time;  **$x, y, z$** : spatial coordinates

**$h$** : matric potential head ;  **$K(h)$** : unsaturated hydraulic conductivity

**$S_w$** : sink term which represents root water uptake

Instead of solving this complicated equation, we proposed a conceptual model (spring model) to explain the potential balance in the rooting zone as shown in Fig. 3.15. In this figure, the gravity water potential and the matric water potential are in a balance state. Increasing the water supply may increase the amount of gravitational water due to the expansion of the water retention zone. But since the rooting zone may also expands due to the plant growth which may also increase the amount of water uptake. It can be considered that the water uptake equilibrates with the penetration pressure generated by capillary water flow to stabilize the formed water retention.

The formation and control of the water retention zone depends on physical properties such as soil pore size and hydraulic conductivity (William and Robert, 2006). A spherical water retention zone can be formed and controlled in this study because this study used artificially controlled soil condition which was homogeneous in physical soil properties.

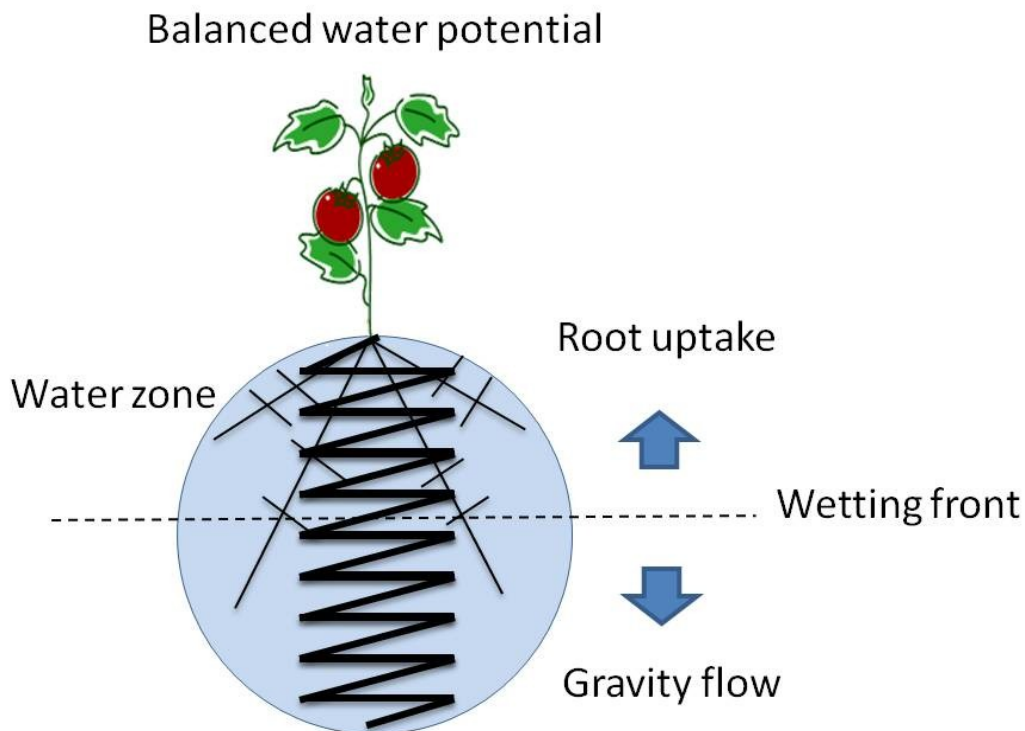


Fig. 3.15 Model of balanced condition of water retention in rooting zone

Figure 3.16 shows the relationship between pF value and the VWC in the wetting process of the experimental soil. As shown in the figure, the VWC decreased distinctly from pF 2.0 to pF 3.5. Together with the response of the soil moisture shown in Fig. 3.7, it can be seen that the pF value was around 3.0 when the VWC researched the peak value of 20% after the water supply. It can be considered that the water was available for plant use at this moment. The soil moisture then decreased to 15% due to plant water uptake and the pF value was 3.4. This pF value can be considered as a threshold or wilting point in this cultivation due to the plant start to wilt at this moisture level. On the other hand, the sensor value at 3 cm from the water source was about 10% during the experimental period. This position was considered as the boundary between wet and dry soil and the value was used for control of the water retention zone. The pF value at this position was about 3.6, which indicated that the negative pressure generated by root water uptake equilibrated with the penetration pressure at the boundary of the water retention zone. Therefore, it can be considered that the water retention zone was stably maintained during the irrigation period.

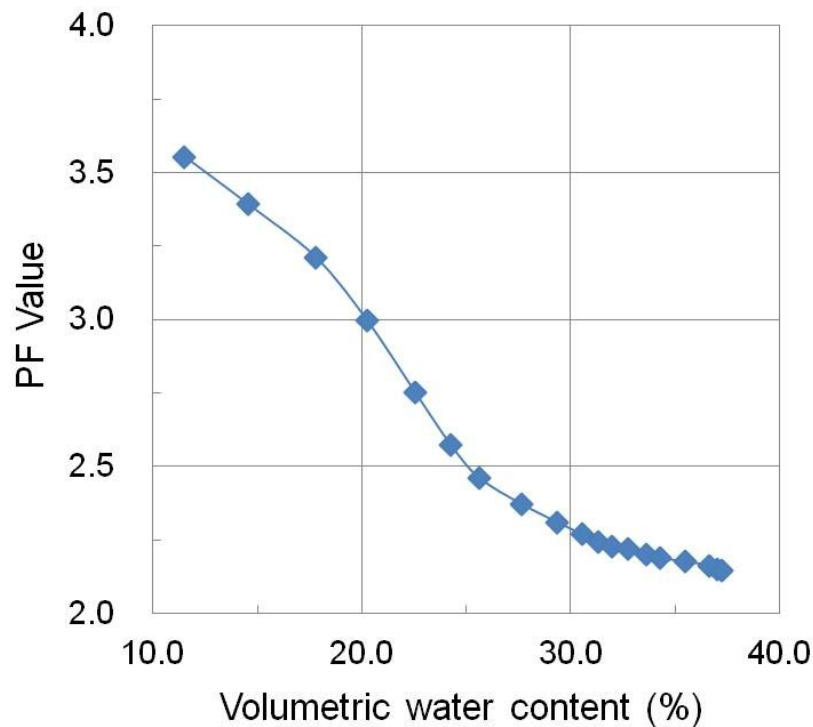


Fig. 3.16 Retention curve of the experimental soil

In this experiment, water supply was conducted based on the responses of the soil moisture sensors as shown in Fig. 3.7. Consequently, a zone of water retention was formed and was stably stayed in the rooting zone during the growth of plant. It can be said that the formation and control of the wet and dry soil region in the cultivation substrate can be realized by precise control of the water supply based on enhanced resolution of soil moisture sensing.

In order to avoid the destruction of the water retention zone due to the saturation or gravity effect which may pull some water down below the root zone, this study used two dimensional soil moisture sensors to measure the water flow in horizontal and vertical direction from the water source. By adjusting the amount and frequency of water supply the water retention zone can be limited and stayed within a small scale region where root can absorb water. As a result, the amount of daily water supply was much smaller than the normal cultivation. In addition, since the nutrients contains in the irrigation water were also quite limited, the growth rate was slower than the ordinary cultivation as shown in the Fig. 3.9 (a). If only considering the total amount of water supply at the time of fruiting as an

index to evaluate the water saving degree, this experiment used less than 4000 ml and this value is 1/5 less than the water saving greenhouse in Netherlands which is known as extremely high WUE (Stanghellini et al., 2003; Shukri 2014). However, in terms of agricultural crop production, the growth rate and fruit yield were both lower than ordinary cultivation. So some problems cannot be discussed using the water saving efficiency alone.

Next, to put the water retention control into practical use, we can consider the plant growth in this experiment as a control system (Hashimoto et al., 2002). The control target is the growth amount, while the control parameters are the amount of water supply and the environmental parameters such as temperature, humidity and light intensity. Plant grows by the photosynthetic activity, and the resources necessary for photosynthesis are the water absorbed by root, CO<sub>2</sub> in the atmosphere and the light. This experiment considered the amount of water supply as the main control parameter in order to realize the water saving cultivation. The amount of the water supply in this experiment was the only operational input variable to the system which was also the limiting factor to the plant growth. In the visual observation of water retention during the experiment, the soil surface was kept dry and there was almost no water loss due to evaporation from the soil surface, while the supplied water was held by the soil particles and pores that stored in the rooting zone. In addition, since the water retention zone formed by the irrigation water was stable in the soil during the growing period, high irrigation efficiency was achieved by supplying water to the vicinity of the rooting zone when only the amount of water supply was used as the only control parameter. However, because this cultivation was carried with a very small amount of water supply from the viewpoint of water saving, the growth rate was slow, and both growth amount (plant height, number of branches) and product (fruit) number were both lower than the normal cultivation. In the vital aspect of crop production, the productivity of water was extremely low. In the future, the practical issues are how to obtain the same amount of growth and production as the ordinary cultivation under the context of water conservation. To put this technique into practical use, it is necessary to calculate water requirement at each growing stage and verify the proportion of the appropriate volume of water retention to the rooting zone.

The soil used in this study had been artificially dried and sieved with uniform physical



properties, so the formed water retention zone had a shape close to a perfect circle. Moreover, controlling the physical properties of the soil facilitated the control of the volume of the water retention zone. The future research issues will be the observation of soil moisture in the soil which has the physical properties close to soil condition in the agricultural field and to examine the method of irrigation control based on the observation.

To realize the ideal water-saving technology and the control method, this research aims to achieve a stable state where moisture exists only in a limit region in soil. That is, water required for plant growth only in the rooting zone. And it can be said that an ideal state in which there is no losses of water applied to the crop by forming such a zone of water retention. In the vital aspect of application efficiency, how to approach to such an ideal state is a viewpoint to evaluate the effectiveness of the irrigation system. From this point of view, observation of the water retention formation can directly evaluate the effectiveness of water saving system, and the qualitative and quantitative observed results will be the fundamental and concrete knowledge for the development of this new water saving technology.

### **3.5 Conclusion**

The purpose of this research is to realize a cultivation method that the minimum moisture required for plant growth exists only in the rooting zone. As the methodology for realizing such was saving cultivation, the method to control the water supply based on improved resolution of soil moisture sensing was developed, and an actual cultivation experiment was conducted using this method. As a result, the water retention zone formed in the rooting zone can be accurately grasped by observing the soil moisture in the soil using proper resolution. By supplying water according to the dynamics of the water retention zone, it is possible to realize cultivation technology with extremely low water loss and high application efficiency.

Besides the wet soil region and the dry soil region illustrated in this study, the plant physiological wilting point or the threshold for indicating irrigation can also be defined. In the

existing cases, the formation of wetting zone in soil as a result of irrigation has been confirmed. However, it has not been confirmed that the wetting zone can be stably formed inside the dry soil region where the soil was kept below the wilting point. In addition, whether it is possible to artificially control the volume of the soil wetting zone has not been clearly verified. In this study, although only tomato was tried with small samples, such verification has been performed through an actual cultivation experiment.

In the future research, based on the results and findings obtained from this study, verification for the practical application of this technology is necessary by examining and practicing the methods to obtain equivalent crop growth and yield as the ordinary cultivation.

## Chapter 4 Conclusion

### 4.1 General conclusion

Water shortage has become a serious problem across the global. And this problem will be worse in the future due to the growth of world population and the climate change. How to improve WUE in agriculture to meet the growing demand for food, feed, fiber and fuel has become an urgent issue. The PA approach has shown a great potential in agricultural management to improve the water and fertilizer use efficiency based on the information and measurement technology. To implement the PA approach in irrigation management to improve the WUE in crop production, this study has presented a new cultivation method that keeps the minimum moisture necessary for plant growth only in rooting zone, and harvested fruits by using only a few percent of normal irrigation water. In addition, this study attempted to observe water dynamics in the rooting zone and the plant physiological response to the irrigation water volume. As a result, it is possible to analyze the irrigation waste against the water requirement of plant organism from the view point of water volume necessary for growth. This study analyzed the irrigation water use efficiency which is not clearly understood in the existing studies. The knowledge gained in this study may contribute to the development of water saving agriculture. Furthermore, based on the fact that the water retention can be controlled within plant rooting zone, the morphological feature of root and the root hydrotropic response to the wet soil condition were able to be precisely observed and analyzed under the controlled condition which cannot be realized in the existing studies.

In order to evaluate the current water saving cultivation system in Japan, this study firstly investigated the spatial variation of soil moisture in the field. In the survey, a sloped citrus field with mulch drip irrigation system was selected and the soil moisture was measured at three points in the depth direction using a capacitance soil moisture sensor. To visualize the results, the measured soil moisture with RTK-GPS location data was used to develop geographical soil moisture map by the ArcGIS tools. And the field moisture

variation was shown in both horizontal and vertical direction. As a result, moist moisture distributed in the deeper soil, which confirmed the irrigation water lost due to gravity. This study also attempted to measure the soil moisture and nutrients by spectroscopic methods and evaluated its prediction accuracy towards 24 soil parameters.

Next, in order to maximize irrigation efficiency to agricultural crops, this study practically verified whether the state where moisture exists only in crop rooting zone can be stably controlled. Experiments were carried out under an artificial climatic environment. Irrigation was done manually through point water source to the rooting zone. Tomatoes were used as cultivars. Homogenous soil was used which was artificially dried and sieved. Temperature, humidity and solar radiation were set artificially, only irrigation volume was used as the control parameter. In order to precisely grasp the moisture dynamics in the rooting zone, the moisture condition was measured with higher resolution of centimeter order soil moisture sensor matrix. Cultivation experiment was conducted to stably create water retention in limited and small soil area around crop rooting zone by finely controlling water volume and timing based on the observed soil moisture dynamics. This study quantitative analyzed the plant growth in response to the water to know the relationship between crop growth and the irrigation water. In this experiment, the irrigation water was attempted to be saved to a limit for plant growth, and cultivated the plants until first fruit was harvested. Less than 50 ml of irrigation water per day was used which was only a few percent of the normal irrigation volume. The water use efficiency and the morphological features of the roots were then analyzed under this extremely water saved condition.

#### 4.1.1 Evaluation of water use efficiency and crop water productivity

In the presented cultivation method, the water used for irrigation was almost absorbed by the plant, while there were no wastes of irrigation water due to the run-off, deep percolation and evaporation. So the application efficiency can be 100%. The plants increased their biomass in response to the water volume applied in the water retention zone. The WUE was then calculated using the ratio of crop yield to the applied water

volume (g/L), and water volume required to produce 1 kg tomatoes (L/kg). The later has been widely published as virtual water content or crop water footprint to compare and evaluate the water consumption for crop production (Mekonnen and Hoekstra, 2014; Evangelou et al., 2016; Lovarelli et al., 2016). Compare to the previous studies, the WUE in this study was about 3 times lower than the field cultivation in Almeria (Spain) and Israel. While the WUE were about 8 times lower than the high-tech climate controlled (CO<sub>2</sub> injected) greenhouse in Holland (Stanghellini 2003, 2014). The lower results of WUE in this study may probably because of the lower crop yield, while the amount of water supply in this study was extremely low across the growth cycle.

In terms of water saving, the water consumed to obtain the first tomato was less than 4000 ml, while the daily averaged irrigation amount was less than 50 ml. According to the water consumption data of the subsurface capillary irrigation system developed in CREST, the mean daily water consumption across the whole planting cycle was about 1300 ml, while the mean daily water consumption at the initial growing stage was about 1000 ml (Shukri, 2014). Therefore, this study only used 1/20 of irrigation water compare to the data obtained from the subsurface capillary irrigation system, while the later was achieved the highest WUE in the published results based on adaptive control of the capillary water flow (Stanghellini 2003; Shukri, 2014).

In terms of crop water productivity, this study was extremely low due to the water only produced a very small amount of crop yield. The reason may be because of that the crop was not fully developed due to the water supply was insufficient for the development of plant tissues. The water supply in this study was conducted based on the wilting point, at which the soil moisture cannot meet the needs of the crop transpiration, and the crop started to wilt. After a water supply event, the plant may recover from wilt. The supplied amount of water can therefore meet a minimal level of the water requirement for transpiration and carbohydrate production. But the growth rate and the weight of the accumulated biomass were extremely lower than the ordinary cultivation.

The transpiration occurs through stomata on the crop leaf, and the water loss from transpiration generates crop water requirement which needs to be compensated from the soil moisture. The stomata have the function to regulate the rate of transpiration based on

the crop hydrologic status (Turner, 1996). When the water is insufficient in soil, the stomata may partially close to prevent the crop tissue from dehydration. This activity may also limit the CO<sub>2</sub> assimilation due to that they share the same pathway. Therefore, one important question has been brought out that how much transpiration can be reduced without much damaging on the plant growth. One thing can be sure from this study that the plant would definitely died if the soil moisture was kept below the wilting point. At the time of wilting if a small amount of water (10 ml in this study) was given to the plant, the plant will recover and maintain a minimal level for its physiological activities such as photosynthesis and transpiration.

Based on this context, it can be considered that the plant yield and the WUE may probably have a linear relationship to some extent. When the applied water increased, the crop yield may also increase due to that more water can be used by the plant to develop tissues, while the WUE may also increase. Some researches believed that the CO<sub>2</sub> assimilation has a saturation level, and reducing certain amount of irrigation water may not reduce the CO<sub>2</sub> assimilation but can reduce the transpiration loss and improving the WUE. This is also the theoretical base of the deficit irrigation approach (Morison et al., 2008). According to the results mentioned above, before the CO<sub>2</sub> assimilation saturates, the applied water may be proportional to the crop yield, which may probably also be proportional to the WUE, when non-productive (non-transpiration) water losses were minimized. Considering the non-transpiration water loss was almost zero based on the water retention control, the optimal WUE may probably exist when the irrigation volume increases to some extent to fulfill the CO<sub>2</sub> assimilation.

#### 4.1.2 Response of root proliferation to the water retention zone

The chapter 3 provides a case study of hydrotropism by analyzing the root morphological features and the biomass distribution at dry and wet soil at the controlled condition that moisture only existed in the rooting zone. In this study, nearly 96% of the root was restricted inside the water retention zone. This indicates that the water may be a cue to

induce the root behavior and the root prefer to proliferate in the region where the soil moisture is rich. In addition, the root skeleton has a circular pattern, and the root bending towards the inside the water retention zone was observed (Fig. 3.13). This observation was in agreement with the hydrotropism assumption, which indicates that the water potential gradient produced at the boundary between the wet and dry soil may induce the hydrotropic response of the tomato roots, while modifying their growth direction towards the higher soil moisture. Therefore, it can be considered that if the water retention zone can be controlled stably in the dry soil, the root can also be restricted inside the watered zone. This also provides the opportunity to study the root-shoot relationship by controlling the formation of the rooting zone by providing water gradient to the roots. The knowledge obtained from the study can contribute to the design of irrigation system for effective application of irrigation water and fertilizer.

In this study, Pot 1 developed more root biomass inside the wet soil with less root growth in dry soil than Pot 2 (Table 3.4). The Pot 1 also developed more above ground biomass and yield than Pot 2. The difference may probably because of the variation in the individual crop hydrological characteristics. The reason cannot be clarified due to this is only one case study. But one assumption can be made that a stronger characteristic in hydrotropic response may use the soil water more efficiently which may contribute to higher WUE. These phenomena need further researches and the experimental system presented in this study can be used to study the hydrotropic behavior in soil due to that a stable and steep water potential gradient can be produced at the boundary between the wet and dry soil during the growth of root.

## **4.2 Uncertainties in the evaluations**

The soil texture is important to soil water holding capacity as it controls the hydraulic conductivity and the soil moisture characteristics (William and Robert 2006). Particle size distribution partly controls soil pore size distribution, and the pore size has important effect on the soil water retention. The difficulty of water retention control may vary

according to the changes in the relationship between the hydraulic conductivity and the soil moisture. In sandy soil, the control of water retention may be difficult due to that the hydraulic conductivity is not sensitive to the soil moisture change. And irrigation water is easier to lose from rooting zone than other type of soil, which may affect the irrigation efficiency by altering the amount of recharge (Burke et al., 1999). Therefore, both the irrigation volume and the soil texture should be taken into account when developing optimal irrigation system.

The spatial variation of the soil texture within field may alter the irrigation efficiency (Burke et al., 1999). This study used homogeneous soil which was dried and sieved with a uniform soil particle size. The formation of water retention zone in a soil close to a field condition has not been tested. In addition, although the Vis-NIR spectroscopy has been tested for prediction of multiple soil physical and chemical properties, this prediction was not aiming at the prediction of the soil water holding capacity across the field. The calibration models developed in this study were not general models which need to be developed again when the soil condition changed. To implement this irrigation method, more robust calibration model need to be developed which can accurately predict the variation of soil water holding capacity across a field. And precision management of irrigation water should be based on the spatial and temporal variation of the soil texture (Mouazen et al., 2014).

Another uncertainty can be the effect of the crop hydrologic characteristics. The deficit irrigation management may depend on the crop sensitivity to drought. If a crop is tolerant to drought, the maximum WUE can be obtained before the full yield potential is reached. While for a drought sensitive crop the full potential ET need to be fulfilled to obtain maximum yield and WUE (Geerts and Raes, 2009). In addition, the water sensitivity may also alter corresponding to different physiological growing stages. The water stress suffered in the sensitive stage may damage the crop production. Therefore, when optimal application efficiency is achieved based on the water retention control, how to manage the irrigation volume according to the variation of crop hydrologic characteristics may be an important issue.

Moreover, the non-water resources such as fertilizer, air temperature and humidity,



light intensity, CO<sub>2</sub> concentration may also affect the WUE. The high WUE achieved in the previous greenhouse cultivations reported by Stanghellini (2003) may be attributed to the excellent management of these factors. This research was designed to enable the soil water availability to be one of the limiting factors to study the crop water relations. Under a given climate condition, proper management of fertilizer to maintain soil productivity can also be a simple and efficient strategy to reduce the transpiration while improving WUE (Turner, 1996; Sato, 2002; Hatfield et al., 2011). Therefore, when performing this technology, precision management of both the soil water and nutrients will be an effective way to improve the WUE.

Finally, the water exchange in the water retention zone may be also accompanied by air exchange in the rooting zone. However, this study only focused on the crop water relation based on the water retention control cultivation method. The other functions of irrigation system such as air exchange and salt leaching are out of the research scope.

## **4.2 Issues and future works**

This study was attempted to maximize the irrigation efficiency by saving water to a limit level of plant organisms' growth, and obtained fruit by using a few percent of normal irrigation water. However, crop yield may also depend on various factors such as sunlight, temperature, water, nutrients, and also the disease and pest management by affecting the biomass assimilation and allocation (Shioi et al., 2009). Therefore, the data produced in this study is one case for the specific environment and management condition. This would be the limitation of this research due these factors were not analyzed. But the approach by controlling irrigation volume as the only control parameter for plant growth is a general case. So the irrigation volume to produce the first fruit is still voluble to compare the water saving level at different environmental condition. Future work is expected to calculate the percentage of potential evapotranspiration to compare the water saving level at various climate conditions due to this term is more widely used.

Also, this study provided a water saving case with limit irrigation water for plant

growth, and cultivated plant until the first fruit maturing. To understand the characteristics of crop water production function, future study should consider the proper management of plant water stress to improve crop water productivity. According to the equation 1.1, the WUE totally depends on the irrigation volume that can meet the plant water requirement when the application efficiency is 100%. The irrigation efficiency can be then calculated from the ratio of water stored in the rooting zone to the water required in the rooting zone. In order to obtain the optimal WUE, future work should seek approaches to manage the irrigation volume according to the growth stages of the crops. However, as discussed in the chapter 3, when the irrigation volume increased, the application efficiency may possibly decrease due to the excessive water flow into dry soil which may destroy the water retention zone. Therefore, the proper management of the irrigation timing and amount is important to control the volume of the water retention zone to meet the water requirement of crop growth.

Since the soil texture is important to the soil water holding capacity, future work need to be conducted to investigate the relationship between water retention and irrigation volume in different type of soil for practical implement of this technology. The spatial variability of soil water holding capacity should be investigated and evaluated based on various soil physical indicators such as partial size, bulk density. The soil water holding capacity has not been evaluated from the tested soil properties in this study. Therefore, the ability of using spectroscopic method to evaluate the water holding capacity needs further research.

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## Abbreviations

WUE	Water Use Efficiency
ET	Evapotranspiration
VWC	Volumetric Water Content
GWC	Gravimetric Water Content
PA	Precision Agriculture
Vis-NIR	Visible and Near Infrared
PLSR	Partial Least Squares Regression
$R^2$	Coefficient of Determination
$R_{cv}^2$	Coefficient of Determination of Cross Validation
$R_p^2$	Coefficient of Determination of Prediction
RMSE	Root Mean Square Error
RPD	Residue Prediction Deviation
SD	Standard Deviation
$R$	Correlation Coefficient
RTK-GPS	Real-Time Kinematic Global Positioning System
MC	Moisture Content
P-a	Available Phosphorus
K	Potassium
EC	Electronic Conductivity
Mg	Magnesium
Ca	Calcium
CSP	Calcium Saturation Percentage
BSP	Base Saturation Percentage
Cu	Copper
Zn	Zinc
Mn	Manganese
B	Boron
N-h	Hot-water Extractable Nitrogen

N-t	Total Nitrogen
C-t	Total Carbon
N-n	Nitrate Nitrogen
N-a	Ammonium Nitrogen
Ca/Mg	Calcium/Magnesium Ratio
Mg/K	Magnesium/Potassium Ratio
PAC	Phosphate Absorption Coefficient
CEC	Cation Exchange Capacity
BD	Bulk Density
y1	Exchangeable Acidity
SPEC	Soil-Plant-Atmosphere-Contiuum
RWI	Root Weight Inside
RWO	Root Weight Outside
RNO	Root Number Outside
TRLO	Total Root Length Outside
MRLO	Mean Root Length Outside