Water Use Efficiency of Precision Irrigation System under Critical Water-saving Condition

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Abstract. *Non-transpiration water loss is often neglected when evaluating water use efficiency (WUE) of precision irrigation system, due to the difficulties in determining water loss from the root zone. The objective of this study is to investigate the feasibility of a new water saving approach by controlling soil water retention around root zone during the plant growth. We grew two tomato cultivars (Anemo, Japanese variety) in an environmental controlled growth chamber, with previously oven dried and sieved red soil as substrate for cultivation. In order to investigate the water productivity at a minimal irrigation level for the tomato growth. The procedure involved supply a meager amount of water (10ml) from a point water source to the plant root zone when the plant started to wilt. The water supply was repeated several times (4-7 times) a day. We confirmed plant growth from seedling to the first fruit maturing under this extreme condition. There were no evaporation and deep percolation losses due to the boundary separated the wet and dry soil was visually observed. Plant increased biomass in response to the water applied in the water retention zone. The fruits weight, dry shoot and root biomass were used to analyze the WUE. As a result, the total water supply was 1/10 less than conventional irrigation while WUE was about 1/4 lower. The approach developed in this study aims to be used to develop new standard for comparison of the water saving degree of precision irrigation system.*

Keywords. *Biomass, crop yield, water retention, water use efficiency, precision irrigation.*

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Introduction

Conventional irrigation management has aimed to maximize full potential of crop yield per unit of field, by applying uniform rate of irrigation water to the field without considering spatial and temporal variability of crop and soil conditions. This method is lack in precision and WUE due to the water losses caused by surface run-off, deep percolation and evaporation from soil (English et al., 2012). The changes in climate and improved environmental standards required improved WUE based on precision agriculture approach. Increasing WUE, by means of increasing crop yield using less irrigation water, can be achieved by precise control of timing, frequency, amount and location to meet specific water requirement of individual plant. The evaluation of WUE for irrigation system has been defined at various scares depending on the specific requirement of an irrigation project (Howell, 2001). The simplest term of WUE is described as crop yield per unit of water used, which is widely used in deficit irrigation (Geerts and Raes, 2009). Due to the water loss from an irrigation event may not directly contribute to the crop yield, the WUE has also been described based on the application efficiency of irrigation system which considered both of water loss from root zone and crop water requirement (Wang et al., 1996). However, the water components described are practically difficult to measure in a real field. In addition, the soil profile can only be measured at a few locations within a field. The spatial and temporal variability of field conditions are often ignored.

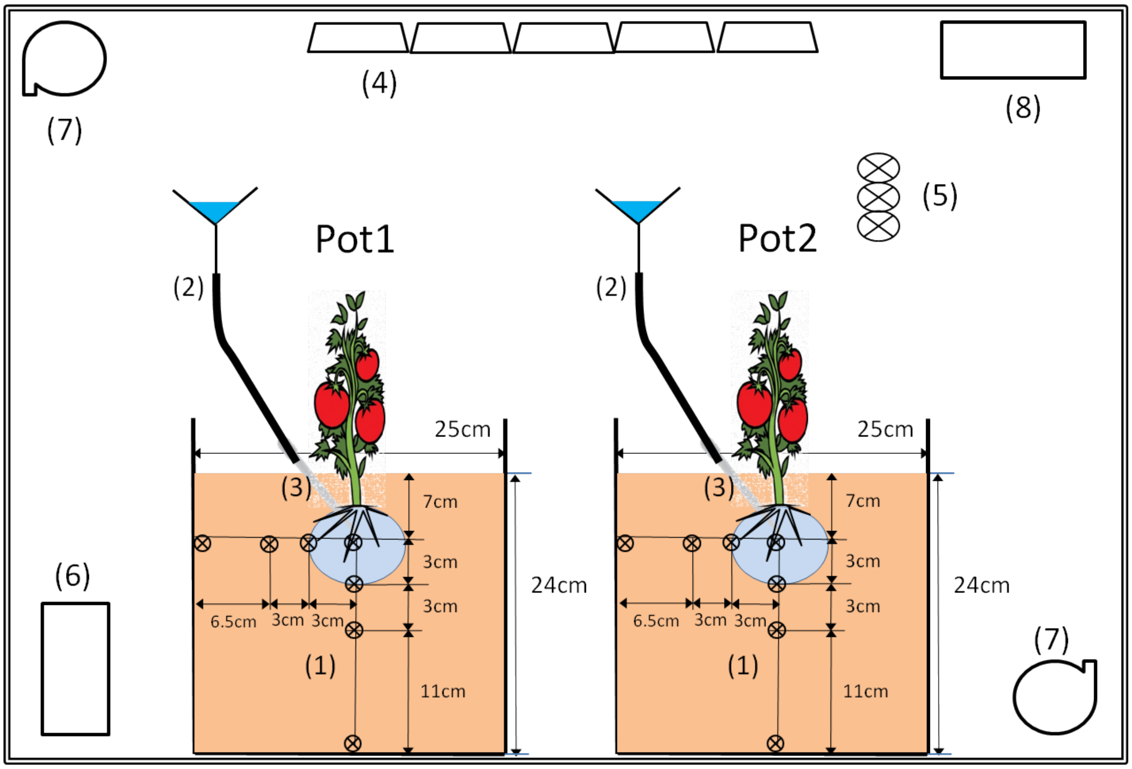
Prior to this study, the authors involved in a five years research project entitled water saving system for precision agriculture (WSSPA) under the Core Research Evolutionary for Science and Technology (CREST) funded by Japan Science and Technology (JST) (Shibusawa, 2016). As the achievements, a capillary 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., 2014). In WSSPA, a key technology is to produce an appropriate zone of water retention during growth of plants by applying precise control of capillary water flow. The water uptake by plant produced negative pressure which equilibrated with the penetration force at the wetting front of irrigation water. Consequently, the soil water retention was stable in root zone without water losses from evaporation and deep percolation (Li et al., 2018). In the vital aspect of application efficiency, the further study aims to use this approach to evaluate WUE of precision irrigation system.

Since crop yield and water supply almost have a logistic relationship, 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 (Geerts and Raes, 2009). This is also the theoretical base of deficit irrigation practice. The deficit irrigation becomes increasingly significant when water is insufficient. 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., 2012). A water productivity function which describes the crop yield response to water supply has been developed for various crops to determine the optimal irrigation strategies. However, the lower limit of the function has been studied in little previous related work (Geerts and Raes, 2009).

When water supply is insufficient during a growth cycle, the crop may not fully developed result in significant loss of yield. The WUE is therefore needed to be researched when water supply is extremely low. Based on the context mentioned above, the objective of this manuscript was to analyze the WUE using a water saving approach based on water retention control, while the effect of limit level of irrigation water to plant growth was investigated. The obtained results are aimed to be newly proposed to evaluate WUE of irrigation system for designing of optimal irrigation strategies.

Materials and Methods

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. Fig.1 shows the experiment setup inside a growth chamber (NK-system, KCLP-1500LED-NCS) which is composed of cultivars, environmental control sector (Fig.1 (5)~(8)) and root zone measurement sector (Fig.1 (1)). As shown in Fig.1, two tomato samples (Anemo, Japanese variety) were grown in cylindrical pots with 25cm 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 1mm 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 ºC for 24 hours before the experiment started. The tomatoes were planted in the horizontal center of the pots, with 17cm from the bottom and 7 cm from the surface (Fig.1 (3)). A point water source made by a fibrous cloth was buried at the root zone. After translating 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 (Li et al., 2018). The dynamic of the water retention was measured by a two dimensional soil moisture sensor matrix (EC-5, Decagon), which was placed in vertical and horizontal direction from the water source (Fig.1 (1)). After the initial irrigation, water was carefully supplied manually according to visually observed plant status and the soil water retention dynamics. A 10 ml distilled water was supplied when plant started to wilt, this water supply repeated several times a day based on confirming there was no excessive water penetrating into the dry soil. Liquid fertilizer (Hyponex, N:P:K=5:5:5) was applied casually with irrigation water during the growth period. 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.



(1) Soil moisture sensors, (2) water supply tube, (3) Pipette, (4) Fluorescent lamp, (5) Environmental sensors, (6) (7) Humidity controller, (8) Temperature controller

Fig 1. Experimental setup

The experiment was started at September 12th 2016, and ended at January 23rd 2017 at when the first fruit matured. The program setting, which was manually setting upped, inside the growth chamber was shown in Table 1. Two patterns inside the growth chamber were designed to simulate 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 photosynthetic photon during the experimental period was 170 μmol/m^2/s, which was measured by a quantum sensor (Li-Cor). The corresponding mean temperature was 30 ºC and the relative humidity was 36% measured by temperature and humidity sensor (HMP-155, Vaisaia). The mean night time temperature and relative humidity were 22 ºC and 60% respectively. The mean CO_2 concentration in both of the patterns was measured by a CO_2 sensor (GMT-222, Vaisaia).

Table1. Program setting inside the growth chamber

	Time	Temperature (℃)	Humidity (%)	Quantum（umol/m^2/s）	CO_2 (ppm)
Pattern 1	8:00～22:00	30	36	170	2082
Pattern 2	22:00～8:00	22	60	0.3	2069

Measurement of plant growth and yield

The plant height, number of fruits and the cumulate water supply were recorded during the plant growth. In order to visually observe the existence of water retention, a small amount of dry soil was removed from the soil surface to the edge of the water retention, and then recovered to stable soil surface. The observation was conducted for pot1 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. After the first fruits matured, the experiment was ended and the dry biomass of shoot, root, and the fruit weight were measured. The roots were carefully sieved and washed to separate them from soil, and then put into the oven with shoot at 80 ºC for 24 hours to obtain the dry biomass. The WUE was measured using the ratio of fruit weight to the cumulative water supply.

Results and discussion

Soil moisture dynamics

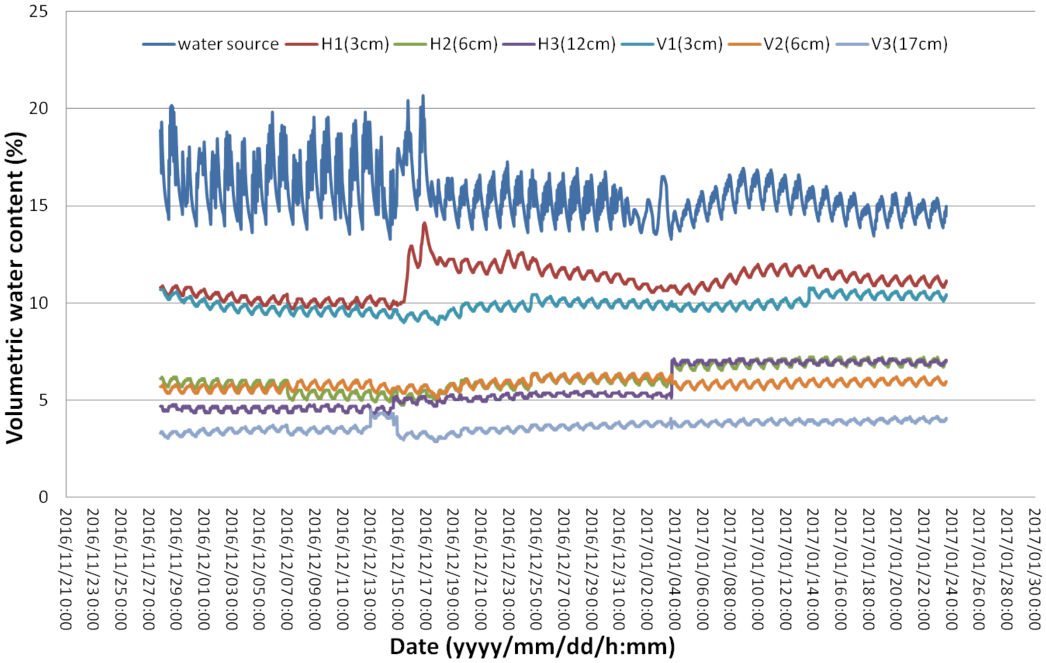


Fig 2. Soil moisture responses at the locations presented in Fig.1 (H: Horizontal, V: Vertical, number in brackets represent the distance from water source)

The soil moisture sensor responses at each location across the growth period are shown in Fig.2. The top curve in the figure was the moisture response at the water source. Each peak represented one water supply event. The red and light blue curve (H1 and V1) were the soil moisture at 3 cm from the water source at horizontal and vertical direction. The moisture here indicated the position boundary of the water retention zone. The other sensors were used just to confirm there was no excessive water flow into the dry soil (Fig. 1 (1)).

Observation of plant growth and water retention

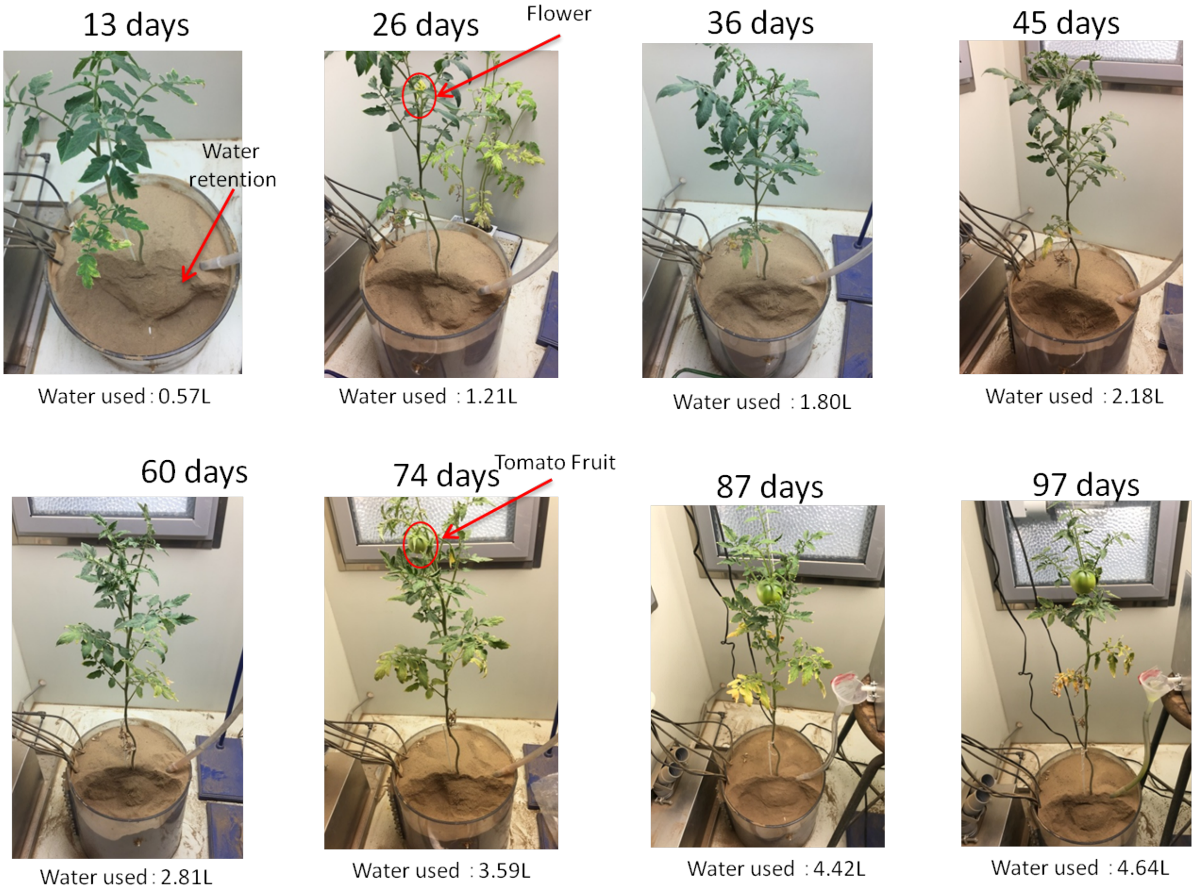


Fig 3. Observation of plant growth and water retention

The observation of water retention was conducted according to the growth stages as shown in Fig.2. The water retention was stable in the root zone during the plant growth, from where plant can absorb water. The water potential difference between the dry, wet and boundary were also measured by collecting soil samples at the three locations (Li et al., 2018). The water loss from evaporation was not observed.

The relationship between plant height and cumulative water supply is shown in Fig.4. 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.4 (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 (Fig.4 (b)). It can be considered 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.

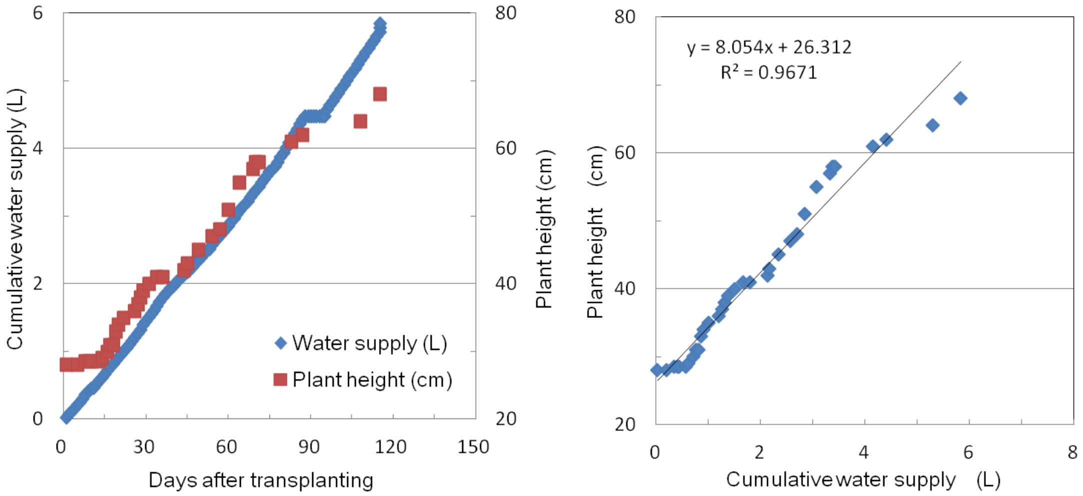


Fig 4. Relationship between plant height and cumulative water supply

Plant yield and water use efficiency

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 2. 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). 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_2 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 about 5 to 6 L. And the amount of water used to produce the first tomato fruit was about 3.6 L (Fig. 3), 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 (Unpublished data).

Table 2. Plant yield and water use efficiency

	Total dry biomass (g)	Number of fruits	Fruit weight (g)	Total water usage (L)	WUE (g/L)	WUE (L/kg)
Pot1	6.12	2	36.06	5.18	6.96	144
Pot2	4.71	1	32.14	6.06	5.30	189
Mean	5.42	1.5	34.1	5.62	6.13	167
SD	0.71	0.5	1.96	0.44	0.83	23

Summary and Conclusion

This manuscript researched the WUE under extreme water saved condition. Soil water retention is germinated and controlled surrounding plant root zone where no distribution losses occurred due to evaporation and deep percolation. The water supply was 40-70 ml per day and 10 ml for one time which was conducted just before the plant wilt. The total amount of water supply was 1/10 less than conventional irrigation. The plant growth, flowering and fruiting were confirmed under this extremely water saving condition. The WUE was about 2-7 times lower. The WUE is not easy to compare due to many factors influence the results. The optimal WUE may exist at an increased water supply. The approach developed in this study is expected to develop crop water productivity curves for various crops for designing of precision irrigation strategies.

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