Improvement of Water and Fertilizer Managements for Enhancing Water Productivity and Net Income of Farmers in Arid and Semi-arid Regions

(乾燥・半乾燥地における農作物の水生産性と純収益の向上のための水および施肥管理の改善)

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Chapter 1

Introduction

Increasing population and food demands have intensified competition for freshwater resources between agriculture, domestic water consumption, and industry. Water scarcity is already an issue on every content of agriculture, presenting a serious threaten to food security. In some arid or semi-arid regions, precipitation is not enough for crop growth, and irrigation water begin to be largely withdrawn from groundwater, posing potential risk of domestic water and industry water. Present rapid depletion of ground water resources throughout the world will soon lead to widespread local shortages. On the other hand, the total global food demand is expected to increase by 35% to 56% between 2010 and 2050 (van Dijk et al., 2021). The risk of hunger caused by escalating water scarcity makes efficient irrigation management an urgent issue to be addressed. Basically, improving irrigation water use efficiency is implemented by supplying appropriate amount of water at the proper time (Soulis & Elmaloglou, 2018). Various irrigation schemes have been proposed to improve water use efficiency (WUE) and crop yield. For a long time, improving WUE is regarded as main strategy to ease water resource limitation in agriculture (Marston et al., 2020). Still, improving WUE is a big challenge in irrigation areas all over the world. In reality, even water scarcity is apparent, farmers are often not willing to implement suggested water management strategies because of the less motivation from the economic consequences (Kamali et al., 2022). As a result, over irrigation combined with excessive supplement of fertilizer had caused large soil drainage and groundwater contamination (Liu et al., 2021). It is therefore necessary to improve the agricultural practices to improve water use efficiency and, at same time, the net income of farmers.

Previous studies have focused on improving irrigation technologies on large water consumption crop season, while paid less attention to the impact of crop rotation on water saving (Ma et al., 2013). The North China Plain (NCP), where different irrigation schedules have been conducted to avoid over-exploitation in winter wheat season (Sun et al., 2019), such as, minimum irrigation schedule (MI) and critical irrigation schedule (CI). Other methods like straw mulching and different tillage treatments before sowing are also applied to reduce the soil evaporation. All these methods are proved to be effective in improving WUE. Meanwhile, to control the unreasonable extraction of groundwater, the government has adopted a series of policies for crop rotation and fallow seasons in specific areas. The purpose of these policies is to reduce the planting area of water consuming crops and recommend crops whose water requirement can be met by the precipitation (Sun et al., 2019). Thereafter, studies focusing on the effect of crop rotation on water consumption and yield production should be conducted.

In addition to irrigation water, excessive fertilizer is also often applied for crops to improve yield, which risks nitrate leaching to the groundwater and P can cause eutrophication of water body (Ierna et al., 2011). Furthermore, fertilizing over a recommended level is inefficacious for production purpose. Thus, it is important to develop a proper irrigation and fertilization management. Since water plays a vital role in the fate and transport of nutrients, and determine the nutrients uptake by crops, appropriate application of fertilizers and irrigation water should be considered together (Ierna et al., 2011). However, few studies have focused on this topic and few studies have been conducted to evaluate the effect of temporal and spatial distribution of water and fertilizer on the production of crops.

With water scarcity increasing, designing polices that encourage water users to conserve has become one of the most important tasks facing government leaders. Nowadays, water pricing polices has been conducted in both developed and developing countries (Toan, 2016). Irrigation water pricing would affect farmers' irrigation activities, allowing farmers to allocate water efficiently during crop cultivation. Many studies focusing on irrigation schemes and methods have been conducted during past decades, but the crop varieties, soil texture and climate condition are varied based on study areas. The calibrated model could simulate different scenarios, which is labor-saving and beneficiated to the improvement of agriculture. Therefore, models combined with priced water and target with improving farmers' net income should be applied in modern agriculture.

By changing cropping systems and finding optimum combination of water and fertilizer to improve water use efficiency and developing a new irrigation scheme using numerical simulation could improve net income of farmers and saving water at the same time. In the following sections, detailed descriptions about 1) the experiments of double cropping silage maize to improve WUE, 2) an experiment using PVC tube to evaluate better combination of water and fertilizer in NCP, and 3) numerical simulation to optimize irrigation depth to improve net income will be presented.

1.1 The definition and determinants of water use efficiency

WUE is defined as the amount of carbon assimilated as biomass or grain produced per unit of water used by a plant. A number of studies have confirmed that improving WUE is a promising way to produce more grains in drought-prone areas (Qiao et al., 2022). Crops planted on water shortage regions or drought seasons easily suffer from drought stress. In addition, under exacerbating climate change situation, increasing population and demand for food put a huge pressure on freshwater, and further, making the crop production limited by drought stress (Lobell et al., 2015). Therefore, it is vital to find methods to improve WUE.

WUE is being affected by a changing climate. Crop responds to changing temperature, precipitation, and carbon dioxide (CO_2) concentration with different water consumption and dry matter accumulation (Hatfield & Dold, 2019). As the concentration of CO_2 continues to increase, the WUE increases accordingly until the temperature exceed the optimum for growth beyond which it begins to decline. At the leaf level, there is a direct relationship to WUE induced by increasing CO_2, because of increased photosynthetic rate and reduction of stomatal conductance. which would exhibit a preferential shift toward larger WUE at the leaf level (El-

Sharkaway & Cock, 1984). Therefore, WUE at leaf level is usually dominated by the physiological process of plants, such as, the temperature in air, CO_2 concentration, and vapor presser difference between air and leaf, and all of which control the stomatal opening and further influence photosynthesis. Zooming out from a leaf to vegetation, the energy exchange happens at both canopy and soil surface, and accordingly, the water consumption contains both plant transpiration, *T,* and soil evaporation, *E*. The total crop water use is represented as evapotranspiration, ET. When we examine WUE at canopy scale, it is important to consider the effect of climate change on each component. Enhancing the WUE at canopy scale can be achieved by reducing the soil evaporation, which is an inefficient water use for plant. Crop residue management, mulching, tillage, and irrigation practice can be conducted to reduce E and increase WUE.

1.2 The importance of improving water use efficiency in agriculture

WUE can be determined from leaf to field level, and it provides a simple way to evaluate the crop yield response under different crop management, thus supply opportunities to researchers to select proper methods to improve water use efficiency (Waraich et al., 2011). As we known, irrigated agriculture plays an important role in total agriculture and provides humanity with a wide range of agricultural products. Effective agricultural management is the only way to save water in the increasing cropland regions. Therefore, the maximization of yield per unit of water is the strategy to tackle water shortage and to mitigate environmental problems.

1.3 Methods to improve WUE

Improving WUE of crops can be achieved by taking advantage of precipitation and make full use of irrigation facilities (Waraich et al., 2011). Using minimum input of water and achieve a higher yield is the core targets needed to improve WUE in agriculture. The timing and amount of irrigation usually play a vital role in affecting plant growth. Deficit irrigation (DI), application of less water than crop required for full ET and maximum yield, has shown to be an efficient method to improve wheat yield and WUE in all over the world (Hao et al., 2014). Rotating the cropping systems according to local food demand and climate condition could also be one of the methods to save water. Several studies have found that the annual grain yield under triple cropping systems was only 13% to 16% less than that under double cropping system, while water consumption was reduced by 35% to 61% (Meng et al., 2012; D. Xiao et al., 2017). Stagnari et al. (2014) reported that mulching with crop residues or plastic improved WUE by 10-20% through reduced soil evaporation and increased plant transpiration, and soil water was kept high during the procedure. In addition, nitrogen is also an important factor in improving WUE and soil water use. Fertilizer applied in moderate water deficit region will stimulate deeper root growth in wheat and thus enabling access to stored soil water under subsoil and reducing the risk of water deficit. However, a huge root system will also increase the ratio of root and shoot, which allocate less dry matter to above ground part. This is not an economic resource allocation. (Liang et al., 2021; Wang et al., 2011). The understanding of the mechanisms that control soil water use and WUE under water and nitrogen application is critical for efficient use of water in semiarid regions in the world (Wang et al., 2018). Furthermore, the water-saving transportation methods will also affect the irrigation efficiency. A more efficient irrigation systems could help improve on-farm WUE.

1.3.1 Improving WUE by deficit irrigation

The reason why WUE increase under DI can be explained by Fig. 1. There is a linear relationship between yield and applied water when small amount of water was supplied. When the irrigation amount over I_M, the relationship becomes nonlinear because some part of water supplied is not used for ET and lost. The yield will not increase anymore, and additional water supplied will not be used for crop production. Thus, the WUE of irrigation water under DI must higher than that under full irrigation. Yu et al (2020) analyzed the effects of DI on wheat WUE and yields by meta-analysis, and found that DI improved wheat WUE by 6.6% but decreased yield by 16.2% (Yu et al., 2020). However, this result would vary depending on the irrigation methods and environmental factors, such as precipitation and soil. DI is more appropriate at areas where precipitation during growing period is less than 200 mm and soil type is loamy or sandy. In detailed DI, crop physiological water saving methods, such as, regulated DI and partial root zone irrigation have been tested with improved WUE and insignificant yield reduction (Du et al., 2010).

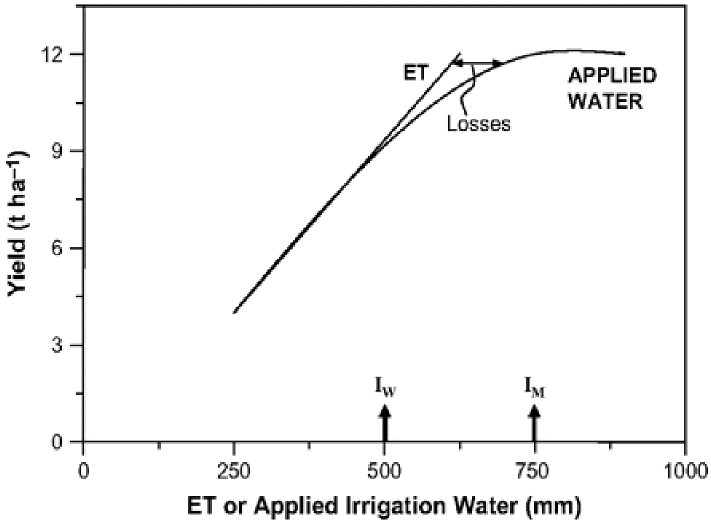


Fig. 1.1 General relationships between applied irrigation water, ET, and crop grain yield. I_W indicates the point beyond which the productivity of irrigation water starts to decrease, and I_M indicates the point beyond which the yield does not increase any further with additional water application. (Fereres & Soriano, 2006)

1.3.2 Improving WUE by rotating cropping system

Diversifying cropping systems has been found to be a sustainable way to increase crop productivity with little or no impact on the environment (Liu et al., 2022). Liu et al (2022) found that intensified crop rotations enhance the carbon conversion from atmosphere CO_2 to plant biomass, therefore sequester more carbon in plant. Furthermore, crop mixture also increases the system resilience, such as, faster recovery from abiotic or biotic stress and weed infestation. Crop rotations including legume could also reduce the synthetic nitrogen fertilizer input thus lowering environment contamination. In the Loess Plateau region of China, changing the traditional cropping system from summer fallow-winter wheat to forage crops could improve forage yield and WUE (Deng et al., 2020). Cropping rotation with forage crops not only increased precipitation use efficiency but also improved crude protein yield (Deng et al., 2020), which could also increase economic income.

1.3.3 Combination of water and fertilizer on WUE

Saving irrigation water and improving fertilizer use efficiency is becoming more and more important in improving crop production (Haefele et al., 2008). Many studies have been conducted to evaluate the effects of different water management and N application on crops. It has been acknowledged that soil water and nutrients distributions play an important role in root development (Hulugalle et al., 2009). In turn, fine roots (<2 mm diameter) drive soil processes such as nutrients changes, carbon cycling and soil aggregates formation (Hulugalle et al., 2015). Roots also affect the uptake of nutrients and water, plant hormone production, and organic acid and amino acid synthesis in plant (Yang et al., 2004). The development of root system is associated with aboveground growth and grain production. Therefore, rational distribution of water and fertilizer are becoming more important in crop production to achieve optimal yield under water scarcity and environment pollution condition (Haefele et al., 2008). However, the effect of spatial distribution of water and nitrogen on water productivity under water deficit and full irrigation condition are still not well documented.

1.4 Enhancing net income for farmers with water pricing policy

Changing crop water management and cropping system are considered as efficient way to tackle the current water crisis (Castellano et al., 2008). From the theoretical and empirical evidence of previous studies that leveraging through water pricing is proposed as the most effective method to improve water allocation between different water sectors and water conservation (Tortajada et al., 2019). With water price setting, water consumers use water more wisely and adopt irrigation technologies with high application efficiency or changing the cropping systems to water-saving patterns (Schoengold et al., 2006). When water price is high, farmer's goal is always to maximum the net income per unit of water used rather than per land unit (Fereres & Soriano, 2006). But from the previous findings, in some countries, the demand for irrigation is inelastic because the price is too low. Only when the price is set to a relative high level, the pricing policy could promote water conservation (Berbel et al., 2018). On the other hand, increasing water prices can induce farmers to save water, and may also weaken farmers' motivation for farming and affect the agricultural production system. Thus, water price should be carefully set so that water is acceptable to users and being financially sustainable for supplier (Nikouei & Ward, 2013). How to improve farmers' net income under the above water pricing condition is becoming another scientific question.

1.5 The importance of weather forecast on agricultural activities

Weather forecasting has long been used to help with farmers' business decisions. It can help them planning for day-to-day agricultural decisions. Proper sowing date, irrigation, fertilizer, and time to spray fungicidal or insecticidal in field depend on the weather forecast. To enhance field yield, farmers can use basic weather information, such as, temperature, humidity, and rainfall. Full use of weather forecast can help farmers enhancing their income. For example, if exact precipitation amount can be obtained from weather forecast, the water consumed for irrigation can be reduced.

Recently, the advantages of crop models have contributed to the improvement of water management in many regions (Allen et al., 2007). An important input for these crop models is the acquisition of high-quality weather data to calculate the reference evapotranspiration (ET_0), which is a key component in crop model (Allen et al., 1998). A density weather station networks are required to be created for this purpose (Gavilán et al., 2006). Nowadays, numerous weather stations have been established all over the world, providing great convenience to researchers and farmers. However, large distance between the irrigation site and weather station, and the huge investment for maintenance have often restricted the use of these facilities (Collins, 2011). And there is no weather station in most of the farm land, thereafter, a new methodology based on the use of weather forecast data from freely and accessible websites has been developed (Lorite et al., 2015). Weather forecast data can be obtained from public and private institutions, and most of them can be freely accessible. These weather forecasts are based on complex numerical model, such as, High Resolution Limited Area Model (HIRLAM) (Undén et al., 2002), *Aire Limitée Adaptation dynamique Développement InterNational* (ALADIN) (TOOL) and Weather Research and Forecasting (WRF) (Done et al., 2004), which has been used extensively in many studies.

Benefited from convenient availability of free weather forecasts data, some irrigation schemes incorporating weather forecast has been proposed. To obtain relatively accurate rainfall data, short-term weather forecast is usually recommended to incorporate into crop models for irrigation decision. Lorite et al (2015) compared ET_0 based on short-term (same-day) and long-term (6-day-ahead) weather forecast with measured data from 50 weather stations and found that differences in ET_0 with root-mean-square error (RMSE) equal to 0.65 and 0.76 mm d−1, respectively. Cai et al (2007) estimated ET_0 with the Penman-Monteith equation from FAO using daily forecast data, indicated that the predicated weather messages are appropriate to be used for real-time water allocation and irrigation management (Cai et al., 2007). Therefore, short-term weather forecast would be a better choice to be used for irrigation decisions.

1.6 Numerical simulation of crop response to irrigation

1.6.1 Crop simulation models

A broad scope of crop models with variable demand on data inputs are being used for several purpose, for instance, possible adaptation strategies under climate change, and on-farm management decisions (Kephe et al., 2021). As widely known, agriculture is vulnerable to global weather and climatic changes. Crop simulation models (CSM) are used as a valuable tool to predict the influence of climate change, cropping system and field management on crop growth, which provide reference for farmers to make decision. The first computational models of crop and soil were developed more than 60 years ago (Jones et al., 2017). Widely used models such as AquaCrop, which was developed by FAO and is based entirely on a water-driven growth module, the CropSyst model, based on water and radiation, and the WOFOST model, which uses a carbon-driven approach and intercepts a portion of the radiation to simulate crop growth (Vandiepen et al., 1989; Stockle et al., 2003; Steduto et al., 2009). In addition, APSIM, which is a comprehensive model developed to simulate biophysical process in agricultural systems, particularly related to the economic and ecological outcomes of field management in the face of climate change. These models have been spread over world to assess the possible impacts on agriculture of climate change and testing adaptation methods. The typically required input parameters include soil condition, weather data, and management practices such as fertilizer use and irrigation treatments, and the characteristics of the crop being grown. The output files from CSM usually include the biomass, yield, and water consumption.

As the models are differ in the level of complexity describing crop management, in the growth module driving the growth development, in the input parameters, it is necessary to compare the accuracy of simulation among them. Todorovic et al (2009) assessed performance of three models in predicting the growth of sunflower under different water regimes, and indicated that AquaCrop required less input parameter compared with CropSyst and WOFOST, while performing similarly with them in simulating biomass and yield after harvesting (Todorovic et al., 2009). However, those crop-based simulation models were found very simple in calculating methods of water and solute movement in soil, which is important for simulating crop water use, and they do not allow water flux influence by time, nor do they allow upward flow (Nimah & Hanks, 1973). Therefore, soil physical models are required to simulate soil water movement, solute and heat transport when the precious irrigation schemes are conducted in field and in regions where solute management are needed.

1.6.2 Soil physical models

Water shortage and soil salinization are two major problems faced in agricultural management. To cope with them, crop growth and associated soil water and solute transport should be quantitively predicted to provide references for developing appropriate agricultural management (Chen et al., 2019). To simulate dynamic change in water and solute contents under various irrigation schemes with plant interaction, many physically based models have been developed, such as, LEACHM (Leaching Estimating and Chemistry model) (Wagenet, 1989), SWAP (Soil Water Atmosphere Plant) (Van Dam et al., 1997), RZWQM (Root Zone Water Quality Model) (Team et al., 1998), and HYDRUS-1D (Simunek et al., 2005). The evapotranspiration, soil water content and salt concentration during crop growth are key factors to simulate the biomass accumulation and yield in CSM. In addition, evaporation from soil surface and transpiration from crop canopy change the soil water distribution and further affect solute migration. Therefore, combine hydrological process with crop growth benefit the understanding of agro-eco-hydrological process and provide reference for better management. Chen et al (2019) presented and validated a one-dimensional agro-eco-hydrological model, LAWSTAC, and compared with SWAP model. The results indicated that LAWSTAC simulate crop growth with a more efficient parameterization than SWAP (Chen et al., 2019). Zhou et al (2012) coupled crop growth model WOFOST with hydrologic model HYDRUS-1D. Good agreement was achieved between the simulated actual evapotranspiration, soil moisture content and production with the measured ones (Zhou et al., 2012).

Though much effort has been made to explore the accurate simulation of soil water, solute movement, and crop growth, few models s have incorporated dynamic crop growth and soil water and solute process. Based on such a background, we proposed an irrigation scheme which optimum irrigation depth using a numerical model which incorporated dynamic crop growth with two-dimensional soil water and solute movement and embedded weather forecast module in the model.

1.7 Objectives of the study

The objective of this study contained two parts. The purpose of first part was to evaluate the possibility of improving WUE by alternating cropping system from traditional cropping system winter wheat-summer maize to two-season silage maize, and to evaluate the effect of improving WUE by combining water and nitrogen at different position of soil profile. The target of second part was to improve net income of farmers by optimizing irrigation depth during each irrigation interval and compared with capital-intensive and water-consumed automatic irrigation.

1.8 Outline of the thesis

This thesis presents studies regarding improving water and fertilizer management for enhancing water productivity and net income of farmers, which focused on optimize agricultural management to save irrigation water and increase revenue under the water stressed conditions in arid or semiarid regions.

In chapter 2, a double silage maize cropping system was compared with the traditional cropping system, winter wheat and summer maize, in North China Plain, where the water deficit is becoming increasingly significant and change the water-consuming cropping system is imminent.

In chapter 3, different spatial water and nutrients combination PVC tube field experiment were set up to estimate the effects on root distribution, crop water consumption, dry matter allocation, yield and water use efficiency.

In chapter 4, a proposed irrigation scheme which determine irrigation depth using numerical model simulation and incorporate with weather forecast was compared with traditional irrigation methods, automatic irrigation and refilling irrigation, to assess the net income improvement under drip irrigation in sandy field condition.

In chapter 5, general conclusion was made to show the advantages of improving water productivity of the proposed alternative cropping system and water and nutrients spatial combination in semi-arid in NCP, and the benefit of improving net income of proposed irrigation scheme in this study.

Chapter 2

Performance of double cropping silage maize with plastic mulch in the North China Plain

Abbreviations

DM, dry matter; NCP, The North China Plain; SM, summer maize; TWF, total water footprint; WF, water footprint; WF_{blue}, blue water footprint; WF_{green}, green water footprint; WF_{grey}, grey water footprint; WW, winter wheat; 2M+PM, double silage maize mulched with plastic film; 2M, double silage maize without plastic film mulch; WW+SM, the traditional annual double cropping of winter wheat and summer maize for grain production.

Abstract

North China Plain (NCP) farmers often utilize maize (*Zea mays*) silage for dairy cows and double cropping of maize may be a feasible way to reduce annual water use and land required to produce feed. The objective of this study was to evaluate the possibility of growing a double crop of silage maize with and without plastic film mulch. An experiment was conducted between 2015 and 2018 and contained three treatments: double cropped (maize) plastic film mulch (2M+PM), double cropped (maize) without plastic film mulch (2M), and double cropped winter wheat (*Triticum aestivum*) and summer maize (WW+SM). Net income, yield, water use efficiency (WUE), and annual water use were determined. The results indicated that silage dry matter yield and WUE were improved by 45.6% and 31.5%, respectively, using plastic film mulch, as compared to without mulch. Total water footprint in producing the silage was also reduced by 24% using plastic film mulch. The annual water use was reduced by 150-190 mm with 2M+PM or 2M compared to WW+SM. Average net income was 429, 926, and 1008 \$ ha^{-1} in 2M, 2M+PM, and WW+SM, respectively. The results indicated that the advantages of the double silage maize system lie in the reduction in the amount of land required to produce maize

silage for dairy cows. However, due to the limited growth duration for the double maize, high silage water contents reduced silage quality.

2.1 Introduction

The consumption of animal products in developing countries has increased by approximately 5 to 6% annually since 2000 (Ingersent et al., 2003). This food source conversion will further pressure global freshwater resources (Khelil-Arfa et al., 2012; Murphy et al., 2017). One approach to reduce this pressure is to reduce the water footprint (WF). The concept of a water footprint was first introduced by Hoekstra (2003), which is defined as the amount of fresh water utilized in the production or supply of the goods and services used by a particular person or group, and it is often used to assess the water volume consumed (evaporated) and/or polluted per unit of a product (Seyam et al., 2003; Palhares & Pezzopane, 2015; Murphy et al., 2017). For example, the average global WF of cow milk is approximately 1000 L kg^{-1} FPCM (fat- and protein-corrected milk). However, WFs can vary greatly by location. For example, in Irish dairy farms, the WF ranged from 534 to 1107 L kg^{-1} FPCM, among which pasture production was responsible for 85% of the water footprint (Capper et al., 2009; Zonderland-Thomassen & Ledgard, 2012; Murphy et al., 2017). Using feed that requires less water during production can reduce the footprint (Lu et al., 2018). One approach to reduce the footprint is to plant species that have high water use efficiencies.

Maize, which has a relatively low water footprint, accounts for 53% of all silage produced (Kowsar et al., 2008). Maize silage is widely used for many dairy farms because it has an excellent nutritional profile and produces high dry matter, allowing farmers to increase the total amount of feed harvested from limited farmland (Lu et al., 2018). To match the yield of maize silage with the increasing numbers of dairy cows and the limited amount of cultivated land, many studies have investigated techniques for increasing maize productivity. Edson (2018) found that combining silage maize with legumes could efficiently improve milk production.

Meanwhile, it has been proven that harvesting silage maize when the dry matter content is between 32 and 35% can result in high quality maize silage (Swanckaert et al., 2017). Apart from the above-mentioned studies, there are also studies on improving the water use efficiency of silage maize by converting the irrigation method and the irrigation amounts (Zhang et al., 2017).

The North China Plain (NCP), located in a temperature monsoon climate zone, is one of the main grain production areas and a major dairy production region in China. In this area, grain production contributes 20.2% and milk contributes 31.1% of the total national production. The major cropping system in the NCP is winter wheat-summer maize, which forms the annual double-cropping system. The average rainfall is approximately 450-550 mm annually, with 70% occurring during the summer maize season. The annual water use for the two crops is approximately 800 mm, and irrigation is usually essential for the high yields of the two crops (Zhang et al., 2011). Winter wheat grows in the dry season and consumes most of the irrigation water applied. Most of the irrigation water is obtained from ground water, which has caused rapid groundwater level declines. New techniques are needed to help reduce groundwater level declines. Zhao (2018) assessed five alternative cropping systems across precipitation gradient to explore various options. One recommendation was to reduce the use of water-intensive crops such as winter wheat. Considering the high demand for maize silage in the NCP, it might be possible to convert farmland from winter wheat-summer maize annual double-cropping system into a double silage maize system. This change could use less water annually than the normal winter wheat and maize system and thereby conserve groundwater resources. This study was undertaken to assess the dry matter production, silage quality and WF of double silage maize growing with and without plastic film mulch. Further comparison was conducted on the annual water use and net returns of this system with the common winter wheat and maize cropping system. We expected that the results from this study might provide references for selecting a better cropping system in the NCP.

2.2 Materials and Methods

2.2.1 Experimental site

This study was conducted for three consecutive years from 2015 to 2018 at Luancheng Agro-Eco-Experimental station, located at 37°53′ N, 114°40′ E, with an elevation of 50 m above sea level. The site is located in a monsoon climate zone. The average rainfall in this region is 480 mm, with 70% of rain occurring in the summer maize growing period (July, August, and September). The typical local planting system is a winter wheat and summer maize rotation annually. The soil at the station is classified as loamy soil with an average water holding capacity of 38% (v v^{-1}) and wilting point of 13% (v v^{-1}) for the top 2 m of soil (Zhang et al., 2010). At the beginning of this experiment, soil nutrient contents for the top 0-20 cm were sampled and measured using the conventional methods (Chen et al., 2020). Organic matter content was 20 g kg^{-1}, total nitrogen was 1.11 g kg^{-1}, and the available N, P, K were 80, 21, 120 mg kg^{-1}, respectively.

2.2.2 Experimental design and field management

This study comprised two parts. The first part was to double crop maize in a single year (2M), and the second part was to grow winter wheat (WW) and summer maize (SM) following the normal annual double-cropping system (WW+SM) in the NCP. For the 2M system, two cultivation systems were used. One system was to use white plastic film mulch in the spring to increase the soil temperature for earlier seeding in order to prolong the duration of the growing season (2M+PM), and the other system did not use plastic film mulch (2M). The traditional winter wheat and maize system (WW+SM) was for grain production. Fig. 2.1 illustrates the arrangements of the crops under the different treatments. All the treatments were irrigated based on soil water monitoring. When the average soil water content of the top 1 m soil profile was below 65% of field capacity, irrigation of 60-80 mm was applied. The soil water condition was maintained as adequate for crop growth. The irrigation timing and amounts are listed in Table 2.1.

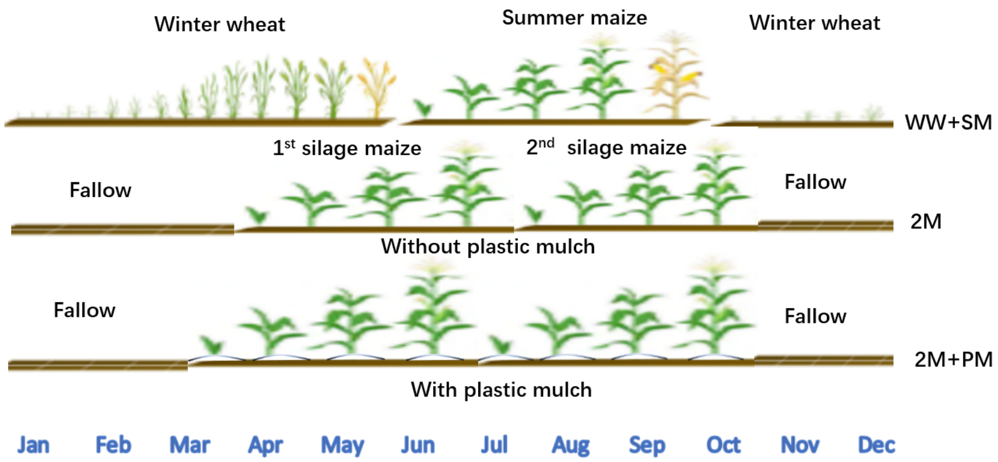


Fig. 2.1 Arrangement of the crops under the three cropping systems (traditional annual double cropping of winter wheat + summer maize, WW+SM; double silage maize with plastic film mulch, 2M+PM; and without mulch, 2M).

Table 2.1 Seasonal rainfall and irrigation amounts for the three cropping systems during 2015-2018.

Cropping system	**Crops**	**2015-2016**		**2016-2017**		**2017-2018**	
		Seasonal rainfall	Irrigation	Seasonal rainfall	Irrigation	Seasonal rainfall	Irrigation
		mm					
Winter wheat and summer maize (WW+SM)	Winter wheat	123.0	270	109.4	260	133.0	240
	Summer maize	374.8	174	239.0	135	207.4	140
Two silage maize with plastic mulch (2M+PM)	1st season maize	134.2	179	119.0	165	131.0	200
	2nd season maize	328.8	119	260.6	105	193.6	130
Two silage maize without plastic mulch (2M)	1st season maize	290.2	106	155.6	156	135.3	229
	2nd season maize	138.2	126	198.4	130	177.2	144

In this study, a field was divided into three blocks with an area of 8×40 m^2 for each block, and the three cropping systems were separately arranged in the three adjacent blocks. This arrangement was used for the convenience in utilization of the machines in cultivation and management of the land, due to facts that the three cropping systems had different cultivation, sowing, and harvest practices and timing. The land used for the study was uniform with only small variations in soil texture and nutrient contents. Each block was further divided into four plots. There was a 2 m buffer zone surrounding each block to reduce the border effects. For the WW+SM system, winter wheat was usually planted around the 10th of October and harvested around the 10th of June of the next year. Before planting winter wheat, the land was cultivated, and base fertilizers were incorporated into the top 20 cm soil layer. The base fertilizer was a composite fertilizer with N-P_2O_5-K_2O at 19%-21%-5%, and the amount applied was 750 kg ha^{-1}. At the jointing stage of winter wheat, urea at 225 kg ha^{-1} (N at 46%) was applied with an irrigation. The cultivar for winter wheat was Shixin633 (Breeder: Shijiazhuang Academy of Agricultural Science, China), a common local cultivar. Summer maize was sown immediately after winter wheat harvesting, and the straw from the winter wheat was left on top of the soil surface as a mulch for the maize. When the summer maize was planted, chemical fertilizer was applied at 750 kg ha^{-1} using a composite fertilizer (N-P_2O_5-K_2O at 25%-8%-12%). The harvesting of summer maize occurred at the end of September. The variety used was Zhendan958 (Breeder: Henan Academy of Agricultural Science, China), a widely used maize cultivar in the NCP.

For the double silage maize planting, maize was sown at the end of March with the plastic film mulch (2M+PM) and around the middle of April without the plastic film mulch (2M), based on the soil temperature. The silage maize was harvested at grain filling stage in early July for 2M+PM and approximately 10 days later for 2M. The second-season silage maize was immediately sown after the harvest of the first-season maize and was harvested at the end of October when the air temperature dropped to the point at which the crop stopped growing (daily maximum temperature below 18 ^{o}C). 2M+PM was planted earlier and harvested earlier in the first season. In the second season, 2M+PM was planted earlier but harvested at the same time as the treatment of 2M. The specific planting and harvesting dates are shown in Fig. 1. The planting density was 9×10^4 plants ha^{-1}. The variety for the first and second silage maize was the same as the summer maize. Plants were seeded in alternating wide-narrow row patterns (alternating row spaces of 80 cm and 40 cm, respectively). Pre-sowing irrigation was applied to ensure the normal emergence of the maize. At each irrigation application, water was applied to each plot by surface irrigation using a low-pressure tube with a flow meter to record the amount of irrigation. A composite fertilizer was applied to maize at sowing in the amount of 750 kg ha^{-1} (N-P_2O_5-K_2O at 25%-8%-12%). For the treatment with plastic mulch, after the land was prepared for sowing, the soil was covered with white plastic film with a thickness of 0.01 mm. Manual sowing was performed by drilling holes in the plastic film. There was a non-mulched zone of approximately 40 cm every two rows to allow for irrigation application. All the crops were managed such that they were free of weeds, pests and disease effects.

2.2.3 Meteorological data

Daily weather data were obtained from a meteorological station located 50 m away from the experimental site. The daily weather factors recorded were maximum temperature (T_{max},°C), minimum temperature (T_{min},°C), average temperature (T,°C), sunshine duration (hr·d^{-1}), rainfall (mm), wind speed (m·s^{-1}) and relative humidity (RH,%).

2.2.4 Soil water contents

A 5 cm diameter aluminium access tube was installed in the centre of each plot, and the soil volumetric water content was monitored every 7 to 10 days in 20 cm increments to a depth of 2 m by a neutron meter (503 DR, CPN International Inc., USA). The soil moisture in the top 20 cm soil layer was regularly sampled with a soil auger.

2.2.5 Fresh and dry matter and crude protein contents for maize silage

Eight maize plants were randomly selected from each plot to measure their fresh weight and dry weight, when maize was harvested for silage at the grain-filling stage. The fresh and dry weights were separately measured for leaves, stems and ears. The N contents of the leaves, stalk and ears were measured using an Elementar N analyzer (vario MACRO cube, Germany).

The content of crude protein (CP) was calculated by multiplying the N content by a constant of 6.25. The planting density was counted and recorded. The fresh and dry biomass production was calculated based on the density and the average yield per plant.

2.2.6 Grain yield of the winter wheat and summer maize

Winter wheat and summer maize were harvested manually at maturity in approximately 10 m^2 of each plot. For winter wheat, all the plants in the harvesting area were cut and immediately sent through a thresher to separate grains from straw. For summer maize, all the ears were collected in the harvesting area, air-dried and threshed to separate grain. All the grains were further air-dried to a constant weight (water contents at 130 g kg^{-1}) for recording the dry grain weight. Before harvesting summer maize, four plants from each plot were randomly selected and cut at the soil surface for measuring the total dry biomass and grain yield. This was done to calculate the harvest index (HI).

2.2.7 Evapotranspiration and water use efficiency

Seasonal evapotranspiration (ET) was calculated according to the following water balance equation:

$$ET = P + I + SWD - R - D + CR \tag{1}$$

where ET is the evapotranspiration (mm) during the growing season, P is the total seasonal precipitation (mm), I is the total seasonal irrigation (mm), SWD is the soil water depletion (mm) (defined as the total soil water contents at sowing subtracting that at harvest for the 2 m soil profile), R is the runoff (mm), D is the drainage from the root zone (mm) and CR is the capillary rise to the root zone (mm). D is calculated based on the relationship of soil moisture with unsaturated hydraulic conductance at the bottom of the root zone profile (Zhang et al., 2008; Liu et al., 2013). The CR was considered to be zero because the groundwater table was 40 m below the soil surface; runoff is also negligible because of the small amount of rainfall and the large water holding capacity of the soil. Each plot also had ridges to prevent the runoff of rainfall or irrigation.

Water use efficiency (WUE) was defined as dry matter or grain yield per unit of water consumed, e.g., WUE=Y/ET, where Y is the grain weight or biomass weight (kg ha^{-1}), and ET is the seasonal evapotranspiration calculated from Eq (1). In this study, the unit of kg m^{-3} for WUE was used.

2.2.8 Silage maize water footprint

Water footprint (WF) is a measure of the direct and indirect water use of a process or a product. Three parts of WF were considered in this study; green water footprint ($WF_{proc,\ green}$, m^3 kg^{-1}) refers to the precipitation consumed during the crop growth season, blue water footprint ($WF_{proc,\ blue}$, m^3 kg^{-1}) refers to the water use from irrigation, and grey water footprint ($WF_{proc,\ grey}$, m^3 kg^{-1}) is the indirect water use associated with the process of assimilating the load of pollutants (Hoekstra & Chapagain, 2008; Zarate, 2010). The calculation of the three components of WF were as follows (Hoekstra et al., 2011; Wang et al., 2014):

$$WFproc, green = \frac{CWU\ green}{B}\left[\frac{\text{volume}}{\text{mass}}\right] \tag{2}$$

$$WFproc, blue = \frac{CWU\ blue + ICW}{B}\left[\frac{\text{volume}}{\text{mass}}\right] \tag{3}$$

$$CWUgreen = 10 \times \sum_{d=1}^{lgp} ETgreen\left[\frac{\text{volume}}{\text{area}}\right] \tag{4}$$

$$CWUblue = 10 \times \sum_{d=1}^{lgp} ETblue\left[\frac{\text{volume}}{\text{area}}\right] \tag{5}$$

$$ET\ green = min(ET, \qquad Peff) \tag{6}$$

$$ET\ blue = \max(0, \qquad ET - Peff) \tag{7}$$

$CWUgreen$ and $CWUblue$ are the crop water used from precipitation and irrigation (m^3 ha^{-1}), respectively; ET_{green} and ET_{blue} are evapotranspiration from rainfall and irrigation (mm), respectively; P_{eff} is the effective precipitation (mm) during the crop growing season; and B is the crop biomass (kg ha^{-1}). ICW is the consumptive water use in producing the farm inputs, which included the water use in producing fertilizers, seeds, pesticides, fuel and electricity (m^3 ha^{-1}). ICW were calculated using the Chinese Reference Life Cycle Database and the Ecoinvent database in this study (Wang et al., 2014).

The $WF_{proc,\ grey}$ is calculated as the water used to assimilate the load of pollutants (Hoekstra & Chapagain., 2008; Zarate et al., 2010). In the present study, N and K_2O leaching were of particular interest. N and K_2O leaching were assumed to be 4.35% and 18%, respectively, based on published estimates for farming systems in China (Hoekstra & Chapagain, 2008). Due to the lower mobility of soil phosphorus, P_2O_5 leaching was not considered (Kochian et al., 2012). The $WF_{proc,\ grey}$ was estimated as follows:

$$WF\ proc, grey = \frac{{}^{a \times AR}\!/_{Cmax - Cnat}}{B} \left[\frac{\text{volume}}{\text{mass}}\right] \tag{8}$$

where α is the leaching runoff fraction (43.5 g kg^{-1} for N and 180 g kg^{-1} for K_2O); AR is the rate of chemical application to the field per hectare (kg ha^{-1}); C_{max} is the maximum acceptable concentration (10 mg L^{-1} for N and 12 mg L^{-1} for K_2O); and C_{nat} is the concentration in natural water, assumed to be 0 mg L^{-1}.

2.2.9 Cropping system net income

Net income is defined as the difference between output value and input costs. The output was the yield either in biomass or grain, multiplied by the market price per unit of production. In this study, wheat grain had a market value of 2.2 yuan kg^{-1} (7 yuan=1 USA$), and the market value of maize grain was 1.6 yuan kg^{-1}. The market value of maize silage was 180 yuan t^{-1} (dry matter content being converted to 320 g kg^{-1}). The partial inputs included the costs of tillage, fertilizer, irrigation, seeds, pesticides, plastic film, sowing, harvesting and labour input. The detailed information on those inputs was provided during the calculation of the net income.

2.2.10 Statistical analysis

Means and standard deviations for each of the selected parameters were calculated across the four plots for each cropping system and season. Means of fresh weight, dry weight, water contents in fresh weight, CP content, ET and WUE were compared using *t*-tests of two independent samples between 2M and 2M+PM for the same season at $\alpha = 0.05$ (Clewer and Scarisbrick, 2001). The mean values of annual ET during the three years for the three cropping systems were calculated. The annual net incomes were calculated across four plots for each of the three cropping systems (WW+SM, 2M+PM and 2M) and two-way comparisons were made using *t*-tests. All the calculations and comparisons were conducted using the EXCEL software.

2.3 Results

2.3.1 Temperature conditions for the different planting systems

Fig. 2.2 indicates that from October to May, the temperature (T) conditions were suitable for growing winter wheat, and from June to September the temperatures were suitable for maize. The average growing degree days (GDD) (10^oC < daily average T < 30^oC) for grain maize in this region is around 2270^oC d. This level does not meet the requirements for growing double grain maize crops, since at least 1600^oC d is required for one season of early maturity maize for grain. However, silage maize does not require as much heat, and therefore annual double silage maize might be possible. Fig. 2.2 also indicates that there are large variations in seasonal temperature, which would influence silage maize production. For example, in 2018, the temperature changed dramatically during the maize season, which had a negative influence on the production of silage maize in this year.

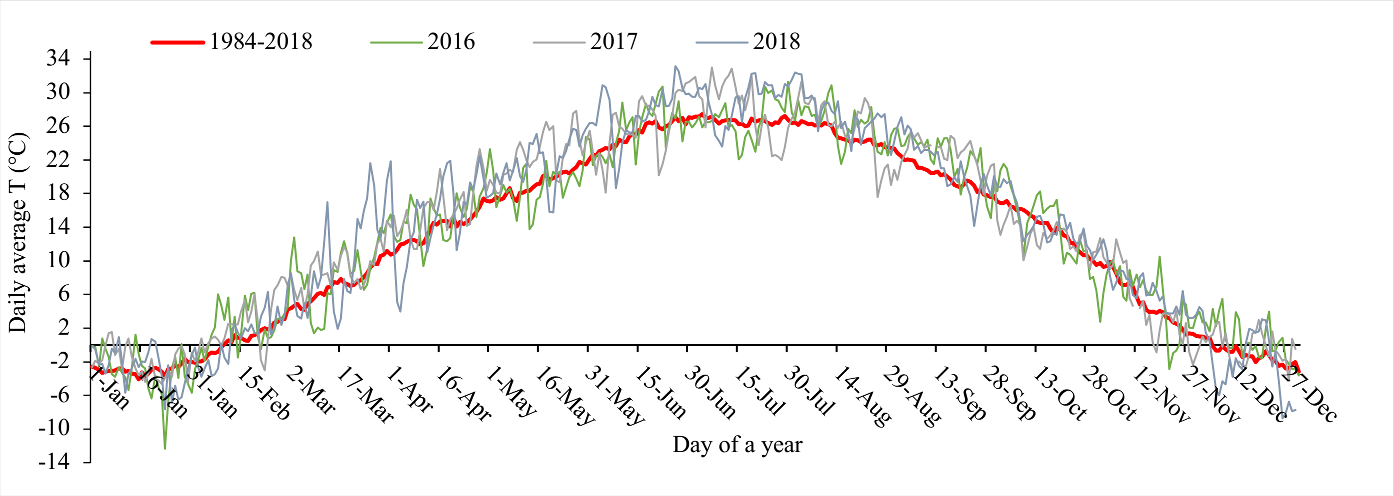


Fig. 2.2 The average daily temperature from 1984 to 2018 and the daily temperature in 2016, 2017 and 2018 at the experimental site.

The GDD for the plastic-mulched silage maize and for the non-mulched treatment during the three seasons were listed in Table 2.2. Though the GDD for silage maize varied over the three years, it was clear that the GDD for the silage maize with plastic film mulch was higher than that for the silage maize without mulch for the second season. These results were attributed to earlier planting for the 2M+PM treatment. The GDD of 2M+PM was 3.5, 4.5 and 0.7%, respectively, higher than that of 2M in the three years, which indicates that silage maize mulched with plastic film could prolong the growing season by sowing earlier and increasing the available heat resources.

Table 2.2 Growing degree days (10 °C <daily average temperature<30 °C) for the double silage maize grown from 2016-2018 under mulch and without mulch.

Treatments	2016		2017		2018	
	1st season	2nd season	1st season	2nd season	1st season	2nd season
	°C d					
With plastic film mulch	1108	1346	1326	1181	1034	1401

Without plastic film mulch	1189	1182	1424	975	1192	1226

2.3.2 Dry matter production and feed quality of the double maize silage production

The maturity at harvesting influences the nutritive value of maize silage (Khan et al., 2014). Earlier harvesting results in less dry matter (DM) that contains lower starch concentration and a lower starch/neutral detergent fibre ratio. It is generally recommended that the optimum harvesting time for silage maize is when the DM content is approximately 300-380 g kg^{-1}. Table 3 lists the fresh weight (FW), DM and DM content of the silage for the three years. Due to the limitations of the growth season, the DM content in most of the seasons did not reach the optimum DM content. The difference in dry matter production between 2M and 2M+PM was also affected by the weather conditions. The average DM production under plastic mulch was 22.37 t ha^{-1} in the 1st season and 17.87 t ha^{-1} in the 2nd season. The average DM production was 17.7 and 9.93 t ha^{-1}, respectively, without the plastic film mulch. The dry matter production was increased by 16% and 31% during the 1st and 2nd seasons, respectively, through plastic film mulching. The average DM contents were 25% for the 1st season and 30% for the 2nd season with mulch, while the values were 23% and 27%, respectively, for the silage maize without mulch. The results indicated that the 2nd season silage maize had a higher DM content than the 1st season, while the latter produced more DM than the former. The total annual DM production averaged over the three years was 40.2 t ha^{-1} under mulch and 27.6 t ha^{-1} without mulch. Table 2.3 also shows the variation in the content of CP in the silage maize. The treatment without mulch had higher CP than that with mulch. Mulch increased the DM production but reduced the CP content, possibly due to the dilution effect in nutrient contents in dry matter production.

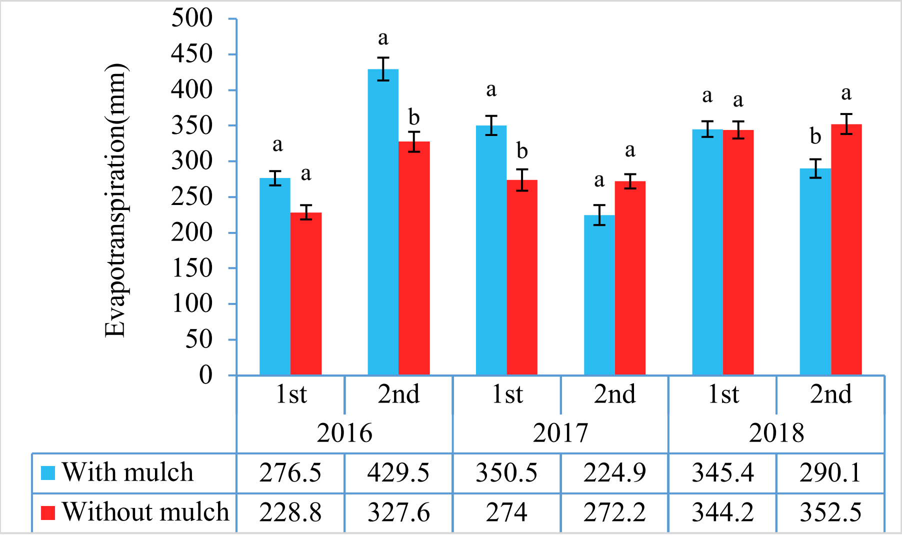
Table 2.3 Fresh weight, dry matter, dry matter content and crude protein contents of double silage maize under plastic mulch (2M+PM) and without mulch (2M).

Items	Units	Season	Treatments	Year		
				2016	2017	2018
Fresh weight	t ha^{-1}	1st	2M+PM	78.6±5.1 a	80.5±3.2 a	113.7±3.1a
			2M	83.3±6.4 a	73.6±4.6 a	73.4±4.6 b
		2nd	2M+PM	60.9±2.0 a	35.0±3.3 a	77.0±4.0 a
			2M	62.5±3.4 a	18.5±3.1 b	38.9±4.4 b
Dry weight		1st	2M+PM	17.2±1.5 b	22.9±0.9 a	27.0±1.5 a
			2M	19.6±1.6 a	17.3±0.9 b	16.2±1.3 b
		2nd	2M+PM	18.7±0.8 a	9.1±0.8 a	25.8±1.2 a
			2M	14.3±1.7 b	5.1±0.5 b	10.4±1.4 b
Dry matter content	g kg^{-1}	1st	2M+PM	218±13 b	284±3 a	237±9 a
			2M	235±4 a	235±6 b	222±13 a
		2nd	2M+PM	307±14 a	260±14 a	335±12 a
			2M	229±12 b	303±16 a	266±11 b
Crude protein content		1st	2M+PM	780±3 a	87±3 a	79±2 a
			2M	82±2 a	113±2 b	102±4 b
		2nd	2M+PM	81±3 a	98±1 a	78±1 a
			2M	96±4 a	103±2 a	104±2 b

Note: data following ± are the standard deviation of four replicates. The different letter following each value indicated that the difference between mulch and without mulch was significant at 0.05% for the same year and the same season.

2.3.3 Seasonal evapotranspiration and water use efficiency in the double silage maize production

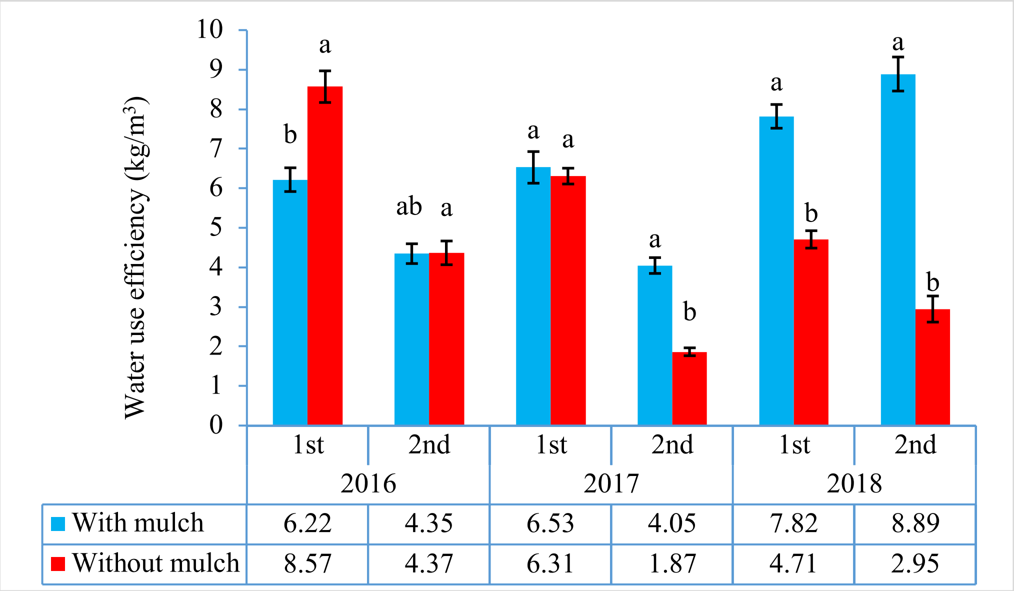
Figure. 2.3 shows the seasonal evapotranspiration (ET) for 2M+PM and 2M during 2016-2018. The water consumption of the silage maize under mulch was approximately 324 mm in the first season and 315 mm in the second season. The water use was similar for the 1st and 2nd seasons, with an annual ET of approximately 639 mm. The water consumption of the silage maize without mulch was 282 mm in the 1st season and 317 mm in the 2nd season. The maize in the first season used less water than maize in the second season. The total annual water use was approximately 600 mm. Due to the lower biomass production of the silage maize without mulch, its water use was lower than the silage maize with plastic film mulch.



	2016		2017		2018	
	1st	2nd	1st	2nd	1st	2nd
🟦 With mulch	276.5	429.5	350.5	224.9	345.4	290.1
🟥 Without mulch	228.8	327.6	274	272.2	344.2	352.5

Fig. 2.3 Seasonal evapotranspiration from silage maize with and without plastic film mulch under sufficient water supply conditions during 2016-2018 (1st and 2nd indicate the first and the second season; bars represent the standard deviation of four replications; the different letter under the same season in the same year indicating significant difference at *P*<0.05).

There was a significant difference (*P*<0.05) in the WUE of the dry matter production between the mulched and non-mulched treatments (Fig.2.4). The average WUE for the 1st season silage maize was 6.86 and 5.76 kg m^{-3} for the mulched and non-mulched treatments, respectively. The WUE for the second season was 6.53 and 3.06 kg m^{-3}, respectively. The plastic film mulch mainly improved the WUE compared with that without mulch in the 2nd season. The annual average WUE was 6.31 kg m^{-3} for the mulched treatment and 4.80 kg m^{-3} for the non-mulched treatment. Plastic film mulch improved WUE by 31.6% annually compared to without mulch.



	2016		2017		2018	
	1st	2nd	1st	2nd	1st	2nd
🟦 With mulch	6.22	4.35	6.53	4.05	7.82	8.89
🟥 Without mulch	8.57	4.37	6.31	1.87	4.71	2.95

Fig. 2.4 Water use efficiency for the dry matter production in silage maize with and without plastic film mulch under sufficient water supply conditions during 2016-2018 (1st and 2nd indicate the first and the second season; bars represent the standard deviation of four replications; the different letter under the same season in the same year indicating significant difference at $P<0.05$).

2.3.4 The water footprint of the double silage maize production

Fig. 2.5 shows the water footprint of silage in dry matter production during the three years. WF_{green} stands for the water used from rainfall. The green water footprint in the second season of silage maize was higher than in the first season, which was due to the higher rainfall in the second season. WF_{blue} represents the water consumed from irrigation and the water consumption included in the materials used for production. The WF_{blue} values of the silage maize with plastic film mulch in both the first and second seasons was 0.09 m^3 kg^{-1}, while the values for silage maize without mulch were 0.06 and 0.18 m^3 kg^{-1}, respectively. The silage maize without mulch in the second season had a higher WF_{blue} than with mulch, which was caused by the lower amount of dry matter production and the higher consumption of irrigation water. WF_{grey} is the amount of water required to dilute the fertilizer pollutants. The average WF_{grey} of silage maize with mulch were 0.08 and 0.13 m^3 kg^{-1} in the first and the second season, respectively, while the WF_{grey} without mulch were 6% and 38% higher, respectively, than that of mulched silage maize in the first and second season. As a result, the average total water footprint of the silage maize without mulch was 0.22 in the first season and 0.58 m^3 kg^{-1} in the second season; and silage maize with mulch was 0.23 and 0.38 m^3 kg^{-1}, respectively. Although the inputs for the mulched silage maize were greater than those without mulch, the increased dry matter production of the former offset the effects of this increase in input and resulted in a lower water footprint than the latter.

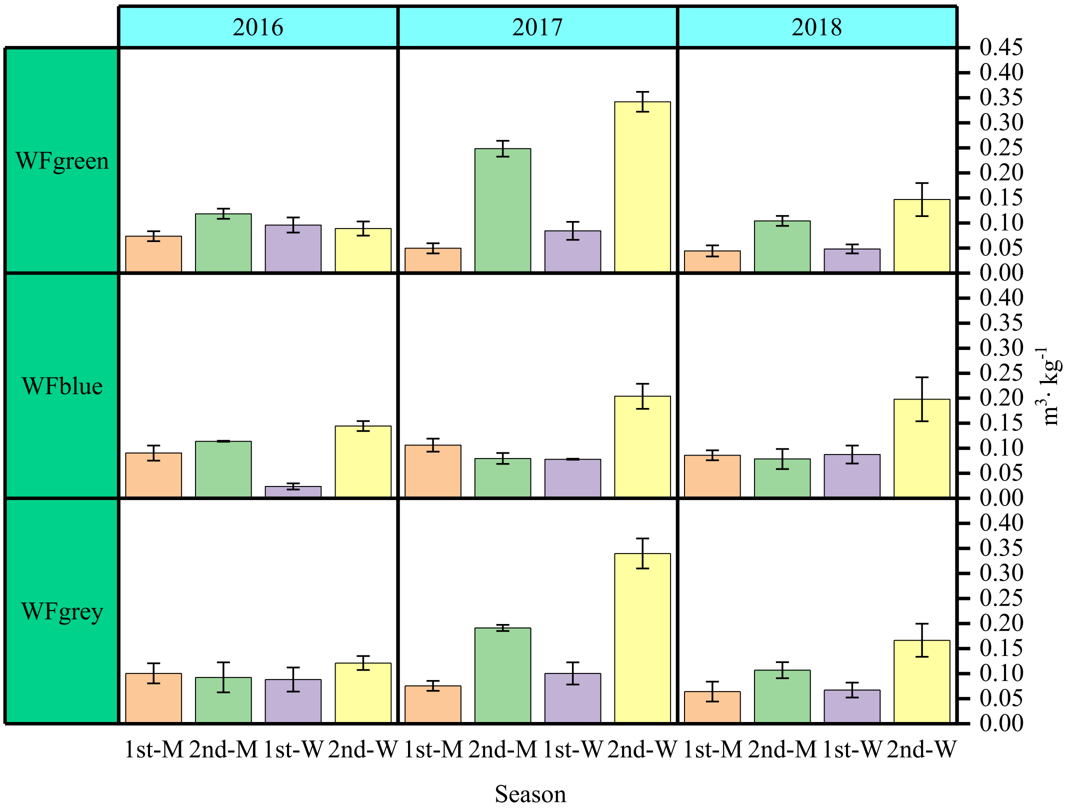


Fig. 2.5 The water footprint (WF) of silage maize with mulch and without mulch from 2016 to 2018 (M stands for silage maize mulched with plastic film, and W stands for silage maize without plastic film mulch; 1st indicates the first season, and 2nd indicates the second season; WF_{green} for green water footprint, WF_{blue} for blue water footprint and WF_{grey} for grey water footprint; bars representing the standard deviation of four plots).

2.3.5 Comparing the double silage production with the winter wheat-maize cropping system

The average grain yield during 2015-2018 was 7704 kg ha^{-1} for winter wheat and 8589 kg ha^{-1} for summer maize in the traditional annual double-cropping system (WW+SM). The average seasonal water use (ET) was 462 mm for winter wheat and 338 mm for summer maize under sufficient water supply conditions. The WUE of grain production was 1.70 and 2.57 kg m^{-3} for winter wheat and maize, respectively. The annual total water use for WW+SM under sufficient water supply conditions was approximately 799 mm, which was 160 and 190 mm greater than that of the double silage maize with mulch and without mulch, respectively. Growing double silage maize used less water than the local traditional cropping system. In terms of WUE in dry matter production, the summer maize in the WW+SM system had a value of 4.75 kg m^{-3}, similar to the value of 4.80 kg m^{-3} for the silage maize without mulch.

Table 2.4 lists the gross income and costs of irrigation, fertilizer, seed and other inputs for the three cropping systems from 2015-2018. There were large seasonal variations in the net income for the two-silage maize cropping systems, due to the large seasonal variations in dry matter production. Averaged across the three seasons, the traditional winter wheat and summer maize cropping system produced the highest net income, mainly due to its high gross income. The average annual net income was 7056 yuan ha^{-1} for this cropping system. The average annual net income was 6483 yuan ha^{-1} for the double silage maize with plastic mulch and 3003 yuan ha^{-1} for the same system without mulch. The net income from silage maize mulched with plastic film was much higher than silage maize without mulch. Thus, growing double silage maize would not increase the net income of the local farmers at current prices. However, from the perspective of groundwater conservation, the silage maize with mulch used 160 mm less water than the traditional winter wheat and summer maize cropping system. From the view of the net economic output per unit water consumption, the two-silage maize system produced

1.01 yuan m^{-3} water, and the traditional winter wheat and maize system had the value of 0.88 yuan m^{-3} water. Therefore, growing double silage maize increased the economic returns per unit water use. Due to the limitations of the heat conditions for the silage maize without mulch, the low production reduced the net economic output per unit of water consumed.

Table 2.4 Comparing the annual inputs, outputs and net incomes for double silage maize with plastic film mulch (2M+PM), without plastic film mulch (2M), and the traditional winter wheat and summer maize system (WW+SM)

Years	Treatments	Gross income	Irrigation cost	Fertilizer cost	Seed cost	Other cost*^{a}	Total cost	Net income*^{b}
		Yuan ha^{-1}						
2015-2016	2M+PM	20194	894	3900	750	8125	16294	3900 c
	2M	19069	696	3900	750	5575	12496	6573 b
	WW+SM	32592	1332	3930	1650	11418	23748	8844 a
2016-2017	2M+PM	18000	810	3900	525	8125	15985	2015 b
	2M	12600	858	3900	525	5575	12433	167 c
	WW+SM	32295	1185	3930	1650	11418	23601	8694 a
2017-2018	2M+PM	29700	990	3900	525	8125	16165	13535 a
	2M	14963	1119	3900	525	5575	12694	2269 c
	WW+SM	27187	1140	3930	1650	11418	23556	3631 b

*^{a} Other costs including the tillage, sowing, harvesting, labor and weed, pest and disease control.

*^{b} Values followed by different letters in the same year being different at *P*<0.05. (Electricity cost for irrigation was estimated at 0.3 yuan m^{-3}; compound fertilizer at 3 yuan kg^{-1}, urea at 2 yuan kg^{-1}; maize straw chopping and incorporation at 1350 yuan ha^{-1}; planting cost at 375 yuan ha^{-1} for each season; harvesting cost at 600 yuan ha^{-1} for each season; pesticide and herbicide cost at 600 yuan ha^{-1} annually; plastic mulch cost at 300 yuan ha^{-1} annually; annual labor input for winter wheat and summer maize cropping system was estimated at 60 days ha^{-1}, at 40 days ha^{-1} for silage maize without plastic mulch, at 55 days ha^{-1} for silage maize with plastic film, and the local price for labor cost at 100 Yuan day^{-1}. 1 USA$=7 Yuan).

2.4 Discussion

2.4.1 Feasibility of planting double silage maize

When growing different crops and implementing different crop rotation systems in a region, the heat requirements of the crops are critical factors to be considered. Temperature is the key factor in crop growth, development and yield (Fang et al., 2015). Maize growth is greatly affected by the spatial-temporal variation of climatic variables, especially solar radiation, temperature and rainfall (Wu et al., 2008). The average GDD was approximately 2270°C (>10°C) for maize; while a single-season maize needs approximately 1600°C GDD on the NCP

(Chen et al., 2011). Generally, the annual GDD was greater than the requirement of one-season maize but did not meet the demands of double grain maize production. Silage maize requires less heat than grain maize production. The results from this study indicated that growing double silage maize was possible.

The results from this study also indicated that, due to the limited growing conditions for the double silage maize, the DM content at harvesting did not reach the optimum level for high quality maize silage. Using plastic mulch to increase the soil temperature in the spring to sow the maize earlier extended the growing duration of the silage maize. The extended growth period not only improved the dry matter yield and water productivity but also reduced the water contents of the maize silage at harvesting, which resulted silage quality improvements. The dry matter was increased by 16% and 31% across the three years of the study in the first and second season, respectively, by using plastic mulch. The water contents in the biomass at harvesting were reduced by 6.8% and 13.0% in the two seasons, respectively, with mulch compared to that without mulch. However, even with the reduced water contents in the silage under mulch, the water contents in the silage was still greater than the requirement for high quality silage.

To further improve maize silage quality, the growth period of the first season silage maize could be extended based on weather conditions (Chen, et al., 2011), and the second-season silage maize harvest could be delayed. Considering that climate change may cause elevated air temperatures, the harvesting time of the second season maize could possibly be extended to reduce the silage water contents in the future (Yan et al., 2020). The cultivar used for the double crop maize in this study was the same cultivar as the summer maize used in the conventional wheat-maize system. Selecting a shorter-season cultivar might help to reduce the heat demands in producing silage, and thereby reduce water contents in fresh weights at harvesting. Further studies might be required to select short season maize varieties and examine the impacts of sowing and harvesting time on the effects of dry matter production and quality of silage maize to obtain optimal cultivation practices. To remedy the issue of higher water content in the silage, the second-season silage maize could also possibly be combined with summer maize to obtain the optimum water content level for the feed. Another issue that should be taken into account for the 2M+PM system is that plastic film would cause environmental pollution. Carefully removing the film after use or using plastic film that is degradable could possibly help reduce these concerns.

2.4.2 The water footprint of the double maize silage

With the intensification of global water shortages, mitigation strategies and conscious utilization of limited water resources are becoming more important (Lovarelli et al., 2016). The concept of a water footprint was developed for the purposes of better understanding production activities and the growing pressures on water that are directly and indirectly embedded in products and services (Mekonnen & Hoekstra, 2010). Water footprint can be used as an indicator to compare the influence of a product on the water environment. Products with lower WF are preferred. Chapagain and Hoekstra (2004) indicated that the global average WF was 0.9, 1.3 and 3.0 m^3 kg^{-1} for maize, wheat and rice, respectively. Other studies also confirmed that maize usually had the lowest WF among the three crops (Mekonnen & Hoekstra, 2010; Hoekstra et al., 2011). However, the values for maize were usually calculated for the grain production. If the whole biomass of the maize was considered, the WF would be reduced to approximately 0.4 to 0.6 m^3 kg^{-1} dry matter. The results of this study indicated that the average total WF of the maize silage mulched with plastic mulch was 0.23 and 0.38 m^3 kg^{-1} in the first season and second season, respectively, and the average total WF of the maize silage without plastic mulch was 0.22 and 0.58 m^3 kg^{-1} in the first season and second season, respectively. The low WF in silage maize production would provide a good source of feed for the animal industry and reduced the amount of water required for animal products.

Lu et al. (2018) have shown that feed components affect the water consumption and WF of milk production for a collective feedlot dairy system in northern China. Water consumption in feed production accounted for 88.6% of the total water use for milk production in the feedlot dairy system, implying that the largest contributor to water use was from the feed. The low WF of silage maize provides an opportunity to reduce the WF of milk. Feeds composed entirely of silage maize usually had a lower water consumption than other feeds (Wernet et al., 2016). The results of this study showed that the WF of silage maize could be further reduced by using plastic film mulch. Lu et al. (2018) have reported that in the feedlot dairy system in China, Chinese wildrye hay had a WF of 1.97 m^3 kg^{-1} dry matter, alfalfa hay had a WF of 1.67 m^3 kg^{-1} dry matter, and oat hay had a WF of 1.26 m^3 kg^{-1} dry matter. The WF of maize silage was less than 0.6 m^3 kg^{-1} dry matter based on the results from this study. Rationally increasing the silage maize in feeds to replace other roughage has the potential to reduce the WF of milk production.

2.4.3 Water use and economic returns of double silage maize versus the traditional cropping system

The results of this study indicated that the total annual water use for the double silage maize cropping system was approximately 640 mm, which was approximately 160 mm less than the traditional annual double-cropping system of winter wheat and summer maize. In the northern part of the NCP, where overdrawn underground water is a serious issue, the reduction in seasonal crop water use would benefit groundwater conservation. Many studies have been conducted on the NCP to address issues related to reducing groundwater use while maintaining land productivity for food security in China. Measures such as optimizing irrigation scheduling and adjusting the cropping systems have been proposed (Kang et al., 2002; Zhang et al., 2008; Zhang et al., 2013). Zhang et al. (2006) and Sun et al. (2014) proposed minimum irrigation and critical irrigation strategies for the winter wheat and maize cropping system. Their results show that, under a critical irrigation strategy, annual water use could be reduced by up to 150 mm. Under the minimum irrigation strategy, sustainable groundwater use could be achieved, but with up to 20% yield penalties. These and other studies (Ali et al., 2019; Araya et al., 2019; Farooq et al., 2019) have demonstrated that irrigation strategies can be effective options for resolving water shortage problems around the world, but it usually comes at the expense of yield.

Many studies have indicated that changing the cropping system to suit regional agricultural resources can improve land productivity and resource use efficiency (Xiao et al., 2017; Luo et al., 2018; Sun et al., 2019). Adjusting the cropping system from two crops per year to three crops every two years, or even to one crop per year, has been well studied in the NCP. Evaluations of the annual water consumption for those systems have been conducted (Sun et al., 2016; Xiao et al., 2017; Zhang et al., 2017; Zhao et al., 2018; Sun et al., 2019; Manevski et al., 2019). A winter wheat-summer maize-spring maize rotation (three crops every two years) and monoculture systems such as continuous spring maize (one crop per year) have been recommended as alternatives to replace the conventional system of winter wheat-summer maize rotation and reduce water use (Min et al., 2011).The introduction of the double silage maize growing system could be another option for cropping system adjustment on the NCP. The results from this study indicated that this system could achieve similar water-saving results as those of reduced cropping intensity or deficit irrigation scheduling.

The economic returns from the double silage maize cropping system were lower than those of the traditional winter wheat and maize double-cropping system under adequate water conditions. The silage maize system had similar water-saving effects as the critical irrigation strategy for the traditional cropping system. If the net economic returns per unit water consumption were compared for these two systems, economic returns were higher for the silage maize with plastic mulch than the traditional cropping system. Therefore, to increase silage production on the NCP, changing the traditional cropping system into double silage maize could increase the economic returns per unit of water consumption, and reduce the irrigation water use. The reduced water consumption for the double silage maize could aid in the conservation of the limited water resources in the NCP, and at the same time silage production requirements with less land use.

2.5 Conclusion

Changing the traditional annual winter wheat and summer maize cropping system into a double silage maize growing system on the North China Plain is an option for reducing irrigation water use while maintaining stable economic returns per unit of water consumption. The double silage maize system could reduce the amount of land used to produce roughage for the livestock industry. However, due to the heat resource limitations in the northern part of the NCP, the water content in the silage maize at harvesting was high, which reduced its quality. With the use of plastic mulch, biomass production and silage quality were simultaneously improved. Measures such as adjusting the sowing and harvesting times and using short-season silage maize cultivars might be options to improve the quality of the double silage maize.

Chapter 3

Spatial soil water and nutrient distribution affecting the water productivity of winter wheat

Abstract

Understanding the effects of the spatial distributions of soil water and nutrients on crop growth and yields is important for optimizing their management to achieve high water productivity (WP) under water deficit conditions. In this study, three spatial distributions of irrigation and nutrients were set up to winter wheat (*Triticum aestivum* L.) grown in 1 m deep tubes (19.2 cm inner diameter) in 2017/18 and 1.4 m deep tubes in 2018/19 buried in the field. The three treatments included: both irrigation water and nutrients applied to the surface soil layer (NS+WS); nutrients in the surface soil layer and irrigation applied to deep soil layer (60 cm below soil surface) (NS+WD); and nutrients and water both applied to the deep soil layer (ND+WD). For the three main treatments, each was supplied with two irrigation levels, i.e., deficit irrigation and full irrigation at 160 mm and 240 mm, respectively, divided into four applications at different growing stages of winter wheat. The results showed that the wheat grain yield and WP at grain yield level (WP_g) under NS+WD were the highest under deficit irrigation, with yields 7.7 % and 20.9% higher, and WP_g 9.2% and 20.4% higher than those of NS+WS and ND+WD averagely for the two seasons, respectively. The NS+WS treatment resulted in the highest grain yield and WP at both grain and biomass levels under full irrigation, with yields 17.7% and 31.8% higher, and WP_g 23.4% and 38.0% higher than those of NS+WD and ND+WD averagely for the two seasons, respectively. Treatments with nutrients located in deep soil layer produced the lowest yield and WP under both irrigation levels. Therefore, nutrients should be located in the top soil layer to increase their availability for crop use anytime during the growing season. Water applied in the deep soil layer could benefit grain production and WP_g under deficit irrigation, possibly related to the increase in the proportion of the water use during reproductive growing stage to achieve higher harvest index (HI). Under

full irrigation, water and nutrients matched in the topsoil layer, where the roots were mostly distributed, increased the availability of water and nutrients for root uptake and reduced the dry-matter allocation to root growth in acquiring resources, which resulted in a lower root/shoot ratio, higher biomass production and higher WP_b. The spatial soil water and nutrient distribution affected their availability for crop use during different growing stages, and influenced the allocation of dry matter to above and belowground parts. Optimizing the spatial distribution of nutrients and water based on water availability would benefit crop production and water productivity.

3.1 Introduction

It was projected that global wheat (*Triticum aestivum* L.) production will reach 758.3 million tons in 2020 and that China had the highest wheat production in 2019 (134 M tons) (FAO, 2020). The North China Plain (NCP) is one of the main wheat-production regions in China, producing two-thirds of the national total wheat output (Lu & Fan, 2013). As the global population grows and the diet structure changes, the requirement for wheat will increase. Increased crop production would require a continuous increase in irrigation water and fertilizer inputs (Gong et al., 2011; Li et al., 2018). With the increase in water shortages around the world, improving water productivity (WP) for wheat production will become more important in the future (Guo et al., 2010).

Winter wheat and summer maize form the traditional annual double cropping system in the NCP (Zhu et al., 1994), which requires considerable irrigation to meet the growth requirements of the two crops. Generally, approximately 200-450 mm of irrigation water is required as supplemental irrigation to guarantee high and stable grain yields of the two crops in this region, and irrigation water is mainly extracted from groundwater (Sun et al., 2006; Xiao et al., 2020; D. P. Xiao et al., 2017). The overdraft of underground water has caused a rapid decline in the groundwater table, and the average rate of decline of groundwater has been approximately one meter annually over the past 40 years (Van Oort et al., 2016).

To reduce water consumption from groundwater, regulated deficit irrigation (RDI) was proposed as an effective irrigation method and has been popularized in the NCP. RDI is an irrigation method that uses a lower water amount than the full amount required by crops (Kang et al., 2017). To adapt to growth requirements and climate changes, RDI with the optimal irrigation timing and amount is conducted to improve WP and grain yields. For example, critical irrigation (irrigation twice during the pre-sowing and jointing periods) and minimum irrigation (irrigation once during the pre-sowing period) both significantly reduced irrigation water utilization without equivalent penalization of the grain yield (Sun et al., 2015; Zhang et al., 2013). On the other hand, under deficit irrigation, winter wheat generally increased its root growth to allow better water extraction (Shepherd et al., 2002). However, nutrients are mainly concentrated in the surface soil layer. Because nutrient absorption is always accompanied by water absorption, root water uptake from different locations in the root zone profile might affect the uptake of soil nutrients. Spatial dislocation of the water and nutrient distribution along the root zone profile might affect the resource use efficiency (Yan et al., 2020). Supplying nutrients to the subsoil could increase the root growth in deep soil layers and improve crop drought resistance (Bardhan et al., 2021).

Soil water and nutrition acquisition is associated with root growth and distribution (Goss et al., 1993). The availability of soil water at different soil depths to crop water use will depend on the root growth to reach a certain soil depth (Zhang et al., 2004). Irrigation applied to deep soil layers will become more active at the late growing stages of a crop with the deepening of the root system. Different location of irrigation application will affect the distribution of crop water use during the growing season, and therefore, the biomass accumulation, harvest index and final grain production (Fang et al., 2021; Mehrabi et al., 2021; Zhang et al., 2013).

Additionally, root morphological characteristics affect nutrient uptake and water absorption (Ehdaie et al., 2010). A well-developed root system architecture (RSA) is essential for the final yields of crops (Liu et al., 2018; Proffitt et al., 1985). As one of the staple foods, wheat has a fibrous root system, and 60-70% of the roots are distributed in the 0-40 cm soil layer. Among the upper roots, lateral roots occupy a large proportion and contribute to the absorption of water and nutrients (Chen et al., 2020; Narayanan et al., 2014). Various water and fertilizer application regimes lead to different soil water contents, which affect the root distribution in the soil (Zhang et al., 2017). Under deficit irrigation, root growth is critical for crops to use soil water (Robertson et al., 1993). Wheat is vulnerable to severe drought and absorbs more water from the deep soil profile by developing deep root systems under conditions with less water (LUO et al., 2011; Xue et al., 2003; Yu et al., 2018). However, the large root system is also a source of assimilation consumption, which will reduce the shoot biomass and in turn reduce the grain yield.

In the NCP, the deficit irrigation schedule generally applies irrigation water during the vegetative growth stages (pre-heading) of winter wheat, and the soil water contents are usually quite low during reproductive stages (post-heading), which restricts water uptake from the surface soil. In this situation, when plants absorb water from the deep soil profile but nutrients are mainly distributed on the surface soil layers the dislocation of the two factors might affect the nutrient contents in the water flow at the xylem and further affect the photosynthetic rate at the leaf level (Abreu et al., 1993). However, because soil surface evaporation is closely linked to the soil moisture content, soil evaporation increases with the increasing in surface soil moisture content (Chen et al., 2018). Controlling the soil water content in surface soil is vital for reducing ineffective evaporation (Liu et al., 2015). Therefore, under drought and water-shortage conditions in the NCP, it is important to optimize the root uptake of water and nutrients by regulating the distribution of irrigation water in spatial distribution to achieve high water use efficiency (Yang et al., 2020).

Understanding the effects of different distributions of water, nutrients and roots on water productivity and assimilation allocation is critical for optimizing the water use by winter wheat in the NCP. The objectives of this study were to use tube experiments to assess the effects of different spatial distribution conditions of nutrients and irrigation water on the root distribution, above- and belowground dry matter production, yield and water productivity of winter wheat under deficit and full water supply conditions to provide references for better water management in the NCP.

3.2 Material and methods

3.2.1 Experimental design

This study was conducted during 2017-2019 over two growing seasons of winter wheat at the Luancheng Agro-Eco-Experimental station of the Chinese Academy of Sciences (37°53′ N, 114°40′ E; 50 m asl). Three spatial irrigation and fertilization treatments were implemented on winter wheat using column tubes. The tubes were made of PVC with a 19.2 cm inner diameter and 1 m depth in the 2017/18 season and a 1.4 m depth in the 2018/19 season. The soil was packed into a tube at a bulk density of 1.4 g cm^{-3}. The bottom of the PVC tube was sealed with thick water-proof plastic film. Soil packed inside the tube was obtained from the surrounding field. Soils from 0-20 cm soil layer and from that below 20 cm were separately collected and mixed for packing into the tubes. Soil nutrient contents and texture for the two sampling locations were listed in Table 3.1. The field capacity of the soil was 24% (g g^{-1}), and the initial soil water content was set at 22% (g g^{-1}) by adding water to mix with the soil before packing.

Table 3.1 Soil texture and nutrient contents for the soils obtained from the field to fill the tubes.

	Soil texture	Soil nutrient contents

Soil depth in the field	Sand	Silt	Clay	Organic matter	Total N	Ava. N (mg/kg)	Ava. P (mg/kg)	Ava. K (mg/kg)
0-20 cm	5.7%	80.8%	13.5%	2.04%	0.16%	86.5	32.4	130.7
Below 20 cm	8.5%	72.9%	18.6%	0.89%	0.07%	31.2	12.2	109.1

To create different spatial distributions of water and nutrients during the two growing seasons of winter wheat, the soils obtained from different depths in the field were packed into the different locations of the tubes (Fig. 3.1). During the growing seasons, irrigations and nutrients fertilizing were applied to different locations of the tubes. The different locations of the fertile soils, and the locations of nutrients and irrigation water applications created three scenarios: nutrients and water coupling on the top soil layers (NS+WS); nutrients and water mismatching with nutrients at top soil layer and water at deep soil layer (NS+WD); and nutrients and water coupling at deep soil layer (ND+WD). The detailed arrangements of the soils and irrigation water application were listed in Table 3.2 and shown in Fig. 3.1.

Table 3.2 The detailed information for the soil used for packing the tubes at different locations, and the locations of irrigation and N fertilizing application.

Treatments	Soil packing in the tubes	Irrigation location	N fertilizing location	Explanations
NS+WS	0-20 cm using top soil from the field, and below the 20 cm using deep soils from the field	Applied to the soil surface	Dissolving into the irrigation water and applied at soil surface	Representing nutrients and water matched in the topsoil layer.
NS+WD	0-20 cm using top soils from the field, and below the 20 cm using deep soils from the field	Applied to the 60 cm depth below soil surface	Buried into the soil surface	Representing nutrients and water mismatched, nutrients on top and water in deep soil layer.
ND+WD	50-70 cm using top soils from the field and other layers using the deep soils obtained from the field	Applied to the 60 cm depth below soil surface	Dissolving into the irrigation water and applied at 60 cm soil depth	Representing nutrients and water matched in the deep soil layer.

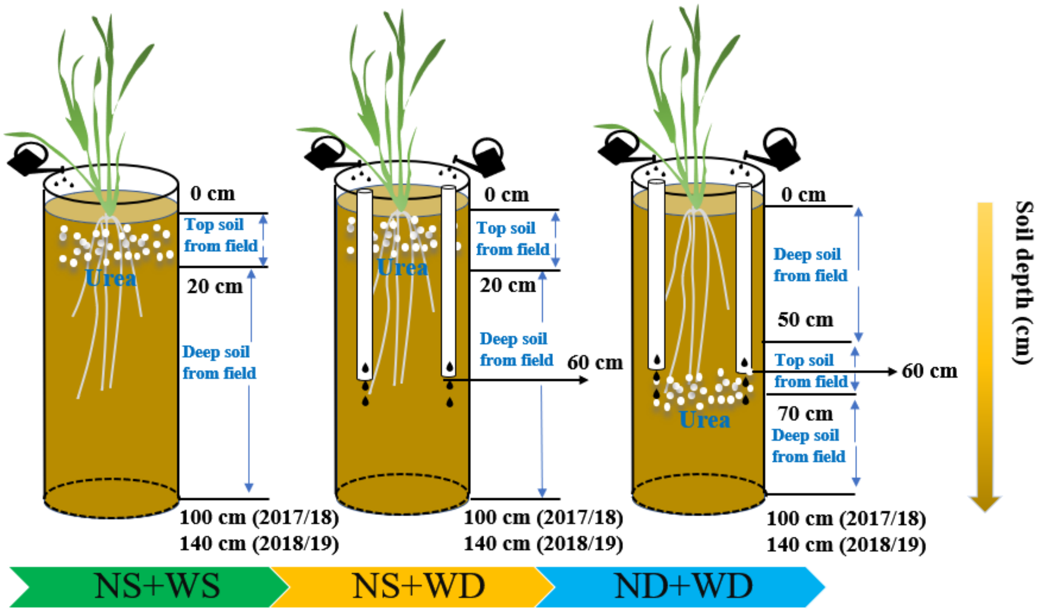


Fig. 3.1 The schematic diagram of PVC tubes showing the three spatial distributions of water and nutrients and the location of the irrigation and N application in the tubes.

For all the three treatments, two irrigation levels of 160 mm and 240 mm were divided into four equal amounts of water applied to winter wheat at the jointing, booting, anthesis and grain-filling stages. The tubes were buried inside the field with a movable roof to prevent rainfall. The two irrigation levels represented the general irrigation schedule of winter wheat in this region, i.e., seasonal rainfall plus 60 mm irrigation as deficit irrigation and seasonal rainfall plus 140 mm irrigation as relative adequate irrigation. nutrients fertilizer was applied at a rate of 4 g urea (46% N)/tube, also divided into four equal parts to be applied at the same time with the four irrigations. Two small tubes (inner diameter of 1 cm) buried into the PVC tubes when packing were used for applying the water and nutrients into the deep soil layers (Fig. 3.1).

All the treatments were conducted in 6 replicates. All tubes were arranged in a completely randomized design. The tubes were buried in the field and surrounded with field-grown winter wheat to avoid microclimate effects on crop growth. Rainfall was prevented using a movable shelter. After emergency, fine sand with depth of 1 cm was used to cover the soil surface of each tube to reduce soil evaporation. The seedlings were thinned to nine plants at the three-leaf stage, which was similar to the density under field conditions.

3.3 Measurements

3.3.1 Weather

Weather data were collected from the meteorological station 50 m away from the experimental site. The daily maximum temperature (° C), minimum temperature (° C), average temperature (° C), relative humidity (%), sunshine duration (h d^{-1}) and wind speed (m s^{-1}) were recorded. The daily reference evapotranspiration (ET_0) was calculated using the above factors by the Penman-Monteith equation, which represents grass water requirements as the reference crop (albedo=0.23, height=0.12 m, and surface resistance=70 s m^{-1}) (Allen et al., 1998).

3.3.2 Agronomic and physiological parameters

The plant height and number of stems in each column were measured at maturity. The leaf photosynthesis rate (*Pn*) were measured at the major growing stages (especially at the anthesis stage). Four flag leaves in each column were chosen to measure *Pn* and Tr using a CO_2 gas exchange system on sunny days from 11:00 to 13:00 local time (LI-6400, LI-COR Inc., USA). The canopy temperature (*Tc*) was measured by an infrared camera (IRC; NEC Avio Technologies Co., Tokyo, Japan) from anthesis to maturity for all tubes. The emissivity was set at 0.98, and the images were collected at noon (from 11:00 to 13:00) on sunny days. The viewing angle was set at 90° C relative to the canopy and shot vertically down.

3.3.3 Grain yield, yield components

At maturity, each column was harvested manually, plants were cut at ground level, and spike numbers were counted. Plants were air-dried to record the dry weight and thereafter threshed to separate grains and straw, and the harvest index (HI) was determined by dividing the grain weight by the total dry biomass. Kernel numbers per spike and thousand-seed weights were recorded accordingly. The weight of the grains was obtained at water content of 13%.

3.3.4 Soil water contents and root measurement

After the ground-parts being harvested, PVC columns were cut into 20 cm segments from top to bottom. Then, the samples were taken to the laboratory. First, approximately 100 g of soil samples from each segment were obtained to measure the soil water contents using the oven-drying method. Before measuring, roots inside this small amount of soil were manually picked up and washed to mix with other roots, which were obtained by washing the soils from each segment. Debris from the roots were separated manually. After the root length was determined based on the line-intersect method using a 1.27-cm grid (Tennant, 1975), the roots were dried at 80° C to measure the dry weight. The root length density (RLD; cm cm^{-3}), root weight density (RWD; mg cm^{-3}), root : shoot ratio (R:S ratio) and specific root length (SRL, m g^{-1}) were calculated using the following formulas:

$$RLD = L/V \tag{1}$$

$$RWD = M/V \tag{2}$$

R:S ratio=total root dry weight/total aboveground dry weight (3)

$$SRL = 10L/M \tag{4}$$

where L is the total root length (cm), M is the total root mass (mg) and V is the sampled soil volume (cm^3). The measured root characteristics were used to assess crop root responses to soil water variations (Ahmadi et al., 2018; Eissenstat, 1991).

3.4 Calculations

3.4.1 Evapotranspiration (ET)

Evapotranspiration (ET, mm) for the whole growing season of winter wheat in this study was calculated using the following water balance equation:

$$ET = SWD + P + I + CR - D - R \tag{5}$$

where SWD (mm) is the soil water depletion, which is defined as the soil water content (*SWC*) of the whole column at sowing after subtracting that at harvesting; ET is the seasonal evapotranspiration (mm) during the whole growth period; *P* is precipitation (mm), which was zero due to the waterproof canopy being used to intercept rainfall; *I* is the total irrigation during the growing season; *CR* is the capillary rise to the root zone (mm); *D* is the drainage from the root zone (mm); and *R* is runoff (mm). The last three factors were taken as zero under the experimental conditions of this study.

3.4.2 Water productivity

Crop water productivity (WP) is defined as the crop yield per unit water consumption (kg m^{-3}), and it was calculated as the crop grain yield divided by seasonal ET for the WP at the grain yield level (WP_g) and as the aboveground dry weight divided by seasonal ET for the WP at the biomass level (WP_b).

3.5 Statistical analysis

Statistical analysis of each factor measured in this study was performed using the SPSS software program (version 19.0, SPSS for Windows, IBM, Armonk, New York, USA). One-way ANOVA was conducted to analyze different factors among different treatments during the same season. The least significant difference (LSD) test ($P<0.05$) was conducted when the differences were significant. The figures were created using OriginPro 2020 (OriginLab Inc., MA, USA).

3.6 Results and discussion

3.6.1 Temperature conditions and reference ET (ET_0)

Fig. 3.2 shows the daily average temperature (T_{ave}) and ET_0 changes from sowing to harvest during the two growing seasons. There was high seasonal T_{ave} variation in the two seasons, which affected the final grain production of winter wheat. From the sowing to recovering stage, T_{ave} in the 2017/18 season was higher than that in the 2018/19 season, while during the jointing to maturity stage, the 2018/19 season had a higher T_{ave}, especially from the recovering stage (days after sowing at 100) to the jointing stage (days after sowing at 150) (Fig. 2A). Figure 2B shows the daily ET_0 changes during the two seasons, which represent the atmospheric evaporation potential. There was a large discrepancy between the two seasons during the reproductive stages of winter wheat, with higher daily ET_0 values in 2018/19 than that in 2017/18. The cumulative ET_0 in the two seasons was 430.8 mm and 561.5 mm, respectively. The results showed that for both seasons before winter dormancy, the temperature was slightly lower than the long-term average, and after winter dormancy, the temperature was much greater than the long-term average, especially in the 2018-2019 season, and the atmospheric evaporation demands were also higher in this season, which affected the actual crop water use.

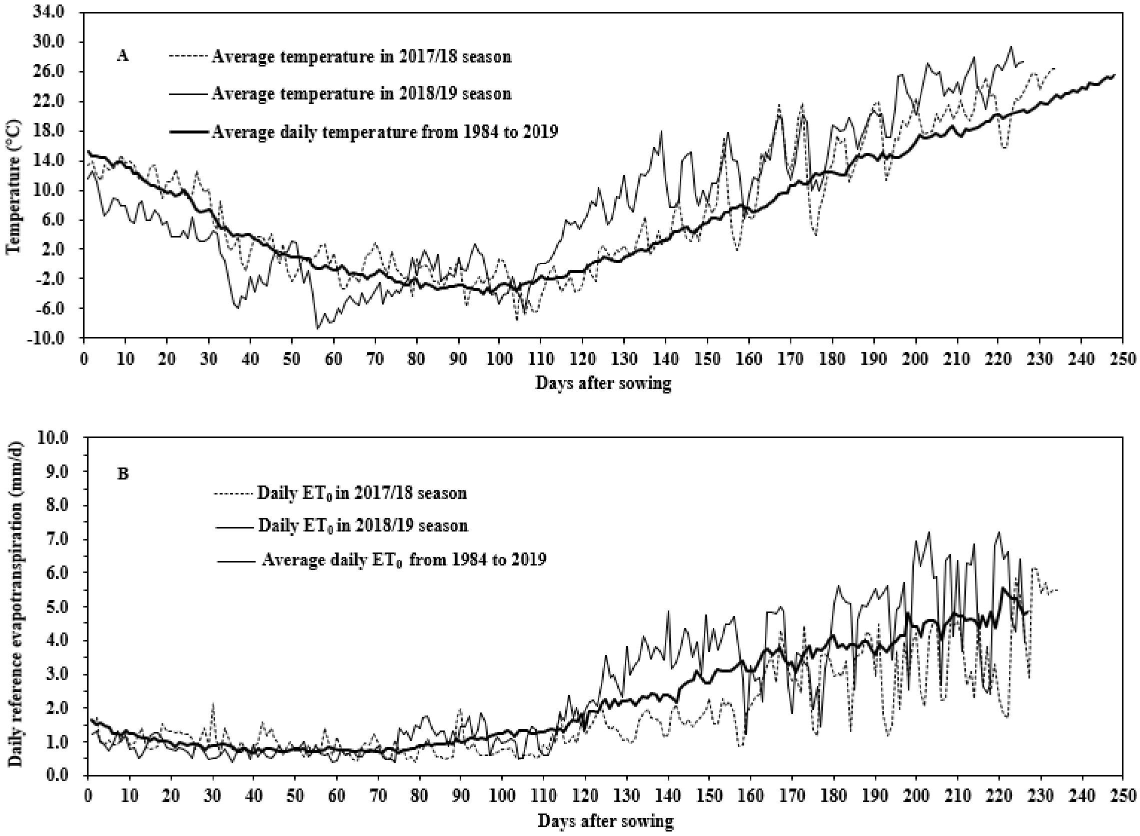


Fig. 3.2 Daily average temperature (°C) (A) and daily reference evapotranspiration (ET_0, mm) (B) from sowing to harvesting for the two seasons of winter wheat and the long-term average temperature from 1984 to 2019 at the experimental site.

3.6.2 Root distribution, soil water consumption and seasonal ET

Fig. 3.3 shows the RLD distribution under the three treatments at two irrigation levels in the 2017/18 and 2018/19 seasons. Although the depths of the tubes in the two seasons were different, the distribution of RLD along the soil profile showed similar trends under the two irrigation levels. The RLD in topsoil and subsoil was not significantly different among the different treatments, except for the significant increase at approximately 60-80 cm under the ND+WD treatments. Coupling of the water and nutrients at that depth significantly improved root growth. Previous studies also indicate that root length and biomass increase or decrease in response to a wide range of soil water and nutrient regimes (Elazab et al., 2016; Mehrabi et al., 2021).

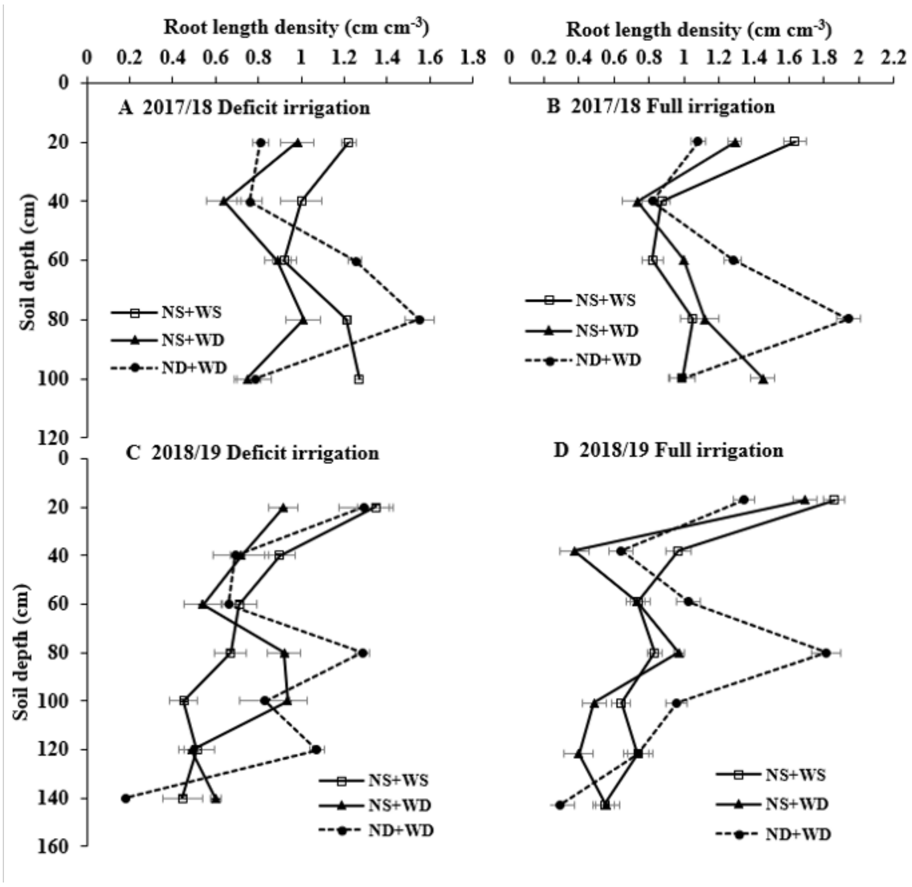


Fig. 3.3 The RLD distribution along the soil profile for the three treatments under deficit and full irrigation conditions in the 2017/18 season (A and B) and 2018/19 season (C and D) (the error bars show the standard deviation of six replicates) (Explanations for treatment symbols can be found in Table 2).

The SRL for different treatments is shown in Table 3.3. With the increase in soil depth, the SRL generally increased. A higher SRL indicates thinner roots, and a lower SRL indicates thicker roots (Ahmadi et al., 2018; De la Riva et al., 2020). Thinner and longer roots are associated with more branching and with a high capacity for water and nutrient uptake due to increased root surface area (Eissenstat et al., 2000). The results indicated a trend that roots in the surface soil were thicker, and with the increase in soil depth, roots became increasingly thinner. The SRL in the 20-60 cm soil layer treated under NS+WD was higher than that of other treatments. The reason might be the water stress condition at the surface soil layer, which stimulates lateral roots to extend to deep soil layer to absorb water with the help of the rich nutrients in the top soil layer. Among the three treatments under the two water levels, the SRL in the 0-20 cm soil layer in the 2018/19 season was higher than that in the 2017/18 season. This situation occurred because the PVC tube used in the second season was longer than that in the first season, which favored root growth.

Table 3.3 Average specific root length at different soil layers under different distribution of water and nutrients in the 2017/18 and 2018/19 seasons.

Water levels	Water and nutrient distribution*	Specific root length (m g^{-1})					
		2017/18 season			2018/19 season		
		0-20 cm	20-60 cm	below 60 cm	0-20 cm	20-60 cm	below 60 cm
Deficit irrigation	NS+WS	34.4 ± 3.3	95.0 ± 4.6	95.1 ± 4.0	72.4 ± 5.4	87.1 ± 8.3	84.5 ± 7.2
	NS+WD	37.0 ± 2.1	95.6 ± 2.8	91.9 ± 3.5	56.2 ± 4.6	88.6 ± 6.4	82.0 ± 4.5
	ND+WD	34.0 ± 2.2	87.0 ± 2.6	110.4 ± 2.1	49.2 ± 2.2	82.6 ± 5.7	88.3 ± 8.6
Full irrigation	NS+WS	37.6 ± 2.9	77.1 ± 3.4	91.9 ± 6.3	53.5 ± 3.7	85.2 ± 4.4	94.5 ± 8.8
	NS+WD	42.0 ± 3.8	82.2 ± 5.4	93.1 ± 11.4	58.3 ± 4.3	87.3 ± 4.8	92.6 ± 10.3
	ND+WD	32.8 ± 2.0	82.7 ± 4.6	83.8 ± 6.8	42.7 ± 3.1	93.2 ± 8.3	97.0 ± 12.8

***:** NS+WS, NS+WD and ND+WD represent the three treatments described in Table 2. “±”represents the standard deviation of six replicates.

Fig. 3.4 shows the soil water contents (SWC) along the tubes at harvest during the two seasons. In the 2017/18 season, the SWC was quite low, approaching the wilting point, for the topsoil layer under the two irrigation levels. With the increase in soil depth, the SWC slightly increased. Combined with the RLD distribution in Fig. 3.3, these results indicated that roots at the soil surface had the ability to use all the available water, while the relatively lower RLD at deep soil layers restricted the full use of the soil water, even though the aboveground parts encountered water stress. For the 2018-2019 season, the depth of the PVC tube was 1.4 m, and the declining trend of the RLD along the surface soil profile was more obvious than that in the 2017/2018 season. The RLD below 1 m was sparsely distributed, and there was more available soil water left that was not fully absorbed by the root system. The results indicated that the smaller RLD in the deep soil layer restricted the full utilization of soil water by crops. Many studies have shown that an RLD of at least 0.8 cm cm^{-3} is required for effective uptake of soil water (Barraclough & Weir, 1988; Zhang et al., 2020; Zhang et al., 2004). A higher RLD in the deep soil layer would promote root water uptake and increase soil water availability to crop water use.

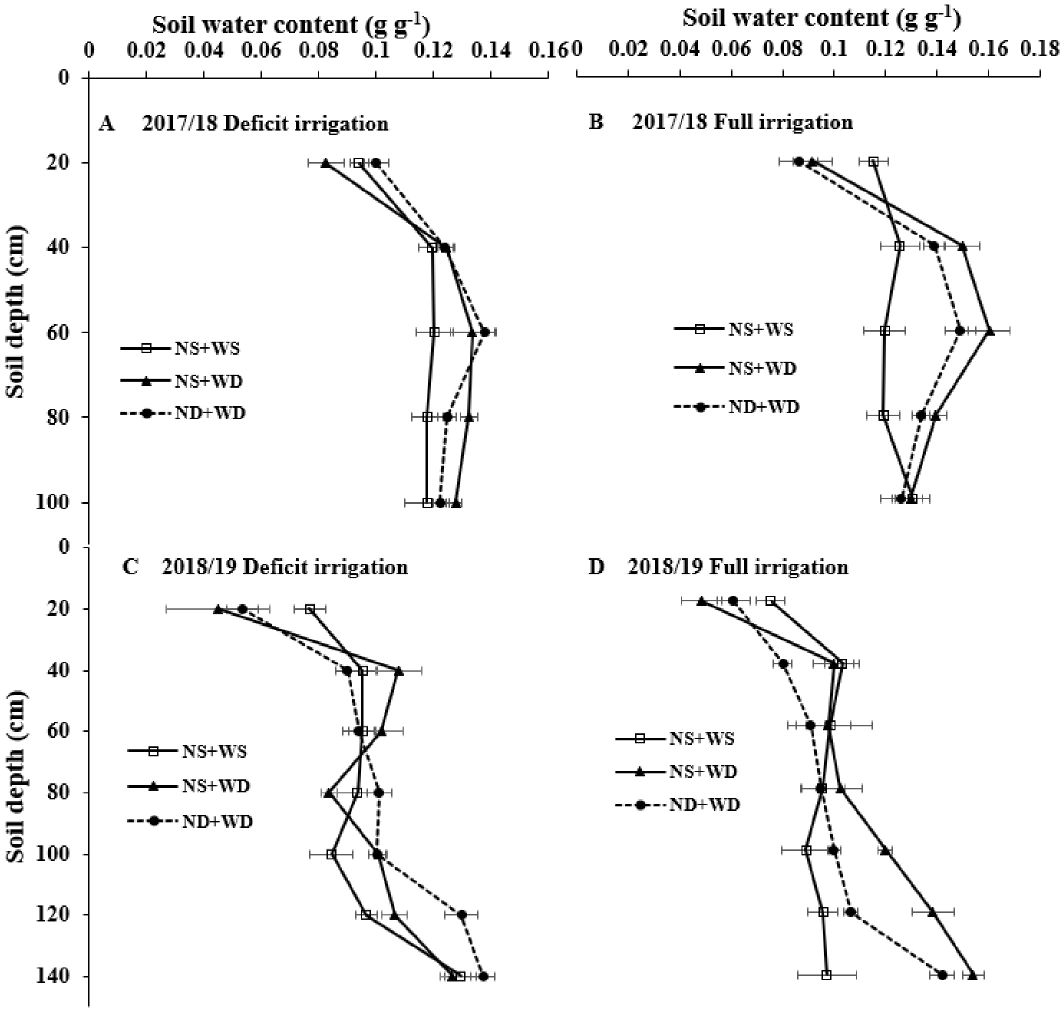


Fig. 3.4 The changes in the soil water content at harvesting along the soil profile during the two growing seasons under deficit irrigation (A and C) and full irrigation (B and D) (The error bars show the standard deviation of six replicates. NS+WS, NS+WD and ND+WD represent the three treatments described in Table 2).

Table 3.4 shows the soil water depletion (SWD) of winter wheat and the ratio of SWD to seasonal ET under the three treatments in the two seasons. The SWD under deficit irrigation was higher than that under full irrigation for all three treatments, which indicated that winter wheat had the ability to withdraw more soil water under deficit irrigation. For the three treatments under deficit irrigation, no significant difference in SWD and SWD/ET ratio was found for the two seasons, indicating that the different locations of water and nutrients did not affect the total water use due to the limited water supply. However, under a full water supply, NS+WS tended to use more water than the other two treatments. Comparing the two seasons, the deep tubes used in the second season increased the available soil water to the crop, and both ET and the ratio of SWD/ET were greater than those for the first season. A deep soil profile benefits soil water utilization by crops under water-deficit conditions (Zhang et al., 2004; Kirkegaard et al., 2007).

Table 3.4 The soil water depletion (SWD) and seasonal evapotranspiration (ET) for the three treatments under two levels of irrigation in the 2017/18 and 2018/19 seasons*.

Season	Irrigation (mm)	Treatments	SWD (mm)	ET (mm)	SWD/ET (%)
2017/18	160 mm	NS+WS	141.5 ± 1.8 ^{a}	301.5 ± 6.7 ^{a}	46.9%
		NS+WD	133.7 ± 14.8 ^{a}	293.7 ± 13.3 ^{a}	45.5%
		ND+WD	131.3 ± 11.5 ^{a}	291.3 ± 10.3 ^{a}	45.1%
	240 mm	NS+WS	131.2 ± 12.5 ^{a}	371.2 ± 7.8 ^{a}	35.3%
		NS+WD	115.8 ± 13.2 ^{b}	355.8 ± 5.5 ^{b}	32.6%
		ND+WD	125.1 ± 8.8 ^{ab}	365.1 ± 5.9 ^{ab}	34.3%
2018/19	160 mm	NS+WS	260.8 ± 11.2 ^{a}	420.8 ± 30.7 ^{a}	62.0%
		NS+WD	260.8 ± 17.3 ^{a}	420.8 ± 39.4 ^{a}	62.0%
		ND+WD	257.8 ± 15.4 ^{b}	417.8 ± 17.9 ^{a}	61.7%
	240 mm	NS+WS	249.2 ± 26.7 ^{a}	489.2 ± 42.8 ^{a}	50.9%
		NS+WD	227.5 ± 25.1 ^{b}	467.5 ± 34.9 ^{b}	48.7%
		ND+WD	237.8 ± 22.7 ^{ab}	477.8 ± 27.6 ^{ab}	49.8%

***:** "±"represents the standard deviation of six replicates; different lowercase letter indicates the significant difference among different treatments at same year and same irrigation level at $P<0.05$.

3.6.3 Biomass production and water productivity at biomass level

Although the total water use of the three treatments under the same irrigation level was similar, a significant difference in the aboveground biomass of winter wheat at harvesting was observed for the two seasons (Fig. 3.5). The highest biomass was achieved under NS+WD under deficit irrigation and NS+WS under full irrigation, which was significantly higher than those of the other two treatments during each season. The biomass of ND+WD was the lowest among the three treatments under the same irrigation level. It has been reported that biomass production was the major factor determining the final grain yield, and lower biomass generally reduced the final yield production (Jin et al., 2014). Water consumption generally has a positive relationship with biomass production (Khan et al., 2020). However, the results from this study indicated that with similar seasonal ET (Table 3.4), biomass production was distinguished due to the difference in the spatial distribution of nutrients and irrigation water supplies.

The difference in biomass production among different treatments might be related to the biomass allocation to belowground parts and the root/shoot (R/S) ratio. A lower R/S ratio might benefit the partitioning of more dry matter to the aboveground biomass to obtain higher biomass production. In this study, NS+WS had the lowest R/S ratio under deficit irrigation (0.046 and 0.045) and full irrigation (0.069 and 0.043) in the two seasons, respectively. The R/S ratio of ND+WD was the highest under deficit irrigation (0.094 and 0.089) and full irrigation (0.134 and 0.077) in the two seasons, respectively. The treatment, in which nutrients and water coupled to surface soil layers allocated more biomass to aboveground parts, was therefore more economic for aboveground biomass production.

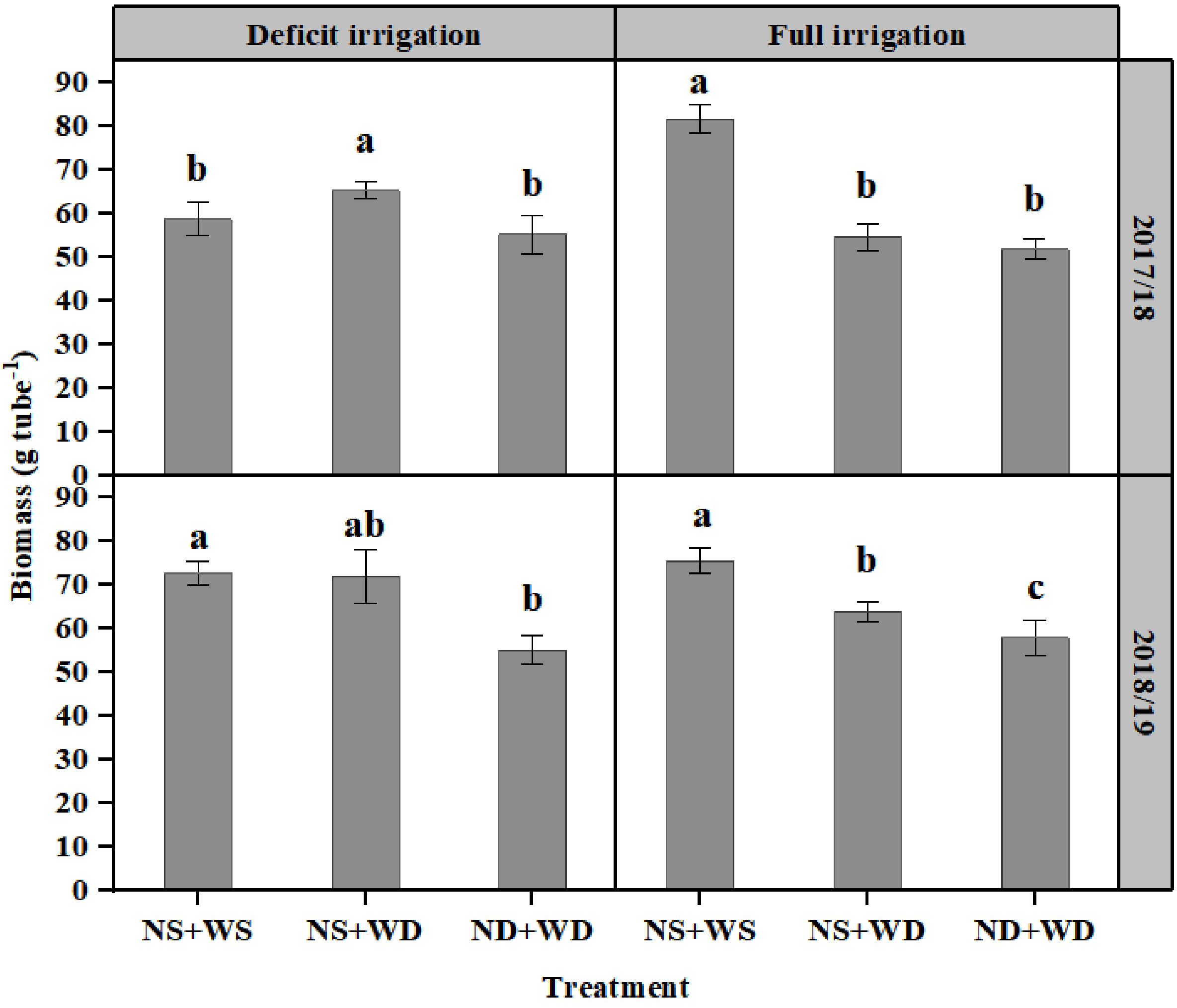


Fig. 3.5 Aboveground biomass among different treatments at harvesting in the 2017/18 and 2018/19 seasons (The bars represent the standard deviation of six replications. Different letters for different treatments in the same year indicate significant difference at $P<0.05$; NS+WS, NS+WD and ND+WD represent the three treatments described in Table 2).

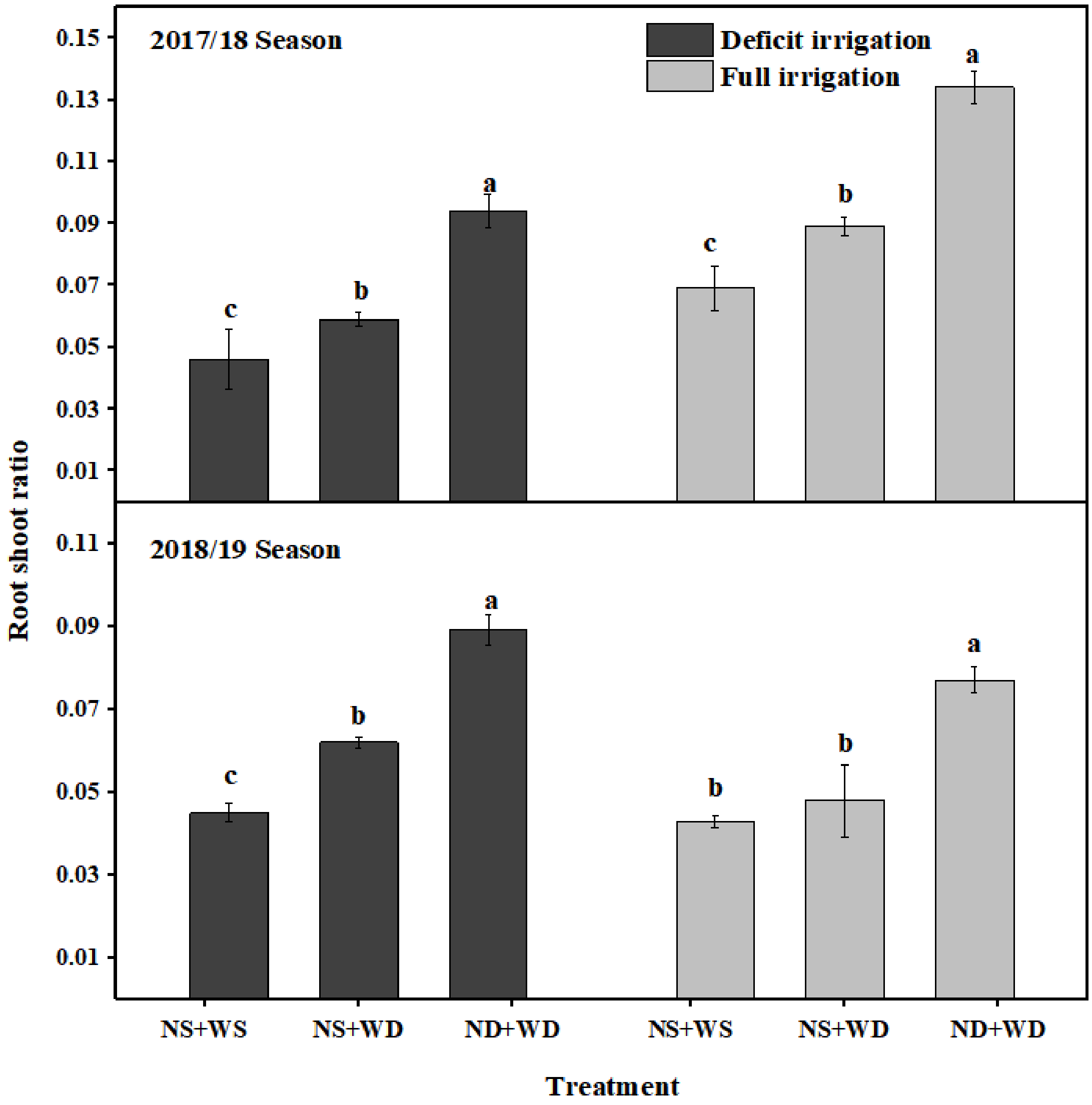


Fig. 3.6 The root : shoot of the three treatments under deficit and full irrigation in 2017/18 and 2018/19 seasons (NS+WS, NS+WD and ND+WD represent the three treatments described in Table 2).

Table 5 shows that there was a significant difference in water productivity at the biomass level (WP_b) for winter wheat among the different treatments. Under full irrigation, the highest WP_b was achieved under NS+WS during the two seasons. The average WP_b value of NS+WS was 29.6% and 35.4% higher than those of NS+WD and ND+WD in the first season and 11.9% and 21.6% higher in the second season, respectively. Under deficit irrigation, NS+WD got highest WP_b in first season and mean of two seasons, which was 13.0% and 15.1% higher than those of NS+WS and ND+WD in first season and 6.9% and 18.9% higher in total two seasons. The results indicated that coupling water and nutrients at the surface soil under full irrigation and supplying nutrients at surface soil and water at subsoil benefited aboveground biomass production and improved water productivity at the biomass level.

When nutrients and water are coupled at the subsoil (ND+WD), crops need to increase root growth to obtain water and nutrient, which results in a large root system in the subsoil (Fig. 3.3). But the cost in producing roots would be greater when large root system occurred. Generally, most roots of cereal crops are concentrated in the top 40 cm soil layer where water and nutrients are abundant, thus reducing the cost in root growth to absorb nutrients and water. It has been reported that when plants grow in productive environments, they have a faster return of investment (de la Riva et al., 2021). In contrast, plants survive in a resource-limiting environment tend to have a slower return of investment (Roumet et al., 2016; Wright et al., 2005; Wright et al., 2004). The coupling of water and nutrients in the top soil layer reduced the cost in soil water and nutrient uptake and enhanced the water productivity in biomass production in this study.

Table 3.5 Water productivity at the biomass level (WP_b) for the three treatments under two irrigation levels in the 2017/18 and 2018/19 seasons*.

Water level	Distributions of water and nutrients*	WP_b (kg m^{-3})		
		2017/18	2018/19	Mean
Deficit irrigation	NS+WS	6.75 ± 1.23^{b}	5.98 ± 2.41^{a}	6.36
	NS+WD	7.76 ± 2.04^{a}	5.91 ± 1.06^{a}	6.83
	ND+WD	6.59 ± 1.42^{b}	4.49 ± 0.79^{b}	5.54
Full irrigation	NS+WS	7.59 ± 1.86^{a}	5.36 ± 2.18^{a}	6.48
	NS+WD	5.34 ± 0.85^{b}	4.72 ± 1.36^{b}	5.03
	ND+WD	4.90 ± 1.40^{c}	4.20 ± 2.68^{c}	4.55

:± represents the standard deviation of six replicates; Different lowercase letter followed by each data means significant difference among different treatments at the same year under same irrigation level at *P*<0.05. NS+WS, NS+WD and ND+WD represent the three treatments described in Table 3.2.

3.6.4 Yield, harvest index and water productivity at the grain yield level

Under deficit irrigation, dry matter accumulated by photosynthesis after flowering and transferred from the vegetative stage accounted for the main part of the final grain yield (Fang et al., 2021; Zhang et al., 2013). Table 3.6 shows that the grain yield and HI were significantly affected by different irrigation and nutrient treatments. Under deficit irrigation, the NS+WD treatment resulted in the highest yield in both 2017/18 (on average, 31.4 g tube^{-1}) and 2018/19 (on average, 28.5 g tube^{-1}), and the ND+WD treatment produced the lowest yield in 2017/18 (on average, 25.6 g tube^{-1}) and 2018/19 (on average, 21.8 g tube^{-1}). Harvest index (HI) shows the same change trend among the treatments as the grain production. The biomass of NS+WD was the highest in the two seasons, and also produced the highest HI. The possible reasons might be that coupling of water and nutrients at the topsoil layer under deficit irrigation would favor root water uptake, with more water consumed during the vegetative growing stages and less water available for water use during the grain-filling stages, which would reduce the photosynthesis activity under water deficit condition.

The possible differences in crop water status among the different treatments during grain-filling stages could be indicated by the canopy temperature (*CT*) and leaf photosynthesis (*Pn*). At the anthesis stage, under deficit irrigation condition the photosynthesis rate for treatments with water applied to deep soil layer was slightly higher than the treatment with water applied at soil surface, although no significant difference was found among the treatments (Fig. 3.8). Under full irrigation, NS+WD had higher leaf *Pn* than the other two treatments. Higher flag leaf *Pn* would favor more biomass production during grain-fill stage, which was quite important for high grain production (Fang et al., 2021). Carbohydrates produced during the grain-fill stage provide the most parts of grains for cereal crops (Dordas, 2012). Post-anthesis dry matter production contributes more than 60% of the final grain yield for wheat (Masoni et al., 2007; Yang & Zhang, 2006). The NS+WS under deficit irrigation reduced the water availability during grain fill, and therefore, reduced the remobilization of pre-anthesis photosynthetic products as well as the after-anthesis products, resulting in lower yield and HI (Asseng et al., 2017).

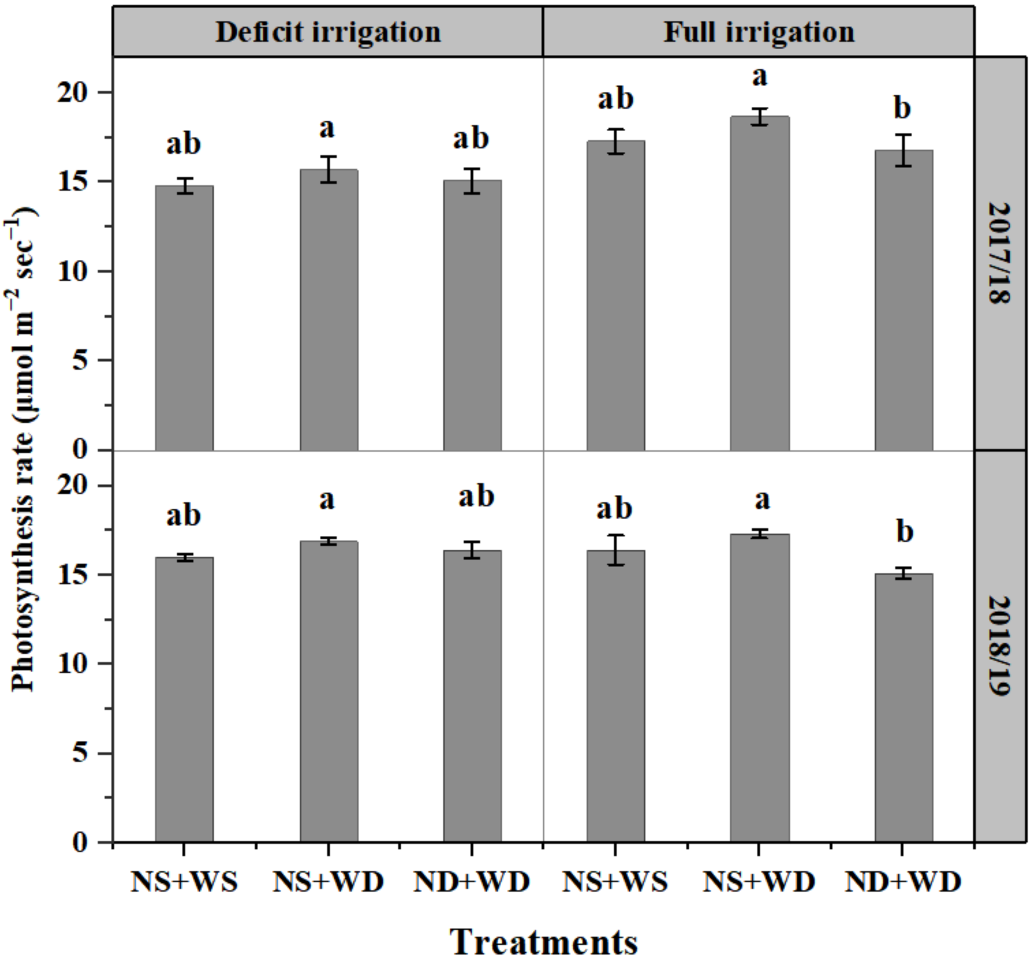


Fig. 3.7 Average photosynthesis rate during the anthesis stage among different treatments in the 2017/18 and 2018/19 seasons. (The bars represent the standard deviation of six replications. Different letters under the different treatments in the same year indicate significant differences at $P<0.05$. NS+WS, NS+WD and ND+WD represent the three treatments described in Table 3.2).

Plants with lower available soil water would reduce transpiration and increase *CT*. The measured *CT* during the grain-filling stages indicated that the *CT* of the NS+WD treatment was the lowest under deficit irrigation among the three treatments (Fig. 3.9), which indicated that water supplied in the deep soil layer would be saved to favor crop water use during the late growing stages. The lower water availability under NS+WS during the grain-filling stage reduced the HI and resulted in lower grain production as compared with the NS+WD treatment under deficit irrigation condition (Table 3.6).

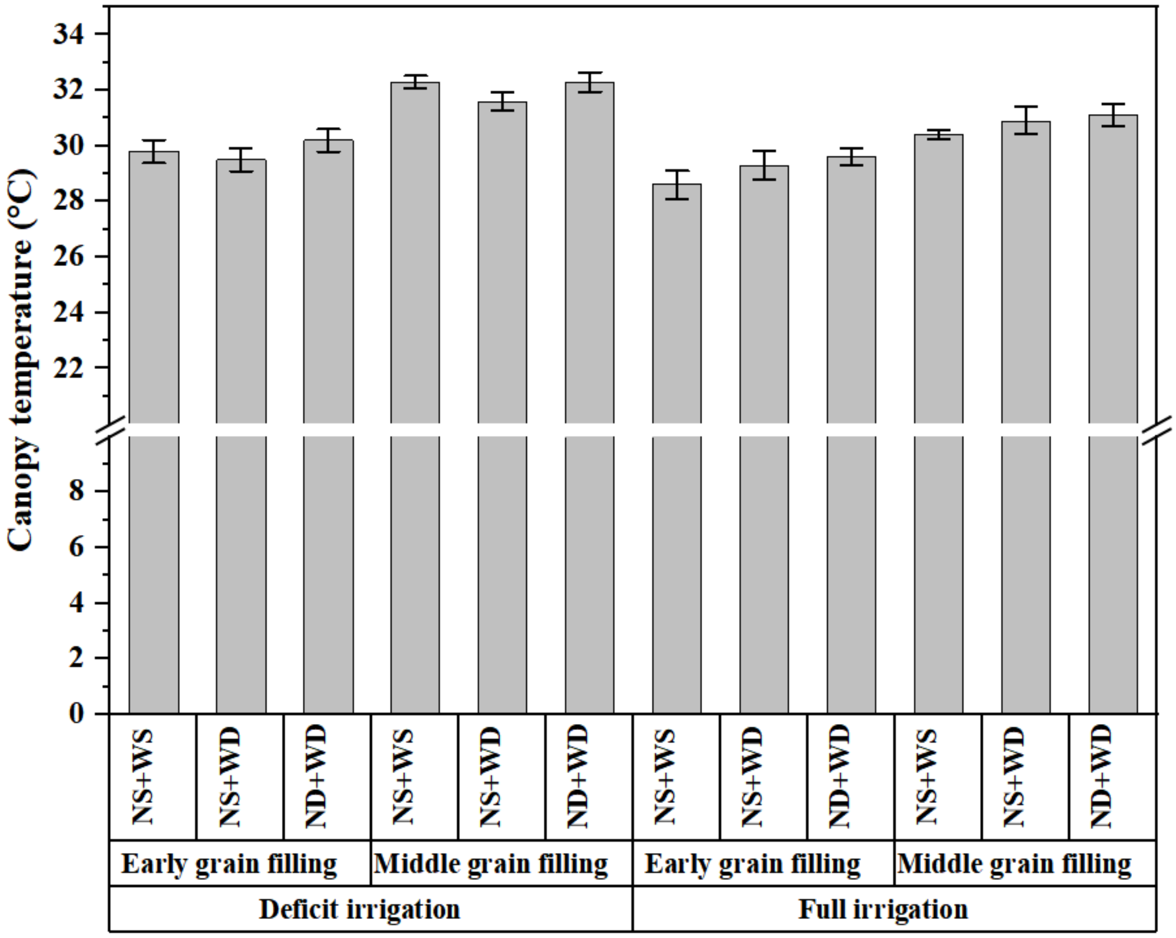


Fig. 3.8 Average canopy temperature during the early and middle grain fill stages among different treatments in the 2017/18 and 2018/19 seasons (The bars represent the standard deviation of six replications. NS+WS, NS+WD and ND+WD represent the three treatments described in Table 3.2).

The higher soil water content in the topsoil layer would also increase soil evaporation consumption, which would result in less water consumption for crop transpiration. Although there was fine sand to reduce soil evaporation under the experimental conditions of this study, soil evaporation for treatments with water supplied to the soil surface would still be greater than that supplied to deep soil layers. Liu et al. (2002) have found that soil evaporation takes up 30% of the total ET for winter wheat at the same site, and soil evaporation is linearly correlated with the surface soil moisture. Therefore, water applied into the deep soil layer would reduce the soil evaporation and increase the water availability for crop transpiration use.

Under the full irrigation treatments, the situation was different. NS+WS produced the highest yield and HI for both seasons (Table 3.6). The yields of NS+WS were 27.7 and 32.6 g tube^{-1} on average in the two seasons, respectively, and they were significantly higher than those of the other two treatments. The average yields of ND+WD were 19.2 and 21.9 g tube^{-1} in the two seasons, respectively, which produced the lowest yields. The high yield of NS+WS was related to the higher spikes per area and seed numbers per spike (Table 3.6). Table 3.6 also shows that nutrients and water coupling at the surface produced higher water productivity under full irrigation in the two seasons, which was related to the higher biomass production and HI. Since ET_0 in the 2017/18 season was lower than that in the 2018/19 season, the WP_g in the first season was higher than that in the latter season (Table 3.6). Different tube depths and weather also affected the values of yield and WP_g for the two seasons.

Table 3.6 The effects of irrigation and nutrient locations on yield, yield components, harvest index (HI) and water productivity at grain yield level (WP$_g$) in 2017/18 and 2018/19 seasons*

Seasons	Water level	Distribution of water and nutrients	Thousand seeds weight (g)	Spikes per tube (spikes tube^{-1})	Seeds per spike	Yield (g tube^{-1})	HI	WP$_g$ (kg m^{-3})
2017/18	160 mm	NS+WS	43.8 ± 3.2 ^{a}	25.0 ± 3.2 ^{a}	26.5 ± 3.7 ^{b}	29.7 ± 0.5 ^{b}	0.52 ± 0.06 ^{a}	3.41 ± 0.54 ^{ab}
		NS+WD	43.8 ± 3.1 ^{a}	23.8 ± 3.6 ^{ab}	29.6 ± 3.1 ^{a}	31.4 ± 0.5 ^{a}	0.48 ± 0.06 ^{b}	3.73 ± 0.41 ^{a}
		ND+WD	42.7 ± 4.1 ^{b}	22.5 ± 3.4 ^{b}	26.9 ± 2.2 ^{b}	25.6 ± 0.4 ^{c}	0.47 ± 0.02 ^{b}	3.06 ± 0.84 ^{b}
	240 mm	NS+WS	50.0 ± 2.0 ^{a}	28.8 ± 2.3 ^{a}	23.7 ± 2.7 ^{a}	27.7 ± 0.8 ^{a}	0.45 ± 0.08 ^{a}	3.17 ± 0.66 ^{a}
		NS+WD	47.6 ± 2.2 ^{b}	22.2 ± 2.1^{c}	21.9 ± 3.1 ^{b}	23.3 ± 0.9 ^{b}	0.42 ± 0.05 ^{b}	2.26 ± 0.79 ^{b}
		ND+WD	48.5 ± 2.7 ^{ab}	24.0 ± 4.8 ^{b}	15.9 ± 1.3 ^{c}	19.2 ± 0.8 ^{c}	0.35 ± 0.02 ^{c}	1.81 ± 0.67 ^{c}
2018/19	160 mm	NS+WS	31.1 ± 2.8 ^{c}	29.4 ± 2.7 ^{a}	28.2 ± 2.1 ^{b}	25.6 ± 0.3 ^{b}	0.35 ± 0.03 ^{b}	2.10 ± 0.42 ^{ab}
		NS+WD	35.4 ± 2.7 ^{b}	25.6 ± 3.4 ^{b}	31.6 ± 3.4 ^{a}	28.5 ± 0.5 ^{a}	0.40 ± 0.04 ^{a}	2.34 ± 0.71 ^{a}
		ND+WD	38.3 ± 1.9 ^{a}	21.0 ± 2.3 ^{c}	26.9 ± 2.5 ^{c}	21.8 ± 0.4^{c}	0.39 ± 0.02 ^{ab}	1.77 ± 0.26 ^{b}
	240 mm	NS+WS	34.2 ± 2.6 ^{b}	26.8 ± 3.2 ^{a}	35.9 ± 2.4 ^{a}	32.6 ± 1.0 ^{a}	0.43 ± 0.03 ^{a}	2.31 ± 0.44 ^{a}
		NS+WD	36.0 ± 2.9 ^{ab}	23.4 ± 3.7 ^{b}	31.6 ± 4.1 ^{b}	26.3 ± 0.4 ^{b}	0.41 ± 0.02 ^{ab}	1.94 ± 0.49 ^{b}
		ND+WD	37.6 ± 4.9 ^{a}	24.0 ± 1.8 ^{b}	26.7 ± 2.7 ^{c}	21.9 ± 0.3 ^{c}	0.38 ± 0.03 ^{b}	1.59 ± 0.35 ^{c}

*: "±" represents the standard deviation; different lowercase letters followed each mean data indicate the significant difference among different treatments at the same year and the same irrigation level at $P<0.05$. NS+WS, NS+WD and ND+WD represent the three treatments described in Table 2.

For the two irrigation levels and the two seasons, ND+WD produced the lowest biomass, yield, HI and water productivity. The results might indicate that during the earlier growth season, the nutrients in the deep soil layer was not accessible to the crop root system, and the lower nutrient supply reduced the aboveground growth at the earlier growth stage. Although the roots could access the nutrients at the later growing stages, the earlier reduced crop growth might not have been replenished by the later growth. Another reason might be related to the deep roots, which were not as effective as the surface roots in taking up nutrients because the latter had a large root surface. The significantly increased root length in the deep soil layer increased the root: shoot ratio, which negatively affected the biomass allocation to the aboveground part.

The results from this study indicated that spatial distribution of soil water affected its total availability to crop water use and its availability at different growing stages of crops which influenced the biomass production, grain yield and harvest index. Grain production could be improved under terminal drought if the water use during the vegetative growing stages was reduced, and soil water availability during grain fill stage was increased (Ma et al., 2008; Yan et al., 2020). Yan et al. (2020) reported that localized root proliferation is found in nutrient-rich soils which is a critical strategy for crop nutrient acquisition. Their results also showed that soil dryness does not reduce nutrient uptake (Oldroyd et al., 2020; Wen et al., 2020). Therefore, nutrients should be applied to the soil layers where roots are abundant to reduce the cost in root growth to absorb nutrients.

Rational combination of water and nutrients increases the water and nutrient use efficiency and creates better interaction of the two factors (Li et al., 2009). Nutrients applied at the topsoil layers benefitted crop production under both adequate and deficient water conditions. Water applied to the deep soil layers favored crop production under deficit irrigation but not under adequate water supply. Although supplying nutrients to the subsoil could increase the RLD in deep soil layers, the energy needed to transfer water and nutrients would be increased, which would increase the cost of producing roots (de la Riva et al., 2021). In this study, nutrients applied to the subsoil increased the R/S and reduced the HI, subsequently resulting in a lower yield and WP_g. The results from this study indicate that coupling water and nutrient management is important for high yields and resource use efficiency. An interaction exists between water and nutrients, and spatial changes in one factor likely affect the influences of the other factor on crop performance.

3.7 Conclusions

This study showed that not only did different irrigation water supplies affect crop performance, but the location of the water and nutrients applied also affected the final grain yield and WP_g for winter wheat. The different spatial distributions of water and nutrients affected the root distribution and dry matter allocation to below- and aboveground parts, further resulting in variations in yield and water productivity. Although there was no significant difference in seasonal ET, the spatial distribution of water and nutrients affected the water use allocation during the vegetative and reproductive stages and carbohydrate allocation to the root system, resulting in different root/shoot ratios and harvest index. These factors significantly affected the grain production and WP_g at the grain yield level. Crops also respond differently to the spatial distribution of water and nutrients under different water application levels. Therefore, it is important to manage water and nutrients based on water availability to achieve high yields and WP_g. The results of this study were from a column study, and the wall of the column might have influenced the root growth and distribution. However, the column used in this study was quite deep, and the crops were grown under the conditions of the field environment. The results of the study could be taken as references in water and nutrient management.

Chapter 4

Determining Irrigation Volumes for Enhancing Profit and N Uptake Efficiency of Potato Using WASH_2D Model

Abstract

Soaring food prices and the intensified scarcity of water resources put a new emphasis on efficient use of water in irrigation. Numerical models for water flow and crop growth can be used to predict crop water stress and make decisions on irrigation management. To this end, a new irrigation scheme was presented to determine the optimum irrigation depths using WASH_2D, a numerical model of water flow and solute transport in soils and crop growth. By using freely available quantitative weather forecasts and volumetric water price as input data to predict soil water flow and give the recommendation of irrigation depths which maximizes net income during each irrigation interval. Field experiments using potato were conducted for two-seasons in a sandy soil in Japan under three irrigation methods, i.e. using the simulation model named treatment "S" (to distinguish, named S1 in first season and S2 in second season), automatic irrigation method using soil moisture sensors named treatment "A", and refilling irrigation management supplying 100% consumed water named treatment "R". To compare S with other two treatments, S1 and A was conducted in the first season, then S2 and R was conducted in the second season. Results showed that S1 improved potato yield by 19%, and reduced water by 28%, resulting in an increased net income by 19% compared with A in the first season. There was no significant difference when compared with R in the second season, which was mainly due to the frequent rainfall during second growing season. In addition, S improved the nitrogen uptake efficiency (NU_PE) by 39% and 11% compared with A and R, respectively. The simulated values of water content were in fair agreement with those measured in the root zone. In short, simulated irrigation method was effective in improving yield, saving

water and increasing NU_PE of potato compared with automatic and refilling irrigation methods in sandy field.

4.1 Introduction

Irrigated agriculture has been the primary user of water in arid and semi-arid zones, which occupies over 70-80% of the total, especially in the water scarce area (Fereres and Soriano, 2007). Continued population growth, limited water supply, and climate change require measures to conserve water in agriculture (Ward and Pulido-Velazquez, 2008). At present and more so in the future, irrigation in a conservation and sustainable way will be the norm rather than the exception. Nevertheless, many farmers still irrigate in the way of unsustainability (Wada and Bierkens, 2014; Liu et al., 2017). The development of more precise and efficient irrigation management is still required. Many studies have focused on reducing the amount of irrigation by supplying water below the needs of crop, termed regulated deficit irrigation (RDI), with the purpose of improving crop water productivity (CWP) (Geerts and Raes, 2009). However, it is net income rather than CWP that farmers expected to maximize from their agricultural activities, and the maximization of net income should be a prerequisite for sustainable farming (Volschenk, 2020). New irrigation schemes aimed at improving net income of farmers should be proposed.

Irrigation events are usually carried out based on soil water status, in which soil moisture is measured to determine the irrigation need or estimated using soil water balance equation. Then the irrigation quota is determined according to the water consumption during the irrigation interval, applying water to meet the crop water requirement (100% ET), or less than crop requirement (lower than 100% ET) (Singh and Singh, 1995; Cabello et al., 2009; Cai et al., 2011). In addition, most of studies have provided solutions for long-term decision making of water allocation to different growth stages of crop using meteorological data of previous years. But interannual variability in climate varies too widely to give accurate irrigation depth at each time (Cao et al., 2019). Therefore, weather forecast (WF) data, as a freely and easily accessible online information, is gradually being incorporated into irrigation decisions, and has been proved that it can save irrigation water if properly utilized (Linker et al., 2016). Brown et al (2007) found that incorporating 2-day weather forecast could reduce water use by 1.5-2.3%, and 3.9-4.6% reduction in water use when 5-day forecast information was incorporated. Lorite et al (2015) compared reference evapotranspiration (ET_0) determined on one day and weekly weather forecast with measured data, and found the performance of weather forecast is acceptable. Muller et al (2021) examined the economic output of incorporating weather forecast into irrigation decisions, predicting that 5% additional profit would be possible when weather forecast is incorporated into the decisions. Anupoju V et al (2021) modified the SWAP model by considering different weather forecast horizons (1, 3, and 5 days), and found conventional irrigation (without weather forecast) resulted in higher water use, percolation losses and lower yield. The successful implementation of the weather forecast has been gaining momentum with the development of irrigation system, which is a decision support system (DSS), and is built on the basis of online, open-source tools to supply instruction for irrigation water management (Simionesei et al., 2020). While the use of weather forecast would improve water productivity, it is inherently uncertain, particularly for the rainfall. Previous studies usually utilized weather forecast data directly for long term without using actual weather data or made the irrigation decision based on historical weather data. By carrying out update run using actual weather data downloaded from nearby weather station, we may minimize the negative effects of errors in weather forecast.

Although the use of sensors and models have made the irrigation system more water-saving, the efficiency in nutrient use under different irrigation schemes should also be evaluated, because inefficient practices usually lead to increase in nutrient leaching, especially in the sandy loam soil (Ajdary et al., 2011). Wang et al (2014) simulated three Christiansen uniformities of drip irrigation using HYDRUS-2D, and demonstrated that deep percolation and nitrate leaching usually happened following a heavy precipitation event. Additionally, sandy loam soil is more susceptible to nitrate leaching than silty loam (Eltarabily et al., 2019). Actually, for most of the irrigation system, root, as the main nutrient and water absorbing organ and grows constantly, was often neglected or too simplified in the numerical models (Liao et al., 2021).

In this study, with the target of maximize net income, and simulate plant growth using specific plant parameters, the irrigation depths were determined by predicting two points of cumulative transpiration at each irrigation event, using actual weather records and WF to update and optimize the simulation. To validate this scheme, field experiments using potato were carried out for two-seasons, and the new scheme was compared with two other conventional irrigation strategies: automatic and refilling schemes. The objectives of this study were to: 1) investigate the feasibility of the proposed irrigation-depth-decision scheme which aims to maximize net income for potato, in comparison with the automated irrigation system managed with tensiometers and refilling irrigation scheme supplying full crop water requirement; 2) evaluate the nitrogen uptake efficiency and nitrate leaching during the irrigation period. Results of this study may contribute to the development of a new irrigation scheme which determines irrigation depths for maximizing net income of farmers and improving water management in water scarce area.

4.2 Material and methods

4.2.1 Maximization of virtual net income

To maximize the net income of farmers and develop sustainable water management in agriculture, Fujimaki et al (2014) proposed an irrigation scheme that determined irrigation depth by maximizing virtual net income, I_n (\$ ha^{-1}) and priced water. Though the net income cannot be achieved until final harvest, we assume that virtual net income is proportional to the cumulative dry matter (DM) accumulated during an irrigation interval, because plant dry matter accumulation is usually correlated with cumulative transpiration, as both CO_2 uptake and water vapor loss take place simultaneously via stomata (Fujimaki et al., 2014; Abd El Baki et al., 2020; Abd El Baki et al., 2021). For the economic yield of crop which contributes to the net income, such as fruit, grain, tuber, is assumed to be proportional to dry matter production. In other words, harvest index, which is defined as edible to entire biomass, is assumed to be constant. Then, cost for water usage and other costs are subtracted from income, presuming that water is volumetrically priced to give incentive to farmers to save water. Thus, the I_n, during an interval is calculated as:

$$I_n = P_c \xi \varepsilon \tau_i k_i - P_w W - C_{ot} \tag{1}$$

where P_c is the producer's price of the crop (\$ kg^{-1} DM), ξ is the harvest index, ε is transpiration efficiency of the crop which is produced DM (kg ha^{-1}) divided by cumulative transpiration (kg ha^{-1}), τ_i is cumulative transpiration during an irrigation interval (1cm = 10^5 kg ha^{-1}), k_i is the income correction factor, subscript i is specific irrigation interval, P_w is the price of water (\$ kg^{-1}), W is the irrigation depth (1 cm = 10^5 kg ha^{-1}), and C_{ot} is other costs during the period such as fertilizers and pesticide, etc. (\$ ha^{-1}).

To avoid an underestimation of the contribution of I_n during the initial growth stage, during which transpiration rate is far smaller compared with later growth stage but equally important in produce economic yield. Thereafter, a correction function of k_i was set based on the basal crop coefficient (Fujimaki et al., 2014). Although the introduction of k_i will not make I_n correspond to the actual net income even the prediction of yield matches the actual well, it may enhance the accuracy of virtual I_n. It was defined as follows:

$$k_i = \frac{\bar{k}_{cb}}{k_{cb}} = \frac{\int k_{cb}\, d\tau}{\tau_f k_{cb}} = \frac{\left(a_{k_{cb}} + c_{k_{cb}}\right)\tau_f - \frac{a_{k_{cb}}}{b_{k_{cb}}}[\exp\,(b_{k_{cb}}\tau_f) - 1] - \frac{d_{k_{cb}}\tau_f^{\,e_{k_{cb}}+1}}{e_{k_{cb}}+1}}{\tau_f k_{cb}} \tag{2}$$

where $\overline{k_{cb}}$ is average values of basal crop coefficient (k_{cb}) across growing period; τ_f is expected cumulative transpiration at final period; $a_{k_{cb}}$, $b_{k_{cb}}$, $c_{k_{cb}}$, $d_{k_{cb}}$ and $e_{k_{cb}}$ are fitting parameters used to calculate basal crop coefficient as a function of cumulative transpiration as described later.

Fujimaki et al (2014) empirically described the τ_i as

$$\tau_i = \int T_r d_t = a_t[1 - \exp(b_t W)] + \tau_0 \tag{3}$$

This nonlinear relationship requires three runs of heavy two-dimensional simulation of water flow to get optimum irrigation depth, which is somewhat time consuming. To reduce the number of trials, Abd EI Baki et al (2020) proposed a simpler function to describe the relationship between W and τ_i, composed of two linear functions, which requires two runs, skipping the third run. The function assumes that τ_i linearly increases with W until the potential transpiration (τ_{max}) is obtained, as follows:

$$\tau_i = \int T_r dt = a_t W + \tau_0, \;\; W < \frac{\tau_{max} - \tau_0}{a_t} \tag{4}$$

$$\tau_i = \tau_{max}, \;\; W > \frac{\tau_{max} - \tau_0}{a_t} \tag{5}$$

where T_r is actual transpiration rate (cm s^{-1}), a_t is a fitting parameter, τ_0 is τ at no irrigation.

4.2.2 Determination of optimum irrigation depth

The optimum irrigation depth, which gives maximum I_n, is obtained when derivative of Eq. (1) with regard to W become zero:

$$\frac{dI_n}{dW} = a_t P_c \varepsilon k_i - P_w, \;\; W < \frac{\tau_{max} - \tau_0}{a_t} \tag{6}$$

$$\frac{dI_n}{dW} = -P_w, \;\; W > \frac{\tau_{max} - \tau_0}{a_t} \tag{7}$$

In the range of $a_t P_c \varepsilon k_i - P_w \geq 0$, the optimum W is $\frac{\tau_{max} - \tau_0}{a_t}$ (Eq. 6).while in the range of $a_t P_c \varepsilon k_i - P_w < 0$, I_n decreases with W(Eq. 7) and no irrigation is recommended. In the scheme, τ_0 and a_t are determined by two trials at W=0 and W_1. Because the cumulative transpiration during the irrigation interval under irrigation should be between τ_0 and ET$_0$, and additional water is somewhat required to compensate evaporation loss W_1 is set at half of τ_0 + ET$_0$. Thereafter, $\alpha_t$was determined by the two points in the linear equation (4), (0, τ_0) and ((τ_0 + ET$_0$)/2, τ_1).

4.2.3 Numerical model

The proposed scheme in sections 2.1, 2.2 and a graphical user interface for entering parameter values have been embedded into a numerical model, WASH_2D, which simulates the two-dimensional movement of water, heat and solute in soils with the finite difference method (Fujimaki et al., 2014). This scheme partitions crop evapotranspiration (ET_c) into two components, actual evaporation and actual transpiration, where actual evaporation was calculated using bulk transfer equation and was described by Fujimaki et al (Fujimaki et al., 2014), and actual transpiration was described in the following. The software used in this study can be freely downloaded with source code under a general public license from https://www.alrc.tottori-u.ac.jp/fujimaki/download/WASH_2D.

The actual transpiration rate, T_r, is computed by integrating the water uptake rate, S (cm s^{-1}), over the root zone (Feddes et al., 2004):

$$T_r = L_x^{-1} \int_0^{L_x} \int_0^{L_z} S d_x d_z \tag{8}$$

where L_x and L_z are the width and depth of the calculated root zone, respectively. The S was described as follows:

$$S = \alpha_w \beta T_p \tag{9}$$

where α_w, β, and T_p are reduction coefficient, normalized root density distribution, and potential transpiration rate (cm s^{-1}), respectively. The α_w is a function of matric (φ, cm) and osmotic potential (φ_o, cm), which is called stress response function. WASH_2D uses an additive form stress response function:

$$\alpha_w = \frac{1}{1+[\frac{\varphi}{\varphi_{50}}+\frac{\varphi_o}{\varphi_{o50}}]^p} \tag{10}$$

where φ_{50}, φ_{o50}, and p are fitting parameters (Van et al., 1987). The φ_{50} and φ_{o50} are heads when water uptake is decreased to 50% of its potential rate and therefore represent simple indices of the tolerance of crops.

The root activity, β , is described as (Fujimaki et al., 2014):

$$\beta = 0.75(b_{rt}+1){d_{rt}}^{-b_{rt}-1}(d_{rt}-z+z_{r0})^{b_{rt}}g_{rt}(1-x^2{g_{rt}}^{-2}) \tag{11}$$

where b_{rt} is a fitting parameter; d_{rt} and g_{rt} are the depth and the width of the plant root zone (cm), respectively; g_{rt} was set 20 cm according to the potato experiment we conducted in same site in 2020; z and z_{ro} are the soil depth and the depth below which the roots exist (cm), respectively; x is horizontal distance from the plant (cm). The d_{rt} is expressed as function of cumulative transpiration from germination, τ, as follows:

$$d_{rt} = a_{drt}[1-\exp(b_{drt}\tau)] + c_{drt} \tag{12}$$

where a_{drt}, b_{drt}, and c_{drt} are fitting parameters.

T_p is calculated by multiplying the reference evapotranspiration rate (ET_0, cm s^{-1}) with basal crop coefficient (k_{cb})as follows:

$$T_p = ET_0 k_{cb} \tag{13}$$

The ET_0 was calculated using Penman-Monteith equation (Allen et al., 1998) into which measured data in weather stations or weather forecast data were input. The k_{cb} is calculated as a function of τ as follows (Abd El Baki et al., 2018):

$$k_{cb} = a_{k_{cb}}\left[1-\exp\left(b_{k_{cb}}\tau\right)\right] + c_{k_{cb}} - d_{k_{cb}}\tau^{e_{k_{cb}}} \tag{14}$$

where $a_{k_{cb}}$, $b_{k_{cb}}$, $c_{k_{cb}}$, $d_{k_{cb}}$, and $e_{k_{cb}}$are fitting parameters, and the last term stands for the decline at last growth stage.

To make the plant growth dynamically respond to drought and salinity stresses, k_{cb} and d_{rt} were expressed as function of τ rather than calculate according to days after sowing. The values of these parameters are listed in the following section (section 2.5 (b)).

4.2.4 Simulation Procedure

The procedure to determine the irrigation depth in proposed scheme is shown in Fig. 4.1. For update produce, (1) the process began with downloading the last two days' weather data from weather station and preparing irrigation records file to set the atmospheric boundary condition, and water content profile at the end of the last update run as the initial condition in water flow module to perform a numerical simulation to update the soil water distribution. Left boundary condition and lower boundary condition were set as impermeable and gravitational flow, respectively. (2) Regarding solute movement module, the file containing solute concentration distribution output at the end of the last update run was input as initial condition, then, the concentration of infiltration water was input as upper boundary condition while zero concentration gradient was set as lower boundary condition. (3) Lastly, the cumulative transpiration was input in plant properties module to set as initial value.

Then, optimization procedure was carried out as follows: (1) the updated soil water distribution file and solute concentration distribution file output from the update run were input as initial condition in water flow module and solute movement module, respectively. Then, (2) weather forecast data (average air temperature, relative humidity, wind speed, solar radiation, and rainfall) until the next scheduled irrigation were input as atmospheric boundary condition to get optimized irrigation depth for that irrigation day. Other settings were the same as update procedure.

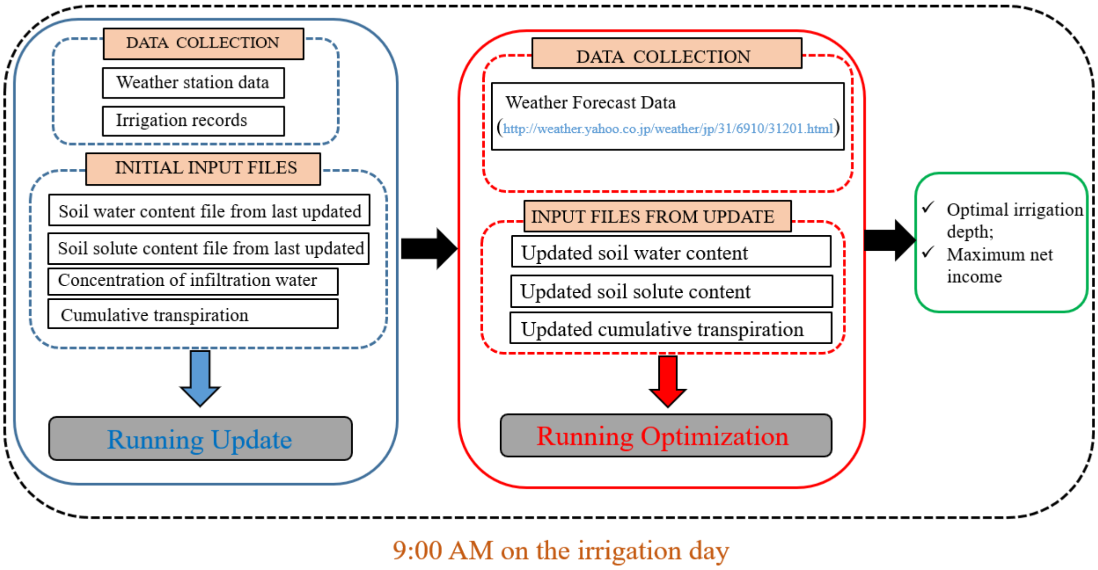


Fig. 4.1 Steps of the proposed irrigation depth determination schedule. Two main steps (Running Update and Optimization runs) were performed by WASH_2D at 9:00 AM of the irrigation day. Left blue box shows the first step of simulation (Update). The right red box shows the second step of simulation (Optimization). The black arrow between two boxes shows the directions of data flow.

4.2.5 Field experiment

(a). Treatments

Field experiments using potato were carried out for two-seasons at Arid Land Research Center (ALRC), Tottori, Japan, in 2021. Three treatments were established: (1) Automated irrigation (Treatment A), based on soil suction monitoring; (2) Refilling irrigation (Treatment R) to recharge simulated volumetric water content in the root zone to field capacity, which may correspond to meeting potential evapotranspiration from last irrigation; (3) proposed scheme (Treatment S1 in first season and S2 in second season). Each treatment had three replicates. Each replicate was established on a drainage lysimeter with a 2 m long, 2 m wide and 2 m deep, filled with the local sandy soil. The soil hydraulic properties of experiment site were shown in Fig. 4.2, which was measured by (Fujimaki et al., 2014). At the bottom of each lysimeter, a small tube to discharge drainage water was installed as depicted in Fig. 4.3. In this study, we measured the amount of drainage for each treatment by installing an ECRN-50 Rain Gauge

(METER Inc., Pullman, Washington, DC, USA). To evaluate the nitrate concentration (NO_3-N) in the drainage water, a plastic cup was set under the Rain Gauge to collect water per week (first season) and per two days (second season). The NO_3-N concentration was measured with IC_SI-90 4E (Shimadzu corporation, Japan).

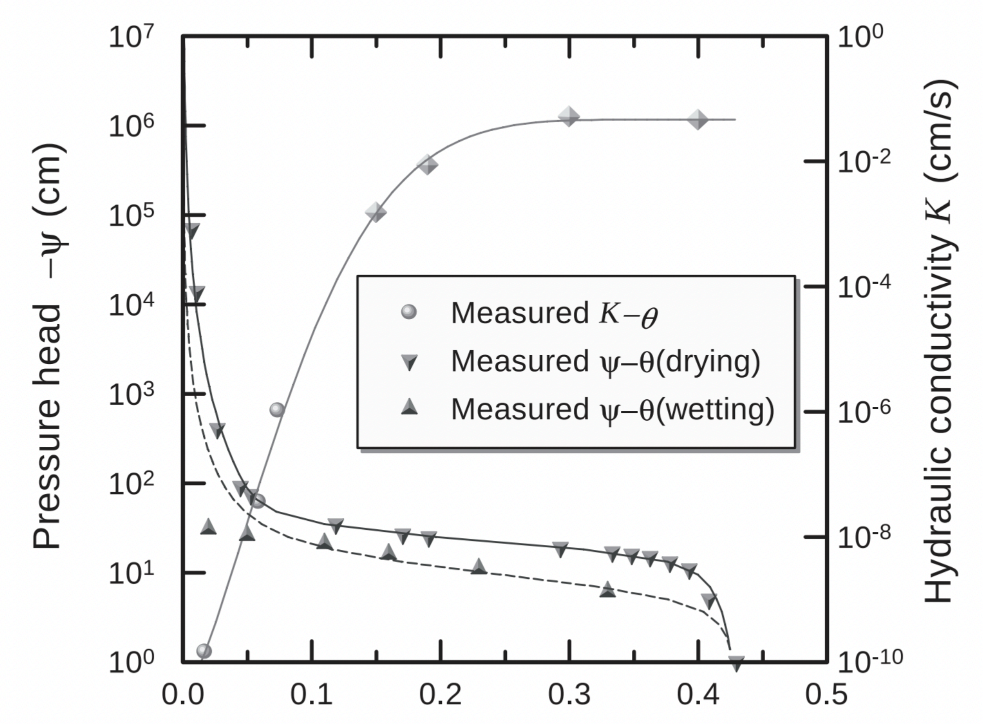


Fig. 4.2 Hydraulic properties of Tottori sand in the experiment site.

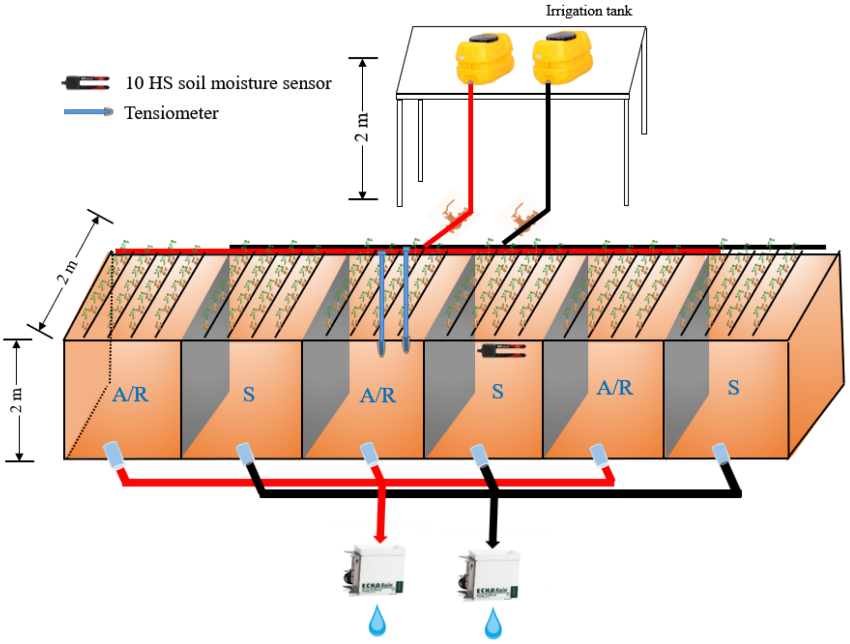


Fig. 4.3 Schematic representation of the experimental setup. The red tube connected to left yellow water tank was arranged for irrigation of A/R plots and black tube connected to right side was for S plots (A/R stands for Automated irrigation in first season or Refilling treatment in second season, S stands for Schemed irrigation). There were four 10 HS sensors installed at different position of soil profile in the middle plot of S treatment (only one shown in Fig). Two 20 cm tensimeters were installed at the middle plot of A/R.

(b). Plant

Potato seed pieces about 30 g (*cv. Nishiyutaka*) were planted every 20 cm at a depth of 15 cm in row spaces 50 cm apart. The sowing, harvest time and total irrigation amount of two seasons were listed in Table 4.1. The potato sprouts germinated in four weeks after planting. The values of drought and salinity stress parameters (φ_{50} and φ_{050}) included in a widely used macroscopic root water uptake model (Feddes et al., 1978; Feddes et al., 1998), were determined by a cost-effective and reliable method presented by Fujimaki et al (2008) before the field experiment. Parameter values of stress response, normalized root density distribution and the depth of root zone functions of potato were listed in Table 2. We set the price of crop at 1 ($ kg^{-1} DM) by referring to the prices received by producers in the USA in 2011 (FAOSTAT, http://faostat.fao.org/) and set price of water at 0.00025 $ kg^{-1} (Cornish et al., 2004). The parameter values of crop coefficient in Eq. (14) were determined by fitting K_{cb} value and cumulative transpiration amount. The K_{cb} value of potato were derived in Table 17 of Allen et al (1998), and daily K_{cb} value was determined by dividing the growing period into four general growth stages and selecting and adjusting the K_{cb} value corresponding to the initial, mid-season and end of late season stages. Meanwhile, according to the local weather condition, the average ET_0 value during initial, development, mid and last stage were set as 3, 4, 5, 5 mm d^{-1}, respectively. The fitting curve is drawn in Fig. 4. During the growing period, leaf area index (LAI) and above ground biomass (g plant^{-1}) were measured four times at key stages. At harvesting, the aboveground fresh weight (FW) and belowground tubers were determined by harvesting all the plants from an area of 1 m^2 in each plot center, leaves, stems and tubers were separately measured. After recording their fresh weight, the samples of potato biomass were oven-dried at 105 °C for two hours and 65 °C to constant weight to determine their dry weight (DW). Subsequently, dried tuber, straw (leaf and stem) were pulverized with a micro plant grinding machine (BMS-A20TP, Biomedical Science Co., Tokyo, Japan) and then sieved manually through 0.5 mm mesh. The nitrogen content of each part was measured with CN coder (Micro Coder JM10, J-Science Lab Co., Tokyo, Japan).

Table 4.1

Dates of sowing and harvest as well as irrigation amount during two growing seasons of potato.

Seasons	Treatment	Dates of sowing (m/d)	Dates of harvest (m/d)	Growth period (days)	Total irrigation amount (mm)
First season	A	Mar.19	Jul.17	120	286
	S1				207
Second season	R	Aug.27	Dec.8	103	99
	S2				115

Note: A stands for Automated irrigation, S1 stands for Simulated irrigation in first season, R stands for Refilling treatment, S2 stands for Simulated irrigation in second season.

Table 4.2

Parameter values for plant stress response and growth properties used in the numerical modeling in this study.

Parameter	Value	Remarks
P_w	0.00025	
P_c	1	Eq (1)
ε	0.002	
$a_{k_{cb}}$	1.03	

$b_{k_{cb}}$	-0.37	Eqs. (2) and (14)
$c_{k_{cb}}$	0.15	
$d_{k_{cb}}$	1.40E-07	
$e_{k_{cb}}$	4.6	
φ_{50} (cm)	-100	Eq. (10)
φ_{050} (cm)	-8200	
p	2.9	
b_{rt}	1	Eqs. (11) and (12)
g_{rt}	20	
z_{rt}	1	
a_{drt}	40	
b_{drt}	-4	
c_{drt}	10	

Note: the meaning of each parameter was explained in corresponding formula site.

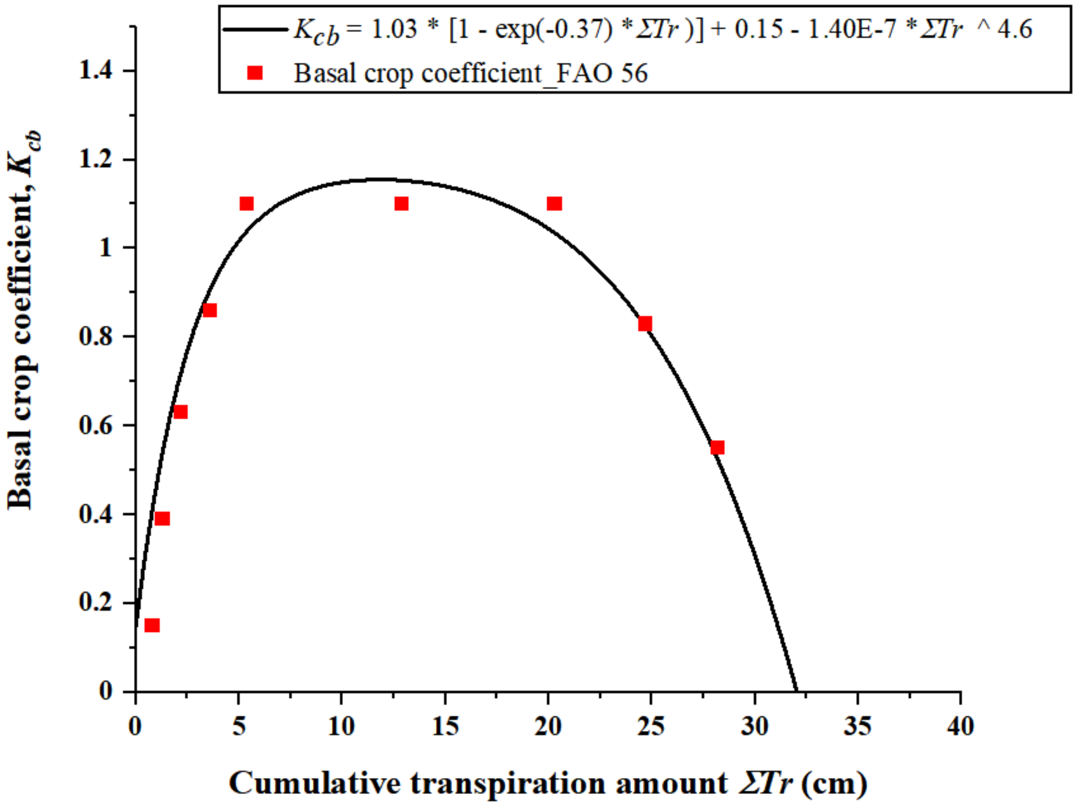


Fig. 4.4 The basal crop coefficient (K_{cb}) of potato as a function of cumulative transpiration ($\sum Tr$) (parameter values of K_{cb} function were obtained by fitting to values reported by Allen et al (1996).

(c). Irrigation and fertilizer

Four drip irrigation tubes with a discharge rate of 1L h^{-1} per emitters were set in each plot, and the lateral and emitter distance spaced as 50 cm and 20 cm respectively as depicted in Fig. 4.3. Irrigation interval for S and R was set at two days, because the field capacity of the sandy soil in experiment site was only 0.09 cm^3 cm^{-3}. Automated irrigation was triggered when the average readings of two tensiometers installed at the depth of 20 cm around plant was over than 45 cm, which was slightly higher than suction at field capacity and suitable for crop growth in sandy soil. To check the accuracy of volumetric water content (VWC) of the model simulated, four 10HS sensors (METER Inc., Pullman, Washington, WA, USA) were inserted into the soil profile at 4 observation points (x, z): (0, 5), (0, 45), (10, 10), (25, 5), respectively, where x is the horizontal distance (cm) from drip tube. The calibration function of 10HS sensor is shown in Fig. 4.5. Composite liquid fertilizer with N-P-K at 8%-4.3%-4.2% was supplied with irrigation water by applying constant amount per irrigation event, while granular fertilizer N-P-K at 8%-3.5%-6.6% was supplied at tuber filling stage. The total N supplied was 152 and 155 kg ha^{-1} for A and S1 in the first season, and 97 and 99 kg ha^{-1} in the second season for R and S2, respectively. The reason for less supplement of fertilizer in second season was frequent rainfall and decreased air temperature, which reduced irrigation times.

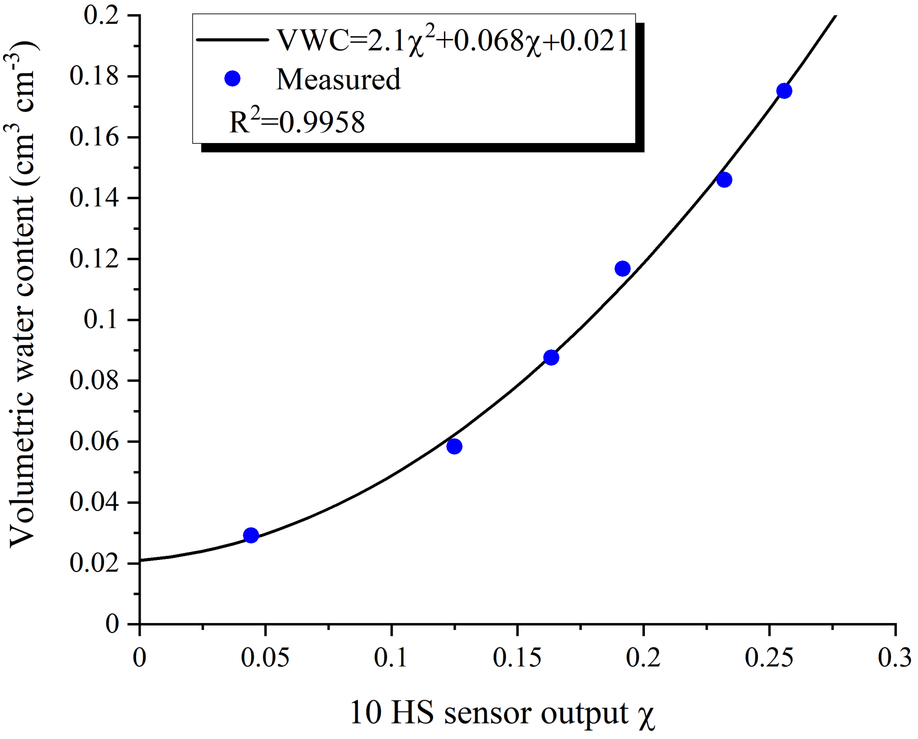


Fig. 4.5 Calibration function for 10 HS sensor in sandy soil in experiment plot.

(d). Weather data

Weather data was collected from weather station located at 50 m away from the field. Weather forecast data was downloaded by a utility program (WeatherForcestDownloader, available from our website: http://www.alrc.tottori-u.ac.jp/fujimaki/download/WeatherForcestDownloader), which can be used to extract 2 days of local WF data from the website of Yahoo! Japan (http://weather.yahoo.co.jp/weather/jp/31/6910/31302.html). Solar radiation data is not included in this website, instead, classes of cloud such as “rain”, “cloudy”, or “clear” were provided. To obtain the exact solar radiation value, an empirical relationship, 1-0.006 × cloud cover (%) (cloud cover (%): “clear” =82%, “cloudy” =63%, and “rain” =32%), was multiplied by extraterrestrial radiation (Fujimaki et al., 2014).

4.2.6 Nitrogen uptake efficiency

Plant nitrogen uptake were calculated using the following equations:

$$N_{uptake} = N_{tuber}Y_{tuber} + N_{straw}Y_{straw} \tag{15}$$

$$NU_pE = N_{uptake}/N_{supply} \tag{16}$$

where N_{uptake} is nitrogen uptake (kg ha^{-1}); N_{tuber} and N_{straw} are nitrogen content in tuber and straw (kg kg^{-1}), respectively; Y_{tuber} and Y_{straw} are biomass yields of tubers and straw (kg ha^{-1}), respectively; Where NU_pE is nitrogen uptake efficiency (kg ha^{-1}); N_{supply} is total nitrogen supplied during crop growth period (kg ha^{-1}).

To evaluate the nitrate content of each soil layer, soil samples at different depths (0-50 cm, 10 cm as increment) were collected. Each treatment had three replicates, and the nitrate content in the fresh soil were extracted with 1 M KCl (20g soil: 100 ml KCl solution) and quantified at 220 nm using UV spectrophotometer (UV-1900i, SHIMADZU co., Kyoto, Japan). The nitrate nitrogen stocks (NNS) at different soil depths were calculated using following equations:

$$NNS_i = NNC_i \times BD_i \times D_i \times 0.1 \text{ } (\mathrm{i}_{1,2,3,4,5} = \text{0-10, 10-20, 20-30, 30-40, 40-50}) \tag{17}$$

$$NNS_{0-50} = NNS_{i1} + NNS_{i2} + NNS_{i3} + NNS_{i4} + NNS_{i5} \tag{18}$$

where NNS_i and NNC_i are nitrate nitrogen stock (kg ha^{-1}) and nitrate nitrogen content (mg kg^{-1}) at the different soil layer (0-50 cm) respectively. BD_i is bulk density (g cm^{-3}) at the different soil layer, D_i is depth of each layer (m).

The nitrate leaching in each of the two seasons was determined by multiplying the nitrate concentration in soil solution with the drainage volume. The nitrate concentration during two sample periods were determined by linear interpolation method.

4.2.7 Soil water balance equation

The soil water balance equation used for estimating actual evapotranspiration (ET_a) is as follows:

$$ET_a = P + I + SWD - D \tag{19}$$

where P is the cumulative precipitation from onset to end (mm); I is the cumulative depth of irrigation from onset to end (mm); SWD is soil water depletion from onset to end (mm); D is drainage amount (mm).

4.2.8 Statistical analysis

The experiment was conducted with three treatments and three replicates per treatment. Data are presented in graphs and tables as means of three replicates, whereas in the graphs the standard. One-way ANOVA was conducted to analyze different factors among different treatments. The least significant difference (LSD) test ($P<0.05$) was conducted when the differences were significant. Figures were created using OriginPro 2020 (OriginLab Inc., MA, USA). The performance of model was evaluated using the root mean square error (RMSE) of VWC, which was calculated as follows:

$$RMSE = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2/n} \qquad (20)$$

where n is the number of measured or simulated data; x_i is the measured VWC; y_i is the estimated VWC.

4.3 Results and discussion

4.3.1 Weather conditions

The values of daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), solar radiation (R_s) and mean relative humidity (RH_{mean}) of two growing seasons are shown in Fig. 4.6. The mean maximum temperature was 21.7 and 22.2°C, the mean minimum temperature was 13.7 and 14.9°C, and the mean solar radiation was 13.3 and 8.0 MJ m^{-2} d^{-1} for the two seasons, respectively. The growing degree days (GDD) of potato was 1607.6 and 1419.8 °C in two seasons, respectively, which was acceptable for final harvest (Martínez-Romero et al., 2019). The RH_{mean} of 74.4% in first season and 74.8% in second season was similar. Lower R_s and temperature at tuber building period in second season affected the yield production.

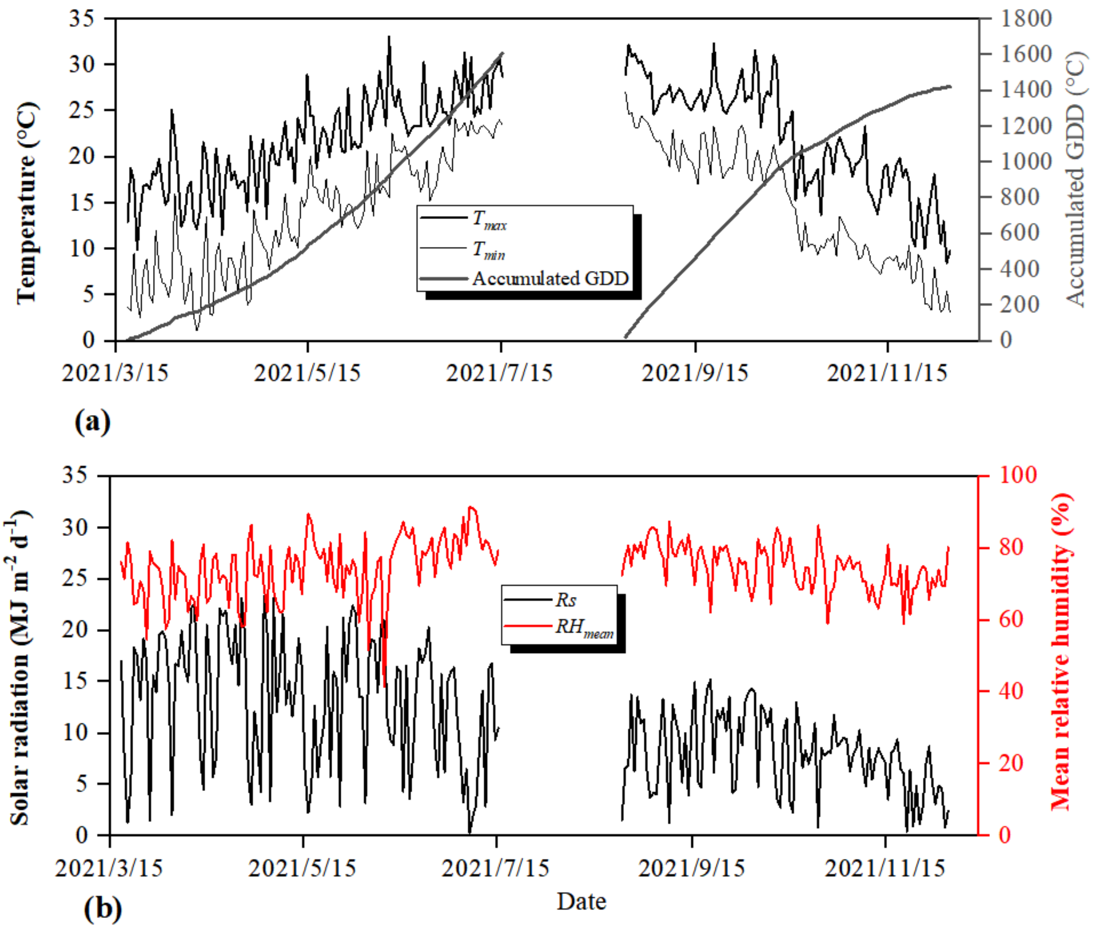
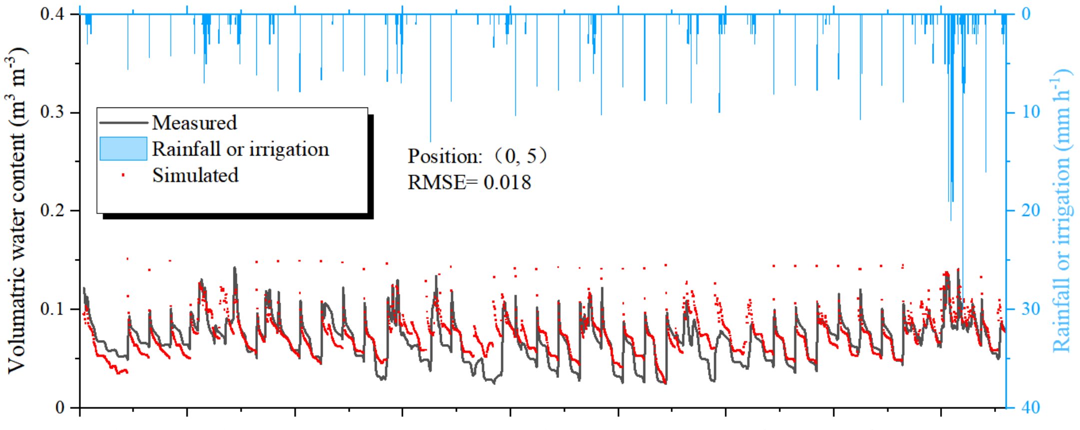


Fig. 4.6 Meteorological condition from sowing to harvest of potato in two growing seasons in 2021. (a) daily maximum temperature, minimum temperature, and accumulated growing degree days (T_{max}, T_{min}, and Accumulated *GDD*, respectively), (b) solar radiation (R_s) and mean relative humidity (RH_{mean}). Accumulated $GDD = [(T_{max} + T_{min}) / 2 - 4.4$ °C], base temperature was set at 4.4 °C (Williams et al., 2006).

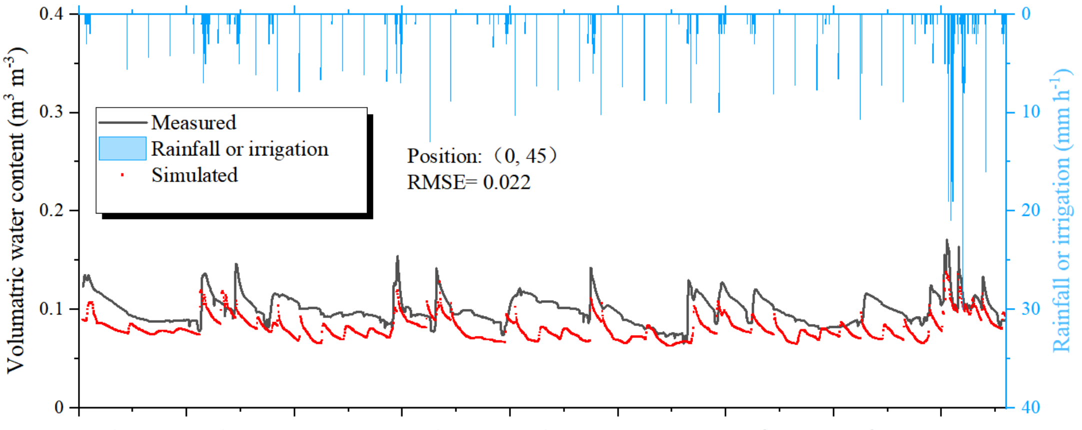
4.3.2 Soil water content change

To evaluate the accuracy of model simulation, we compared the measured and simulated volumetric water content (VWC) of treatment S. The simulated VWC was derived from the result of update procedure at each irrigation event, where weather station data was input as upper boundary condition. Fig. 4.7 shows the measured and simulated VWC change at the depth of 5 cm and 45 cm below the drip tube in two seasons. The RMSE of VWC at the depth of 5 cm (Fig. 4.7 (a) and (c)) during the two seasons were 0.018 and 0.024 m^3 m^{-3}, respectively, which indicates that WASH_2D model could simulate soil moisture change in fair agreement. However, model overestimated the VWC at the time when irrigation or rainfall just occurred. The reason of this overestimation would be because of an underestimation of hydraulic conductivity when the VWC at around 0.12 m^3 m^{-3}.

At the depth of 45 cm (Fig. 4.7. (b) and (d)), VWC significantly increased when there was a heavy or continuous rainfall, such as, April 29 and May 2 in the first season, and October 17, 23 in second season. The RMSE at the depth of 45 cm was 0.022 and 0.014 m^3 m^{-3} in the first and second season, respectively, indicating that simulated and measured VWC were in fair agreement at deep zone.



(a)



(b)

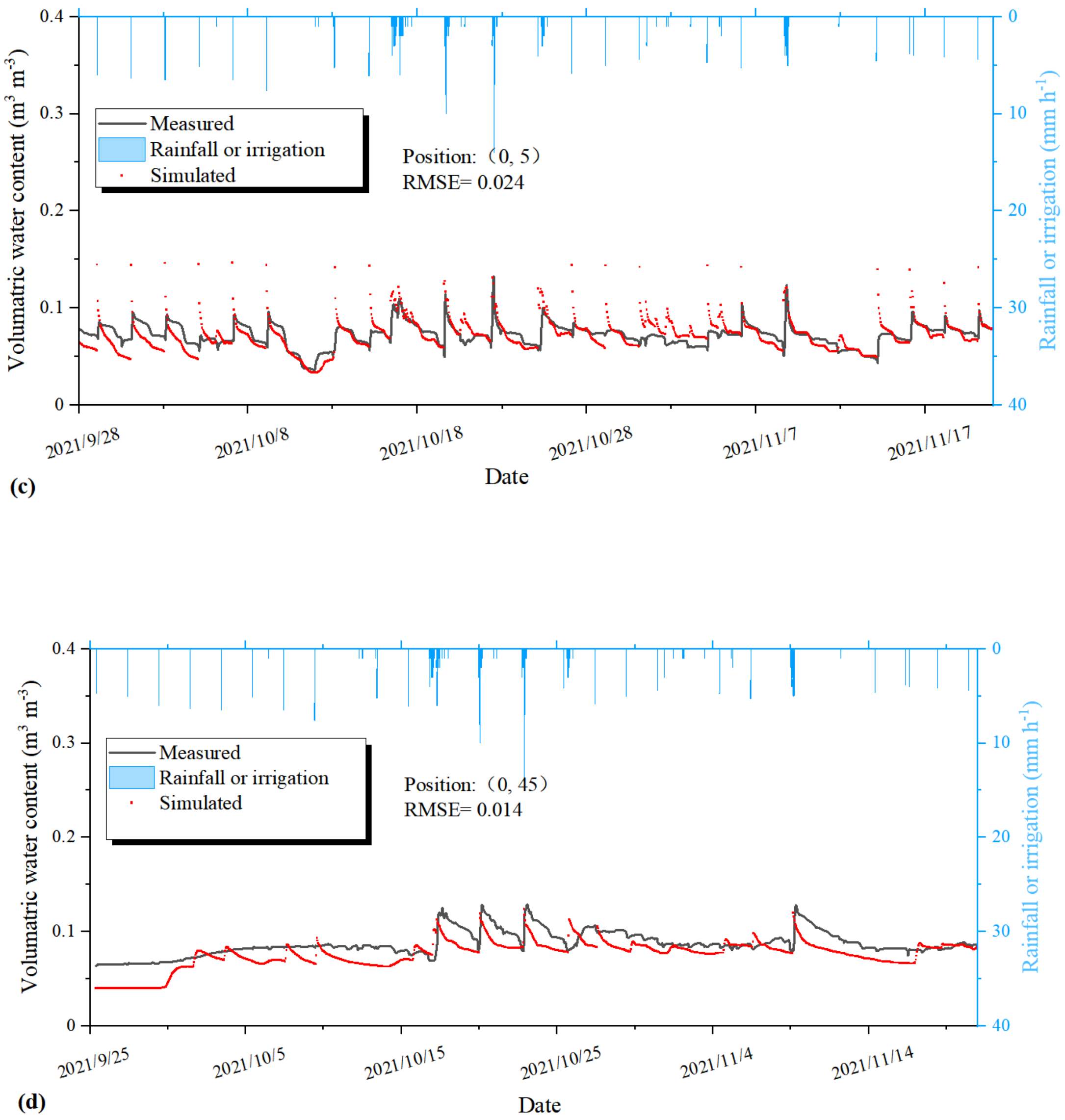


Fig. 4.7 Comparison of simulated and measured VWC of treatment S at the depth of 5 cm and 45 cm below the drip tube in two seasons. (a) and (b) are the VWC at the site of (0, 5) and (0, 45) in the first season, respectively; (c) and (d) are the VWC at the site of (0, 5) and (0, 45) in the second season, respectively. RMSE is root mean square error.

4.3.3 Evapotranspiration

To compare the simulated ET_c and measured ET_a, two periods in each season were chosen as shown in Fig. 4.8. ET_c of automatic and refilling treatments were also simulated by entering irrigation records and actual weather data into the model to compare the outputs with measured data. Daily average ET_a calculated using Eq. (19) were estimated between two heavy rainfall events, assuming the same VWC at field capacity in the root zone and hydrostatic profile in the deeper layer (0.09 m^3 m^{-3}) at one-day after heavy rainfall. The simulated ET_c in the first season was higher than measured ET_a, which might be mainly caused by the overestimation of basal crop coefficient growth This overestimation may be avoided by measuring basal crop coefficient as a function of cumulative transpiration. In the second season, the simulated ET_c agreed well with measured one. Overall, the RMSE between measured and simulated was 0.8 mm day^{-1}. In addition, we also compared the simulated daily ET_c of different treatments with ET_0. As shown in Fig. 4.9, those of automated scheme was higher than those of simulated scheme in first season and has no difference in the second season. The cumulative ET_0 and ET_c of, S1, and A in the first season were 190, 175 and 189 mm, while those in the second season were 76, 70 and 67 mm for ET_0, S2 and R, respectively.

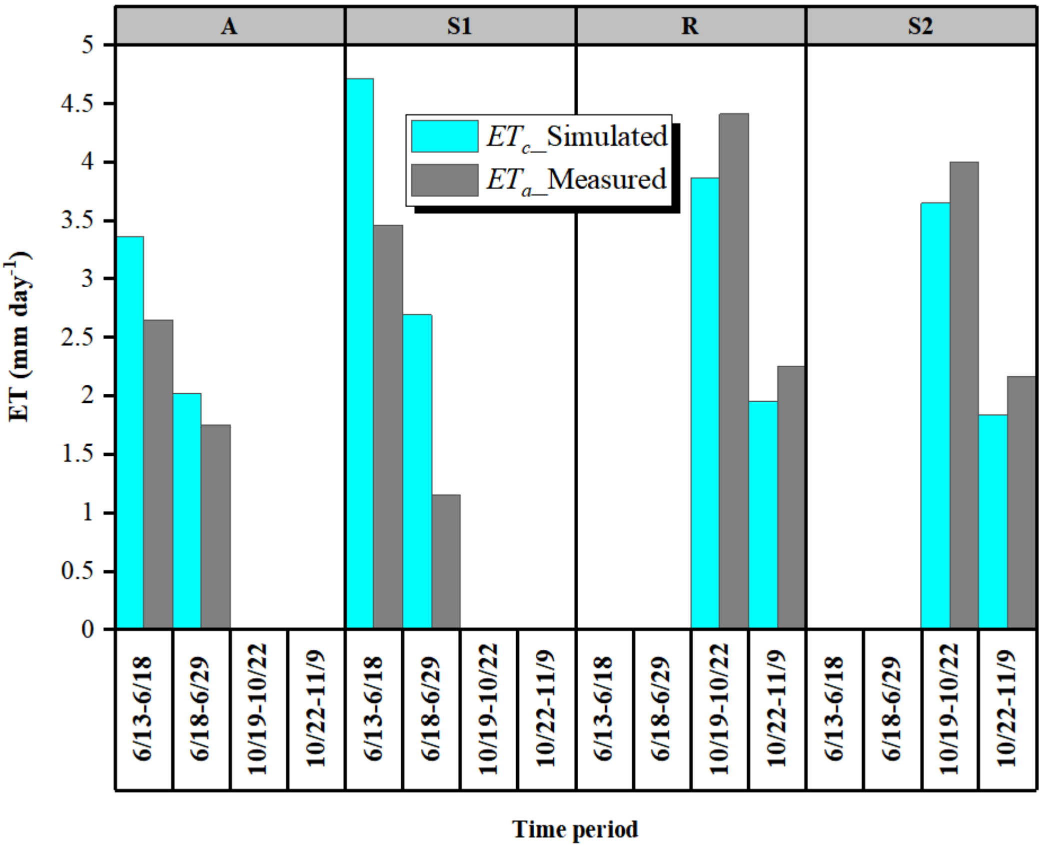


Fig. 4.8 Comparison of measured ET_a and simulated ET_c under different treatment in two seasons. (6/13-6/18 and 6/18-6/29 time periods were chosen for the first season, 10/19-10/22 and 10/22-11/9 time periods were chosen for the second season)

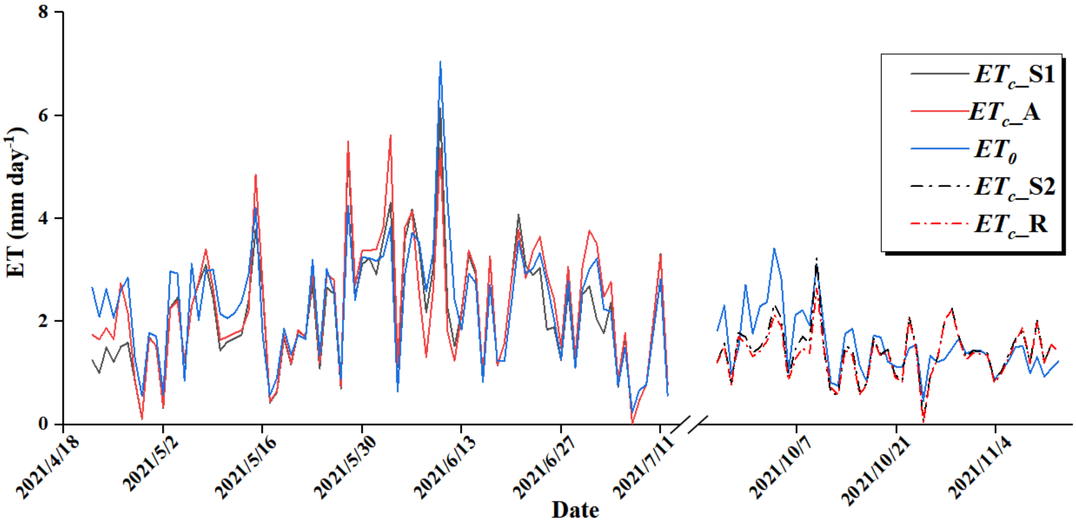


Fig. 4.9 Time evolution of the reference ET (ET_0) and daily ET_c of different treatments during crop growth period in two growing seasons.

4.3.4 Growth of potato

Fig. 4.10 shows the LAI and above ground biomass (AGB) of potato measured in the two seasons. LAI and AGB are important indicators of crop growth, which determine the light interception capacity of the crop and photosynthetic accumulation of crop (Kross et al., 2015; Weraduwagel et al., 2015). Both LAI and AGB had no significant difference at establishment and stolon initiation stage (15<DAP<40) in two seasons. But at the tuber initiation and filling stage (45<DAP<90), S1 and S2 were significantly higher than A and R in the first and second season, respectively, no matter for LAI or AGB. This situation might be due to higher nutrient utilization of S, especially nitrogen (N), a macronutrient that promotes carbon metabolism and plant growth, leading to biomass accumulation (Gao et al., 2020). At the maturity stage (DAP>90), both LAI and AGB decreased due to leaf senescence. It should be noted that the smaller canopy structure of potato in the second season led to delayed growth and reduced final yield, which mainly comes from low temperature and solar radiation during the critical growth stage.

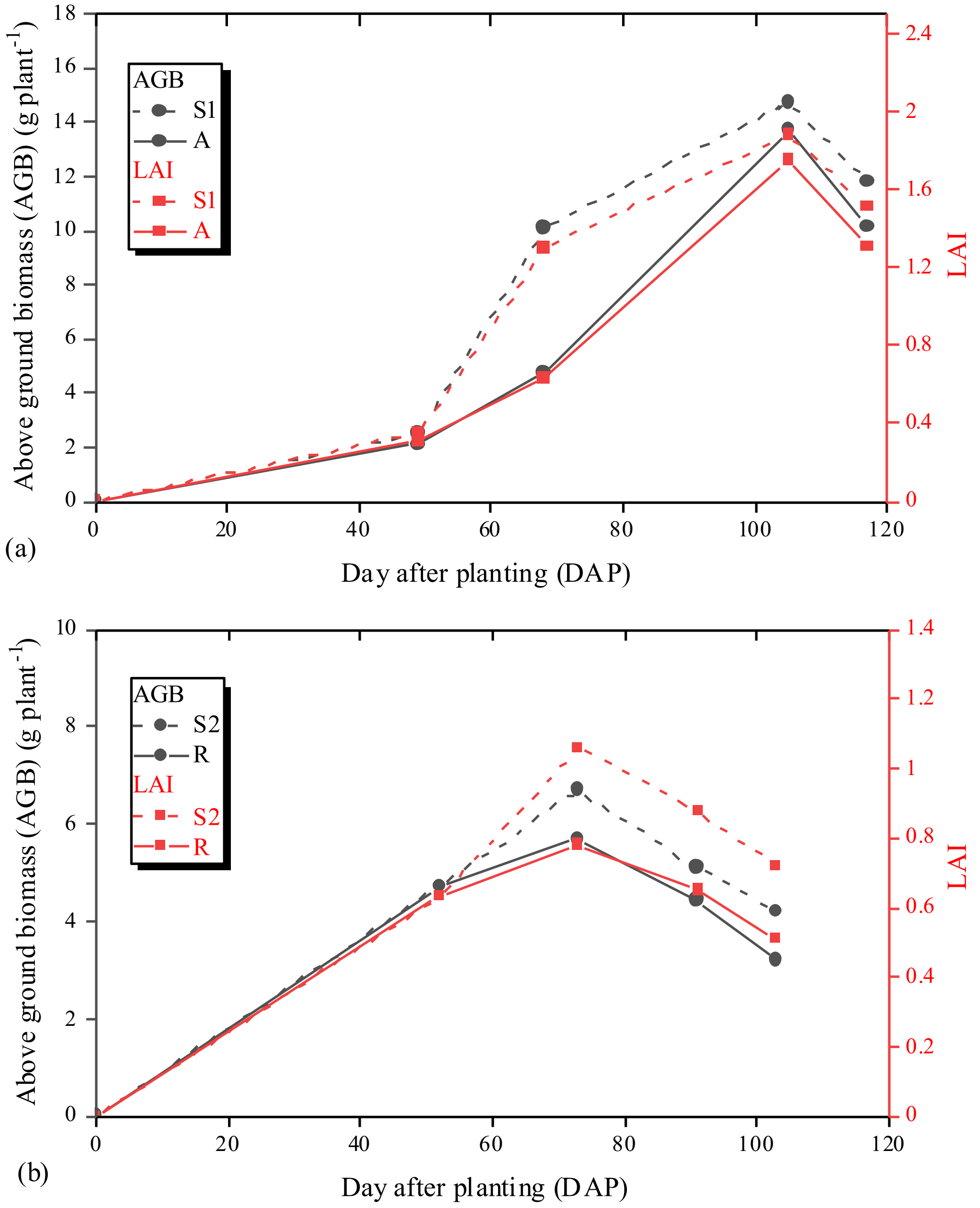


Fig. 4.10 The time evolution of LAI and AGB for the potato under different treatments in first season (a) and second season (b).

4.3.5 Yield and net income

Fig. 4.11 compares yield and net income of three different treatments in two seasons. We counted only cost for fertilizer only to calculate C_{ot} in eq. (1) by multiplying the total amount of fertilizers used and the price of the fertilizer. In the first season, the yield and net income of S1 were 19% and 19% higher than A, respectively. At the same time, S1 reduced 28% of irrigation water compared with A. These results coincide with the previous experiments by Abd EI Baki et al (2020) using corn. In the second season, S2 and R had no significant difference for both yield and net income. The yield and net income of schemed treatment in the second season was decreased by 41% and 41% compared with former season, respectively, and obtained similar values compared with R. The low temperature at maturity stage and solar radiation at whole growth stage (Fig. 4.6) may have restricted the photosynthesis and lead to a lower production. Considering the water consumption and yield production at two seasons, proposed irrigation scheme saved water and improved farmers' net income.

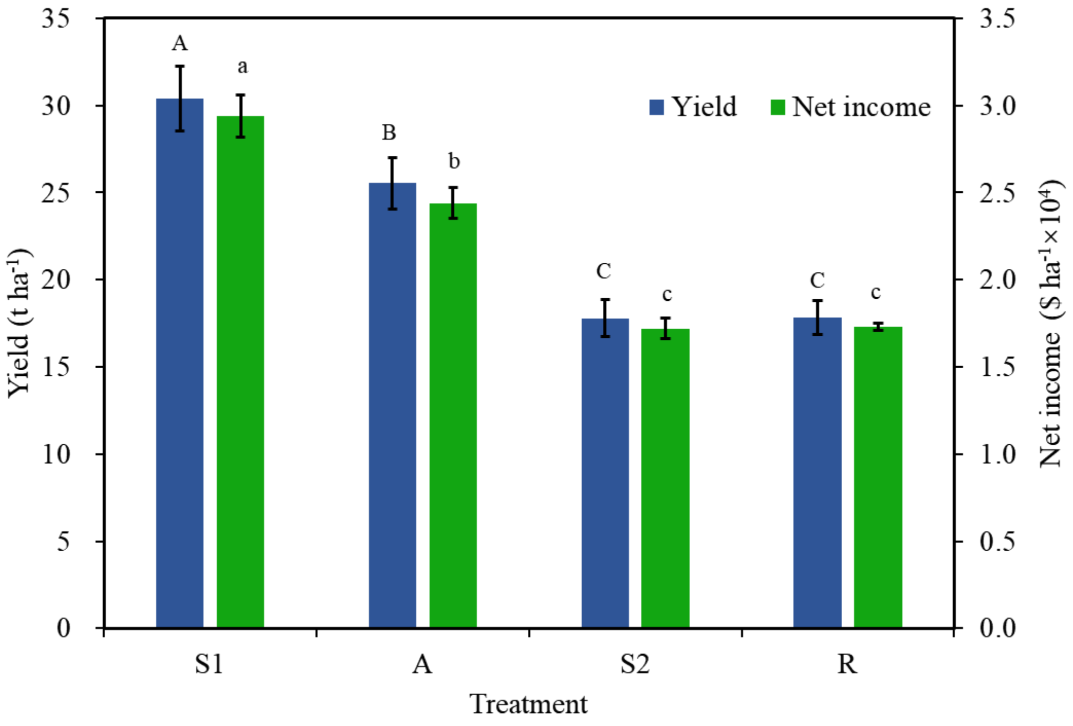


Fig. 4.11 Comparison of yield and net income of different treatments in two seasons. (The error bars show the standard deviation of three replicates. The different uppercase letters indicating

significant difference of yield under different treatments at *P<0.05*, while the lowercase letters indicating significant difference of net income under different treatments at *P<0.05*).

4.3.6 Nitrogen uptake and nitrate leaching

The nitrogen storages in each part of potato are listed in Fig. 4.12. The total nitrogen uptake for A and S1 in the first season were 138 and 182 kg ha^{-1} while that for R and S2 in the second season were 95 and 97 kg ha^{-1}. The NU_PE of S1 and S2 were 39% and 11% higher than A and R, respectively. Among that, the nitrogen storage in the tuber was the highest. The discrepancy of nitrogen uptake between two seasons was due to less nitrogen input and dry matter in the second season. The higher nitrogen uptake may have contributed to higher yield.

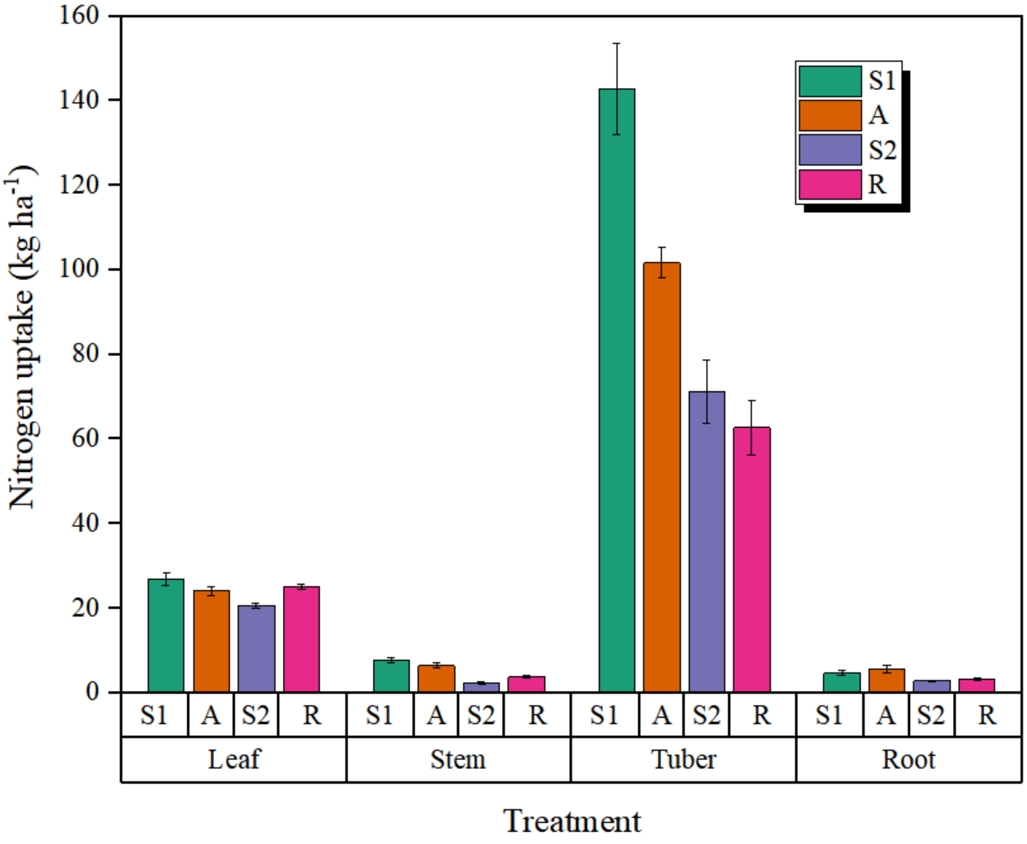


Fig. 4.12 Nitrogen uptake of the different parts (Leaf, stem, tuber and root) of crop under different irrigation schemes in two seasons (The error bars show the standard deviation of three replicates).

As shown in Fig. 4.13, the accumulative nitrate leaching at the outlet of the lysimeters of S1 and S2 were 105 and 54 kg ha^{-1}, which were 51 and 22% higher than A and R, respectively. The higher nitrate leaching in the first season is likely due to higher N supply and evenly distributed irrigation and precipitation. Though the total irrigation amount of A was higher than S1 in first season, the irrigation activities were concentrated in the early stage, while during late growth stage, less water was supplied due to large amount of rainfall. Such as from June 3 to 23, there was only 4.8 mm irrigation for A. Another possible reason is that frequent irrigation in treatment S increased the chance of nitrate leaching, while large amount of irrigation in treatment A for each time diluted the concentration of nitrogen. According to the results of this study, intensive irrigation might lead to nitrate leaching. In addition, we further analyzed the relationship between the nitrate leaching and water supply in terms of precipitation plus irrigation during second season (Fig. 4.14). The linear regression can describe the relationships well between precipitation plus irrigation and nitrate leaching (R^2=0.80). Huang et al [36] also reported similar relationship between monthly precipitation plus irrigation and monthly nitrate leaching. The accumulated soil nitrate after crop harvest matched the accumulative nitrate leaching. Higher accumulated soil nitrate of A and R (550 and 78 kg ha^{-1}) coincide with lower nitrate leaching in the two seasons, respectively. Furthermore, we also measured the soil nitrate content at different soil depths to evaluate the soil nitrate distribution at root zone (Fig. 4.15). The nitrate content of A changed from 5.1 to 10.8 kg ha^{-1} at 0-50 cm soil layer in first season, higher than that of S1 except for the depth of 30-40 cm. The same trend was obtained in the second season, nitrate content of R ranged from 8.0 to 14.3 kg ha^{-1}. The increment of soil nitrate content in the second season might be due to decreased amount of precipitation plus irrigation (average 297 mm) compared with the first season (average 807 mm), resulting in a decrease in nitrate leaching and an increase in soil nitrate stock.

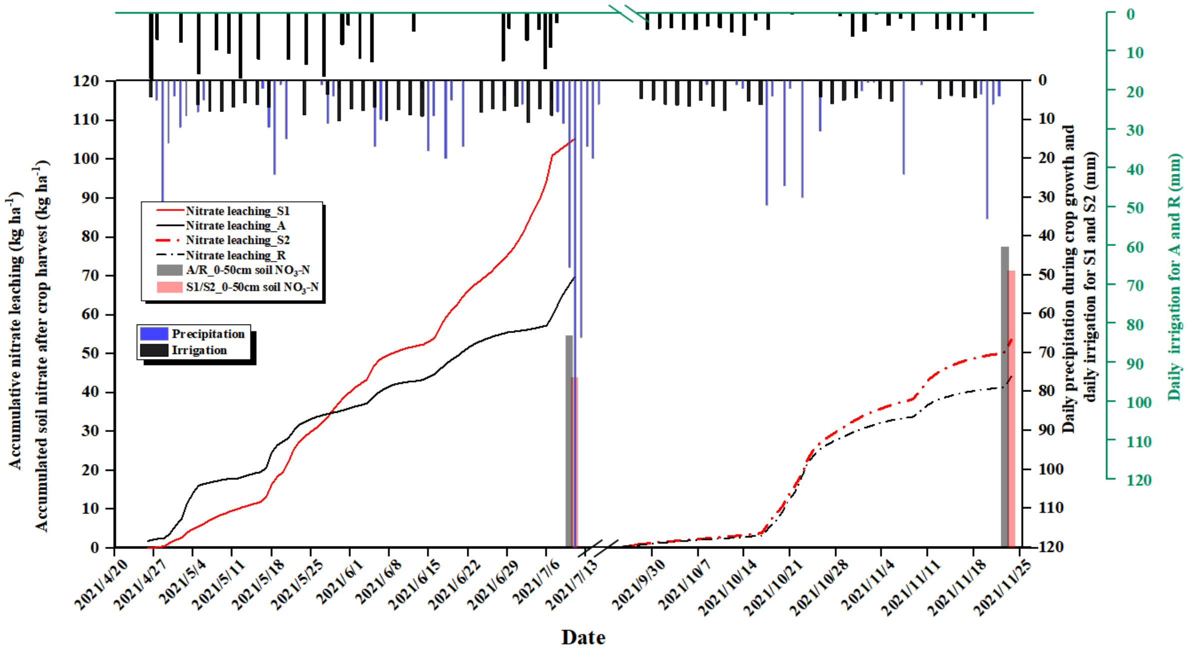


Fig. 4.13 Accumulative nitrate leaching (2 m soil depth) during the growing period and accumulated soil nitrate content after crop harvest at 0-50 cm root zone depth (left axis); Daily precipitation amount in two seasons and daily irrigation amount for S1, S2, A and R (S1 and S2 using inner right axis, while A and R using outer right axis).

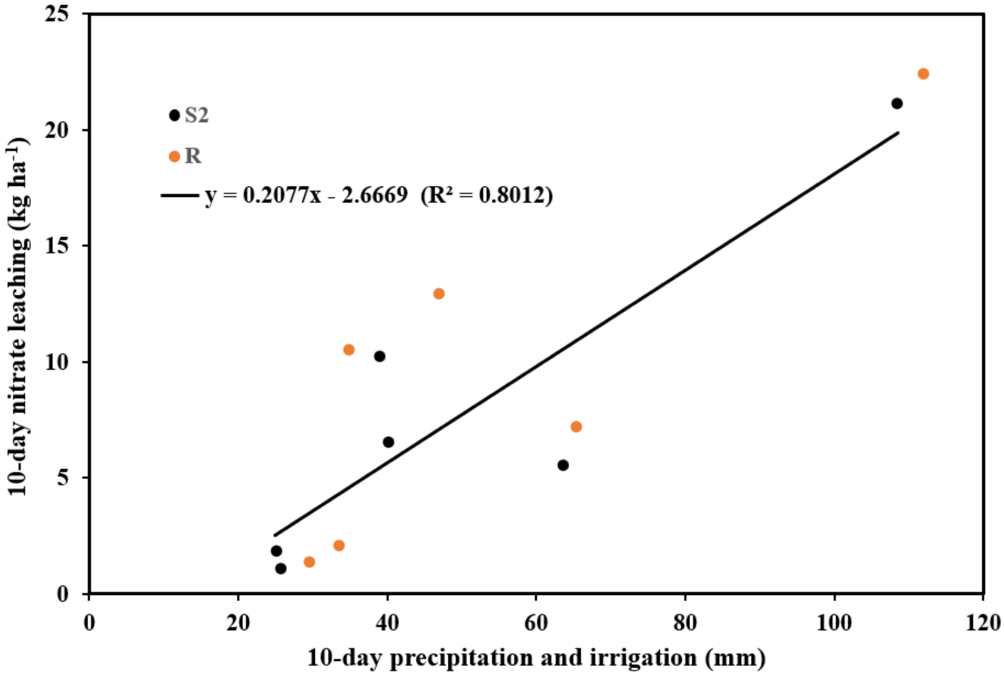


Fig. 4.14 Linear regression between 10-day precipitation plus irrigation and 10-day nitrate leaching at 2 m soil depth in second season.

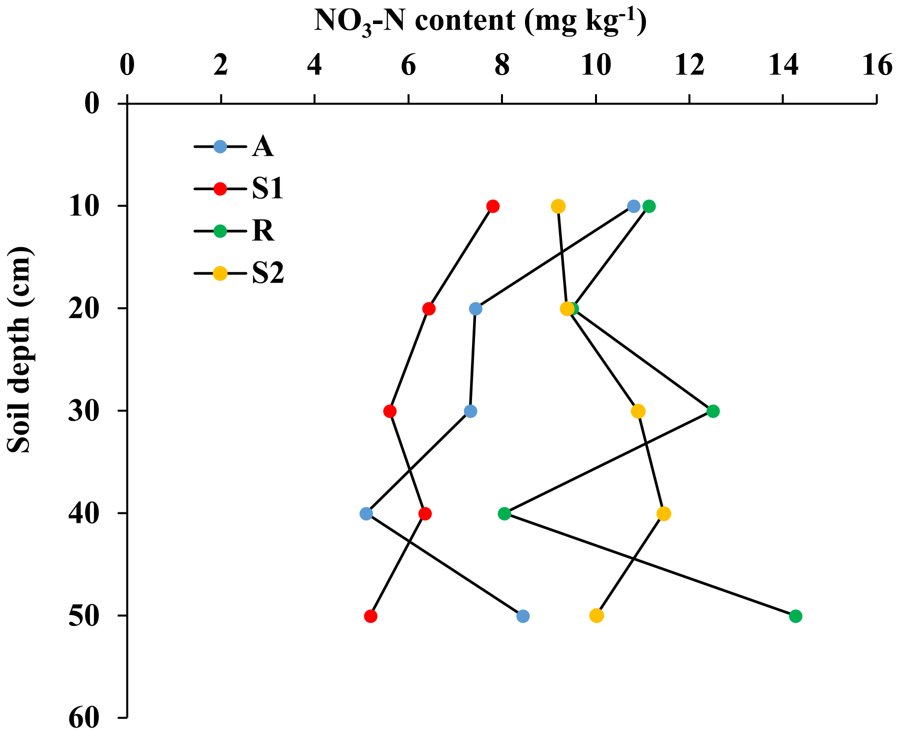


Fig. 4.15 Soil NO3-N content at different soil depths under different treatments in two seasons.

4.3.7 Accuracy of weather forecast

The accuracy of weather forecast has a large effect on the performance of model simulation. Fig. 16 compares between observed weather data from weather station and forecast weather data. Because WF does not include data beyond 24:00 of the second day, we discard time period during night (from 0:00 to 9:00). The average temperature and relative humidity, as primary inputs weather data in model, matched well with measure data, with the RMSE of 1.7 °C and 10.2 %, respectively. The rainfall, as an indirect factor modifying many of the crop growth and developmental processes (Hoogenboom et al., 2000), with the RMSE of 9.5 mm, which was not matching well with the measured data and may affect the recommendation of irrigation depths from model. For example, on June 19, 16 mm rainfall was forecast and therefore no irrigation was recommended from model, but actually no rain occurred (Fig. 4.13). This situation may lead to temporary drought stress on crop. Although there was a large difference between the rainfall amount of weather forecast and measured one, the derived parameter, ET_0, calculated by forecasted data were in fair agreement with the measured ones, with an RMSE of 0.9 mm, which was acceptable. Since the accuracy of ET_0 is important to optimize irrigation depth as explained in Eqs. (1), (8), (9) and (13), if the prediction of ET_0 is within the acceptable range, the first term of Eq. (1) could be estimated in fair accuracy. In addition to advance in climatology and steadily increasing speed and memory of super computers used for running general circulation models, deep learning model is being used to improve the accuracy of weather forecast model such as European Centre for Medium-Range Weather Forecasts (ECMWF) or performed well compared with standard numerical weather prediction (Frnda et al., 2022). Thus, we can expect the accuracy of weather forecast will keep improving. Although the prediction of rainfall was out of expectation, the proposed scheme performed better in production and net income compared with other irrigation methods.

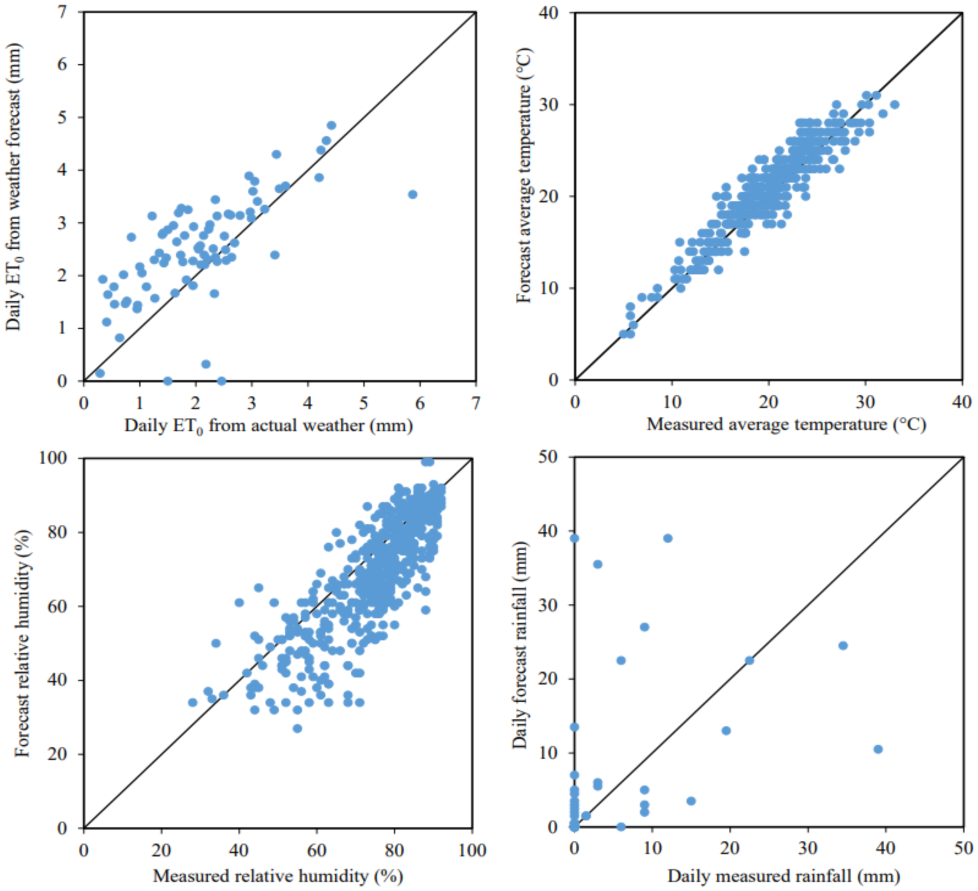


Fig. 4.16 The comparison between weather station measured and forecast weather factors. (a) reference evapotranspiration (ET_0), mm; (b) hourly average temperature, °C; (c) hourly relative humidity, %; (d) daily rainfall, mm.

4.4 Conclusion

A newly proposed irrigation scheme incorporating WF and targeting with maximum net income by running a numerical model, WASH_2D, was applied to potato cultivation on a sandy soil for two seasons, which could save one third time compared with original scheme proposed by Fujimaki et al (2014). In this study, net income using proposed irrigation scheme was compared with an automated and refilling irrigation scheme in two seasons. During the first season (from April to July), treatment S1 obtained 19% higher net income and 19% larger yield, and saved the water by 28% compared with A. Meanwhile, compared with A, the nitrogen uptake of S1 was improved by 39%. In the second season (from August to December), due to low temperature and solar radiation at late growth stage, the total irrigation amounts of S2 and R were halved of those in the first season, which lead to lower yield. Although the yield and net income of two treatments in the second season has no significant difference, S2 improved nitrogen uptake by 11% compared with R, which suggests that the scheme may contribute for reducing fertilizer input. As for the accuracy of model, the simulated values of water content were in fair agreement with those measured in the root zone. As for the accuracy of weather forecast, although there was somewhat large deviation between the predicted rainfall and measured one, the derived comprehensive weather factor, ET_0, were within acceptable error range. Contribution of rainfall in drylands to total water supply is far lower than that in the place where this study was carried out. On the other hand, as explained in the text, the higher nitrate leaching of the proposed irrigation scheme compared with other two irrigation schemes under the current sandy soil and climate condition should also be noted. Considering the improved NU_PE and net income, reducing fertilizer inputs would be one of the options to eliminate the nitrate leaching issue in sandy soil, which has low water and nutrient holding capacity and high soil drainage. More studies on reconciling environmental pollution and farmer's income will be conducted in future.

In general, this study revealed that the proposed irrigation scheme combined with weather forecast could reduce water use and improved yield and net income compared with automatic irrigation in sandy soil, which could largely benefit for farmers. Though the proposed scheme has less advantage when compared with refilling irrigation, the enhanced nitrogen uptake efficiency should also be taken into consideration. This study would present an irrigation scheme that could improve net income of farmers and has potential to decrease fertilizer input in future.

Chapter 5 General conclusions

Water scarcity is a high impact global risk. At the same time, uneven temporal and spatial variations of rain lead to the occurrence of regional droughts. In arid and semi-arid regions, improving crop yields with limited water is a common goal among governments, researchers, and farmers. It is also a great challenge for all stakeholders. For farmers, the motivation to save water occurs only when it will increase their net income. Therefore, there are two objectives in this study: 1) improve WUE by changing cropping systems from traditional water consuming management to water saving systems. And optimum spatial distribution of water and fertilizer application to obtain higher yield and WUE. 2) optimization of irrigation depth for maximizing net income using a numerical model, WASH_2D.

Regarding the first objective, an alternative cropping system, double silage maize, was proposed to compare the water productivity with the traditional winter wheat-summer maize cropping system in NCP. Considering the short growing period of silage maize, we set one of the treatments of two seasons silage maize with plastic mulch to increase temperature of the microenvironment and reduce evaporation. Water footprint, which is the reciprocal of WUE, was used in this study to evaluate the water consumption composition of three different treatments. To find the optimum combinations of the spatial distributions of water and fertilizer, three different combinations of water and fertilizer treatments at two irrigation levels (deficit and full irrigation) were set up for winter wheat in NCP. Supplying water and fertilizer at topsoil layer stands for the scenario that nutrients and water coupling at soil surface, which is a common agricultural practice in most area. Supplying fertilizer at surface and water at deep soil (60 cm) stands for the scenario that nutrients and water mismatched, which is the real water and nutrients distribution in the soil. While supplying water and fertilizer both at deep soil layer, it stands for the scenario that nutrients and water coupled in the deep soil. By comparing the yield and water productivity of different scenarios, a recommend combination was presented in this semi-arid region.

For the second objective, to improve net income of farmers and saving water at the same time, a new numerical irrigation scheme to optimize irrigation depths at each irrigation interval was developed. The proposed scheme was implemented by a numerical model incorporated with crop growth and weather forecast modules. The irrigation depth was determined assuming that net income can be estimated and maximized at each irrigation interval. WASH_2D model was used to simulate water and solute transport in soil to get water and solute distribution under drip irrigation. An experiment cultivating potato for two seasons was set up to estimate the feasibility of proposed irrigation scheme. In this study, we compared the proposed scheme with an automatic irrigation scheme and refilling scheme in sandy soil. Considering the low water capacity in sandy soil, the irrigation interval was set as two days for proposed scheme and refilling scheme.

The results of double silage maize experiment indicated that proposed double silage maize with plastic mulch cropping system improved dry matter and grain yield by 45.6% and 31.5% compared with no mulch treatment, respectively. And the total water footprint reduced 24% compared with no mulch. The annual water use of silage maize with or without mulch reduced 150-190 mm compared with traditional cropping system. These results strongly support the idea that alternative double silage maize could improve water productivity. In terms of the net income between different cropping systems, the average net income of silage maize with plastic mulch was similar with that of traditional cropping system, but the treatment without mulch was significantly lower than other two. In conclusion, the double silage maize system reduced the amount of land required to produce maize silage for dairy cows and improved water productivity in produce dry matter.

The results of different combinations of water and fertilizer application indicate that wheat yield and WP at grain yield level under NS+WD were the highest under deficit irrigation, while NS+WS was highest under full irrigation. This result indicates that nutrients should be located at the top soil layer to increase their availability for crop use any time during crop growth seasons. The reason why water applied at deep soil layer could facilitated grain production and water productivity under deficit irrigation was because soil moisture in reproductive stage was relatively high for grain filling process. Under full irrigation, water and nutrients coupled in the topsoil layer, where the roots mostly distributed, increased the availability of water and nutrients for root uptake and reduced the dry-matter allocation to root growth in acquiring resources, which resulted in a lower root/shoot ratio, higher biomass production and higher WP_b. The spatial soil water and nutrient distribution affected their availability for crop use during different growing stages and influenced the allocation of dry matter to above- and below-ground parts. Adjusting the spatial distribution of nutrients and water based on water availability would benefit crop production and water productivity.

Regarding the optimization of irrigation depth, the proposed irrigation scheme achieved higher yield and net income by 19% and 19% compared with automatic irrigation, and reduced water by 28%. While there was no significant difference compared with proposed scheme with refilling irrigation scheme in second season. The possible reason was due to the frequent rainfall in second season reduced the influence from irrigation. On the other hand, the proposed irrigation scheme improved the NU_pE by 39% and 11% compared with automatic and refilling irrigation, respectively. In conclusion, the simulated irrigation method was effective in improving yield, saving water and increasing NUPE of potato compared with automatic and refilling irrigation methods in sandy field.

In summary, the proposed cropping system showed advantages in saving irrigation water and improving silage maize production in NCP. And the improved spatial distributions of water and fertilizer was proposed under different irrigation levels to regulate dry matter allocation and improve water productivity. The irrigation scheme incorporated with weather forecast using numerical simulation obtained better yield and net income compared with traditional methods in sandy soil. This study provided instructions for alternative cropping system, water and fertilizer application management and irrigation schemes in semi-arid and sandy soil.

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Summary

With rising water demands due to population growth, the frequency and degree to which the supply of water falls short of its demand will increase as well. In arid and semi-arid regions where the natural rainfall cannot meet the crop water requirement, supplementary irrigation water is suppled to increase yield. However, excessive use of diverted river flows and groundwaters has caused decrease in underwater level and severe environment pollution. In addition, fertilizers have often been overapplied, resulting in lower net income and groundwater pollution. Nowadays, farmers all over the world face rapidly soaring prices of fertilizer. Fertilizer application does increase yield, but with diminishing return. Once maximum yield is achieved, further application would only decrease yield and pollute groundwater. Also, yield response to fertilizer varies with crop, soil type, soil moisture condition, and other limiting factors. The soil moisture and nutrients are two most important factors affecting plant growth and agricultural production, which has interactive effects on plant growth, water use efficiency and nitrogen uptake efficiency. Previous studies have found that stage-based deficit irrigation, subsurface irrigation and alternate partial root-zone irrigation could save water and improve yield. However, little research considering the combination effect of water and fertilizer on crop, especially the effects of spatial soil water and nutrient distribution on water productivity. Also, few studies have focused on the alternative cropping system on water productivity. Therefore, investigations of water and fertilizer coupling have important role in terms of designing high-efficiency, high-yield crop irrigation and fertilization systems that conserve limited resources and are cost-effective and sustainable.

To evaluate the possibility of growing double silage maize with and without film mulch, three years consecutive field experiment was conducted in North China Plain. In chapter 2, the newly proposed cropping system, double silage maize was compared with traditional system, winter wheat and summer maize. In the view of feasibility of planting double silage

maize in NCP, an important plant growth factor, growing degree days, GDD, was considered to assess the possibility of growing double maize. Results indicated that the average GDD in this region is about 2270 °C (>10°C), which is possible for double silage maize but not enough for double edible maize. Although the dry matter of silage maize was not in good quality due to limited growth period, plastic film mulch management increased yield by 16% and 31% in first and second season, respectively. To evaluate the influence of different cropping systems on water use, we employed water footprint, WF, to indicate the water pressure under different situation. Previous studies have shown that the WF of maize was about 0.4-0.6 m^3 kg^{-1}, which is lowest among three staple crops (Mekonnen & Hoekstra, 2010; Hoekstra et al., 2011). In our study, the average total WF of maize silage with mulch was 0.23 and 0.38 m^3 kg^{-1}, and the average total WF of maize silage without mulch was 0.22 and 0.58 m^3 kg^{-1} in the first and second season, respectively. The lower WF of silage maize would present one of the options for sustainable development of agriculture in NCP. Considering the water consumption and economic returns, the double silage maize saved 160 mm water than traditional WW+SM cropping system, but the net income considering the cost for mulch was lower than the traditional one, which indicated that the proposed cropping system in this study could not improve the net income at the current crop price but diminish the pressure of overdrawn of underground water. The most important thing would be that double silage maize improved the net income per unit water consumption from 0.88 ¥ m^{-3} of traditional to 1.01¥ m^{-3}, which increased the revenue return of water. This implies that if water is volumetrically priced, the practice would enhance net income.

To understand the spatial distribution of water and nutrient on crop growth and yield, in chapter 3, I introduced the study about three different combinations of water and nutrients at two watering levels were set up for winter wheat grown in 1 m deep tubes in 2017/18 and 1.4 m deep tubes in 2018/19 in the field. Supplying fertilizer on surface and water at deep soil gave highest yield and WP at both grain and biomass levels ($WP_{g)}$, under deficit irrigation, with yield 7.7% and 20.9% higher, and WP_g 9.2% and 20.4% higher than NS+WS and ND+WD, respectively. The NS+WS treatment resulted in the highest grain yield and WP at both grain and biomass levels (WP_b) under full irrigation, with yields 17.7% and 31.8% higher, and WP_g 23.4% and 38.0% higher than those of NS+WD and ND+WD averagely for the two seasons, respectively. The differences in yield and water productivity were mainly coming from dry matter allocation. A lower R/S ratio might benefit the partitioning of more dry matter to aboveground biomass to produce higher grain. In this study, fertilizer applied at topsoil profile could increase the availability to plants considering large root system at surface soil. Meanwhile, under deficit irrigation condition, water applied at subsoil could retain relatively higher soil moisture until reproductive stage to provide water for grain filling. In contrast, under full irrigation condition, both water and fertilizer supplied at surface gave optimal combination, which was mainly due to a more efficient root system built under this situation. The lower R/S ratio of NS+WS proved that the plants formed a shallow root system in the water and fertilizer-rich surface soil, thus facilitating the plants to distribute more dry matter to the above-ground parts. This study would provide an example for optimizing spatial management of water and fertilizer under deficit or full irrigation condition in water stressed regions.

Furthermore, farmer-led intensified irrigation is becoming more and more popular, modern technology-controlled irrigation systems are springing up, such as, sensors based automatic irrigation. Such systems require high initial investment, controlling systems and cannot modified irrigation depths according to crop growth process. Therefore, a numerical model to determine irrigation depths which is target with maximum net could be one of the options to save water resources and improve farmers’ net income.

In chapter 4, to compare the net income between proposed irrigation scheme and traditional automatic irrigation and refilling irrigation, two-season field experiment of potato was conducted in sandy soil. The proposed scheme determined irrigation depths using WASH_2D model, which is a numerical model of soil water and solute transport and incorporate weather forecast and crop growth. The results indicated that S1 increased potato yield and net income by 19% and 19% compared with A in first season, respectively. Meanwhile, the irrigation water reduced by 28%. In second season, there was no significant difference between S2 and R, which was mainly due to frequent rainfall during potato growth period. Nevertheless, S improved the NU_pE by 39% and 11% compared with A and R, respectively. As for the accuracy of weather forecast, although the rainfall forecast was not in good match with measured one, the comprehensive weather factor, ET_0, was in fair agreement with the value calculated from weather station. It should be noted that the nitrate leaching of the proposed scheme was higher than A and R, this phenomenon come both from the lower water holding capacity of sandy soil and frequently irrigation of S. Higher NU_pE of S helps to reduce the fertilizer input and therefore, to some extent, reduce the nitrate leaching. In conclusion, the proposed scheme combined with weather forecast reduced water use and improved yield and net income compared with other two traditional schemes. This study presented a promising irrigation scheme that could improve net income of farmers and has potential to decrease fertilizer input in future.

和文摘要

人口増加に伴う水需要の増加に伴い、水の供給が需要を下回る頻度や程度も増加すると予想されている。乾燥・半乾燥地域では、自然降雨では作物の水需要を満たせないため、補助的に灌漑用水を供給して収量を増やしている。しかし、河川流域や地下水の過剰な利用は水位低下や深刻な環境汚染を引き起こしている。また、通常、肥料は収量を増加させるが、収量が増加するにつれその単位投入量当たりの増収効果は減少する。また、肥料に対する収量の反応は、作物、土壌の種類、土壌水分の状態、その他の制限要因によって異なる。土壌水分と養分は、植物の成長と農業生産に影響を与える 2 つの最も重要な要因であり、植物の成長、水利用効率、室素吸収効率の間に相互作用がある。これまでの研究で、段階的な赤字灌漑、地下灌漑、部分的な根群域交互灌漑が節水と収量の向上につながることが分かっている。しかし、水と肥料の組み合わせによる作物への影響、特に土壌水と養分の空間的分布が水生産性に及ぼす影響について検討する研究はほとんどない。また、水生産性に対する代替作物システムに焦点を当てた研究も行われていない。したがって、水と肥料の組み合わせに関する研究は、限られた資源を節約し、費用対効果が高く、持続可能な高効率・高収量の作物灌漑・施肥システムを設計する上で重要な役割を担っている。

フィルムマルチを用いた場合と用いない場合のダブルサイレージメイズの栽培可能性を評価するために，華北平野で 3 年連続の圃場実験を行った。 第 2 章では，新たに提案したダブルサイレージメイズの作付体系を，従来の冬小麦と夏トウモロコシの作付体系で比較した。2 章では，新たに提案した作型であるダブルサイレージメイズの栽培可能性を評価するために，植物成長因子の一つである生育日数につ

いて検討した。その結果、この地域の平均 GDD は約 2270 ℃ (>10℃) であり、ダブルサイレージメイズには可能であるが、ダブル食用メイズには十分でないことが示された。サイレージ用トウモロコシの乾物は生育期間が限られているため品質が良くないが、プラスチックフィルムによるマルチ管理で 1 期目に 16%、2 期目に 31% 増加した。異なる作付体系が水資源に及ぼす影響を評価するために、異なる状況下での水の圧力を示すウォーターフットプリント(WF)を用いている。これまでの研究で、トウモロコシの WF は約 0.4-0.6 m^3 kg^{-1} で、3 種類の主食作物の中で最も低いことが分かっている（Mekonnen & Hoekstra, 2010; Hoekstra et al.）我々の研究では、マルチングを行ったトウモロコシサイレージの平均総週間収量は、第 1 シーズンで 0.23 と 0.38 m^3 kg^{-1} 、マルチングを行わなかったトウモロコシサイレージの平均総週間収量は 0.22 と 0.58 m^3 kg^{-1} であった。サイレージトウモロコシの WF が低いことは，NCP の農業の持続的発展のための選択肢の 1 つになると思われる。水消費量と経済的リターンを考慮すると、ダブルサイレージメイズは従来の WW+SM 作付システムよりも 160mm 水を節約したが、経済的リターンは従来のものよりも低かった。これは、本研究で提案した作付システムは、現在の作物価格では収入を改善できないが、地下水の過剰汲み上げ圧力を減少させることができる可能性を示したものである。最も重要なことは，ダブルサイレージメイズによって単位水消費量あたりの純利益が従来の 0.88 ¥ m^{-3} から 1.01 ¥ m^{-3} に向上し，水の収益還元性が高まったことである。

作物の生育と収量に及ぼす水と養分の空間分布を理解するために，第 3 章では，2017/18 年に深さ 1m のポットで，2018/19 年に深さ 1.4m のポットで栽培した冬小麦に対して，2 つの水準で 3 種類の水と養分の組み合わせを設定した研究を紹介しまし

た。表層に肥料を供給し，深層土壌に水を供給すると，不足灌漑下で収量と WP_g が最も高くなり，NS+WS と ND+WD に比べて収量が 7.7％，WP_g が 20.9％，9.2％と高くなった。NS+WS 処理では、完全灌漑下での穀物収量および穀物・バイオマス両レベルの WP（WPb）が最も高く、収量は NS+WD および ND+WD と比較してそれぞれ 17.7% および 31.8% 、WPg は 23.4% および 38.0% 高いことが示された。収量と水生産性の差は主に乾物配分に起因している。R/S 比が低いほど，地上部バイオマスへの乾物配分が多くなり，より高い穀粒が得られる可能性がある。本研究では，表土の根系が大きいことを考慮し，表土に肥料を施用することで，植物への利用率を向上させることができた。一方、不足灌漑条件下では、生殖期まで土壌水分を相対的に高く保つことができ、登熟のための水分を供給することができた。一方、完全灌漑条件下では、水と肥料を共に表土に供給することで最適な組み合わせとなったが、これは主にこの状況下でより経済的な根系が構築されたためであると考えられる。NS+WS の R/S 比が低いことは、植物が水と肥料に富んだ表層土壌で浅い根系を形成し、地上部により多くの乾物 を分配しやすくしていることを証明している。本研究は，水ストレス地域における不足灌漑または完全灌漑条件下での水と肥料の空間的管理の改善の一例を提供するものである。

さらに、農家主導の集約型灌漑が普及し、センサーによる自動灌漑など、最新の技術で制御された灌漑システムも登場している。このようなシステムは、高い初期投資と制御システムを必要とし、作物の成長過程に応じて灌漑深度を変更することができない。そこで、灌漑深度を決定するための数値モデルが、水資源を節約し、農家の純益を向上させるための選択肢の 1 つとなり得る。

第4章では、提案する灌漑方式と従来の自動灌漑および補給灌漑の純収益を比較するために、砂質土壌でジャガイモの2シーズンでの圃場実験を行った。提案した方式では、土壌の水・溶質輸送の数値モデルであるWASH_2Dモデルを用い、天気予報と作物の生育を組み込んで灌漑深度を決定した。その結果，S1は，1期目のAに比べてジャガイモの収量を19％，純益を19％増加させることが示された。一方、灌漑用水は28%削減された。2シーズン目では、S2とRの間に有意差はなかったが、これは主にジャガイモの生育期間中に頻繁に雨が降ったためである。しかし、SはAおよびRと比較して、$NU_p E$、それぞれ39％および11％改善された。天気予報の精度については、降雨量の予報は実測値とあまり一致しなかったが、総合天気因子ET_0は気象台から計算した値とほぼ一致した。これは、砂質土の保水力が低いことと、Sの灌漑頻度が高いことに起因する。Sの$NU_p E$が高ければ、肥料投入量を減らすことができるので、硝酸塩溶出量もある程度は減少する。結論として、天気予報と組み合わせた提案スキームは、他の2つの伝統的なスキームと比較して、水使用量を削減し、収量と純益を向上させることができた。本研究は、農家の純所得を向上させ、将来的に肥料投入量を減少させる可能性のある有望な灌漑方式を提示した。

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List of publications

Shuoshuo Liang, Xiying Zhang, Yang Lu, Ping An, Zongzheng Yan, Suying Chen. Performance of double cropping silage maize with plastic mulch in the North China Plain. (2020). Agronomy Journal. Vol. 112 (5) (Chapter 2)

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