Analysis of Nitrogen and Water Use Efficiencies of Potato Production in a field experiment in Hailar, Inner Mongolia, China

MSc Thesis

Plant Production Systems

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Preface

This MSc. thesis, together with my MSc. internship *Conducting a Field Experiment for Nitrogen and Water Use Efficiencies of Potato Production in Hailar, Inner Mongolia, China*, are combined into one project from May 2017 to June 2018. This project is part of Na Wang's PhD project *Trade-off between Narrowing Yield Gaps, Resource Use Efficiency and Environmental Impact of Potato Production in China* in Wageningen University from January 2016 to December 2019.

I took part in the field experiment of the 2017 growing season in Hailar from the emergence to the harvest. The data collected on the field and received from the local laboratory for the soil and harvested samples are reported in the internship report. The report also includes the schedule of field management, methods of data collection and events occurred during the field experiment (disease, late irrigation, etc.). This thesis focuses on the data analysis, tries to find the relationships among the nitrogen use efficiency, water use efficiency and tuber yield, and compares them with other studies. Due to the limitation of data collected from the experiment, the impact on the environment is not discussed in the thesis.

I deeply appreciate everyone in the Plant Production Systems group, who has contributed to the nice atmosphere in the office and inspired me through their presentations or feedbacks on my thesis and internship report. In particular, I would like to thank my supervisors dr. Pytrik Reidsma and Na Wang, who patiently helped me through the whole process, leaded me to a better understanding of the crop production systems, and taught me the methods of scientific researches. I would also like to thank dr. Joost van Heerwaarden for helping me out of the struggling with statistics.

I thank you in advance for reading this thesis and I will appreciate all your feedbacks.

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Abstract

Potato became the fourth staple food in China in 2015 with the purpose of satisfying the food demand of the country's growing population. Due to the limitation of resources (land, water and nutrients) and considering the economic and environmental costs, it is important to improve the yield and the resource use efficiencies. The law of diminishing returns leads to a tradeoff between the yield and resource use efficiencies, and studies have shown correlations between the water use efficiency and nutrient use efficiencies. In this research, the relationships among the tuber yield, water use efficiency (WUE) and nitrogen use efficiency (NUE) in Hailar, Inner Mongolia, China were analyzed based on a field experiment conducted during the growing season of 2017. Four levels of N fertilizer input (0, 184, 225 and 267 kg ha^{-1}) and three levels of water input (0, 235 and 280 mm) were designed in the experiment. The weights, sizes and NPK contents of different plant parts were also analyzed to help explaining the differences in the yield, NUE and WUE. The tuber dry yield significantly increased with irrigation from 0 to 235 mm (15.7 to 42.9 ton ha^{-1}), but a further increase in irrigation did not push up dry yield. N input did not significantly increase yield, except for the N input of 184 and 225 kg ha^{-1}. High yields were achieved with zero N input. As a result, NUE_{PFP} (the ratio between tuber dry yield and N input) increased with irrigation from 0 to 235 mm while decreased with N fertilization from 184 to 267 kg ha^{-1}, and the optimal NUE_{RE2} of 98% (the ratio between N uptake and N input) occurred with an irrigation of 235 mm. Also, WUE_{agri} (the ratio between the tuber dry yield over the sum of precipitation and irrigation) reached the peak (23 kg ha^{-1} mm^{-1}) under 235 mm irrigation. However, WUE_{irri} (the ratio between tuber dry yield and irrigation) decreased with irrigation from 235 to 280 mm, because the percentage increase in irrigation exceeded that in the tuber dry yield. No tradeoff was found between NUE and WUE. The tuber fresh yield was positively related to all NUEs and WUEs except NUE_{physio} (the ratio between the increase in tuber dry yield and the increase in N uptake due to N fertilization). The analyses indicate that the soil N content at sowing might have been high, and thus the application of N fertilizers did not benefit the yield. However, the changes in N uptake showed that the excessive N input was taken up by the plant, while it was not utilized to produce dry yield. Thus a soil test should be done before each sowing in this region considering the unknown management of the former crop in the rotation. It is possible that zero N fertilization is the optimal choice. Also, the comparison between NUE_{RE2} and NUE_{IE} (the ratio between tuber dry yield and N uptake) indicates that the increase in irrigation only improved the efficiency in uptaking N, while did not benefit the efficiency in utilizing the N uptake to produce dry yield. The interactions between water and N treatments were not significant for most variables.

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1. Introduction

1.1 Background

Potato is one of the four main crops in the world (Alva et al., 2011). As of year 2013, 19 million ha of land across the world was used for potato cultivation, and the total production was 380 million tons (Lu, 2015). Originated from eight thousand years ago in Peru (Lutaladio & Castaldi, 2009), potato was introduced to China from the west in the 17th century (Singh & Kaur, 2016) and then widely spread in the country due to its resistance to the high altitude and cold weather and ability to grow with different soil types and climates (Zhang et al., 2017; Alva et al., 2011).

China is currently the largest potato producer in the world (Jansky et al., 2009; Lu, 2015). Both the total production and the cultivation area of potato in China have been on the rise. In 2006, China produced 22% (70 million tons) of the world's potatoes on 26% of the world's land for potato cultivation. While in 2013, 30% (5.8 million ha) of the world's potato cultivation area was located in China, and the production went up to 89 million tons, which made up 24% of the world production. In 1998, the potato production in China was only 56 million tons with a cultivation area of 4.1 million ha. The Ministry of Agriculture of China aims to allocate 6.7 million ha of land to potato production by 2020 (Ministry of Agriculture of the People's Republic of China, 2016). In 2013, six provinces (in total there are 23 provinces in China) contributed 2/3 of the total potato production in China (Li et al., 2015). Nearly half of the country's potatoes were produced in the northern part (Alva et al., 2011). Inner Mongolia in northern China, as one of the six provinces, takes around 10% of both the country's potato land and potato production in the recent years (Li, 2016).

In 2015, the Ministry of Agriculture of China listed potato as the fourth staple food after rice, wheat and corn, in order to supply enough food for the growing population, improve the nutrition balance in Chinese cuisine, as well as contributing to the sustainable development (Lu, 2015; Zhang et al., 2017). As a staple food, potato not only provides carbohydrate, but also carries protein, minerals and vitamins with lower calories, which is "a near-optimum balance of nutrients for human consumption" (Alva et al., 2011). Potato helps to release the stress of land and water shortage in China, where 6% of the world's fresh water and 9% of the world's farmlands should be well managed to feed 21% of the world's population (Frenken, 2012). In addition, planting potatoes can help reducing soil erosion. As for the food security, there is a bigger potential in increasing the yield of potato than that of rice, wheat or corn because the yields of the latter three in China are already high compared to the world levels, while the yield of potato is still lower than the world average. In 2013, the average potato yield in China was 15.4 ton ha^{-1}, which was 20% lower than the world average level (18.9 ton ha^{-1}), and much lower than that in the Netherlands (over 45 ton ha^{-1}) and North America (41.2 ton ha^{-1}) (Kempenaar et al., 2017; FAOSTAT, 2008). It was also lower than the target for year 2020 set by the Ministry of Agriculture of China, which aims to increase the yield to 19.5 ton ha^{-1} (Li, 2016).

1.2 Water, nutrients and yield gaps

As the world population goes up to over 9 billion in the near future, crop yields of current levels will not be able to maintain the food security even if all existing cultivation lands are utilized, thus increasing crop yields is necessary for human survival (van Ittersum et al., 2013). The potential for yield increase varies for different regions, and it can be estimated by the yield gaps (Y_G) in each region. Y_G is defined as the gap between the potential yield (Y_P) and the actual yield (Y_A) under irrigated conditions, and between the water-limited potential yield (Y_W) and Y_A under rainfed conditions (van Ittersum et al., 2013). There are also other definitions of Y_G. According to Sadras et al. (2015), the Y_G defines the difference between two levels of yields, and different Y_G's are chosen according to the research purpose.

Y_P is achieved when adequate water and nutrients are supplied and weeds, pests and diseases are well controlled (van Ittersum et al., 2013). Y_P of a crop in a certain region is determined by the light, temperature, CO_2 supply, and the genetics of the cultivar. Since the access to irrigation is different in different regions, which affects the level of achievable yield, the water-limited potential yield (Y_W) is introduced. Y_W is the potential that can be reached under rainfed conditions. When nutrients and biotic stress are not limiting, the yield of the crop under inadequate irrigation lies between Y_P and Y_W. Since the field topography (runoff) and the soil type (water holding capacity and rooting depth) influence the water supply to crops, they also contribute to the gap between Y_P and Y_W (van Ittersum et al., 2013; Sadras et al., 2015). Y_A, the actual yield of a certain cultivar in a region, is limited by water, nutrients, as well as all the possible biotic stress. In addition to Y_P, Y_W and Y_A, Sadras et al. (2015) defined an "attainable yield", which is "the best yield achieved through skillful use of the best available technology"

For the situation of potato production in China, China Potato GAP 2013-2016 (Kempenaar et al., 2017) calculated the attainable tuber fresh yield with LINTUL growth model for five provinces including Inner Mongolia. The attainable yield in China ranged from 55 to 80 ton ha^{-1}, and the yield gaps (between the attainable yields and Y_A's) varied between 12 and 45 ton ha^{-1}. For Dalate Qi in Inner Mongolia, the project proposed that the attainable yield was 72 ton ha^{-1}, which almost doubled the local actual yield (38 ton ha^{-1}), while the local actual yield was already much higher than the average level of the whole province.

Although the yield gap indicates the potential of yield increase in a certain region, reaching the potential yield is not commonly preferred due to the law of diminishing returns (van Ittersum et al., 2013; Sadras et al., 2015). When more water or nutrients are applied, the curve of the relationship between yield and input flattens out (de Wit, 1992), which means a decrease in the efficiency of water or nutrient use. In other words, there is a trade-off between the yield and the resource use efficiencies.

Silva et al. (2017) decomposed Y_G (defined to be the difference between Y_P and Y_A) into Efficiency Y_G, Resource Y_G and Technology Y_G. When two inputs (water and N) are interacted, the effects of them on the crop yield concern both the Efficiency Y_G and Resource Y_G. Increasing one input can narrow the Resource Y_G of this input, while better management of another input can narrow the Efficiency Y_G of it.

1.3 Resource use efficiencies

1.3.1 Nitrogen use efficiency (NUE)

Since the World War II, chemical fertilizers have been widely used as a result of the increasing demand for food and the development in technology (de Wit, 1992). However, as predicted by the law of diminishing returns, although the yield can still increase with larger fertilizer input, the marginal return is going down without new improvement in technology. Since more fertilizer input is needed to push up the yield when the production is already high, a large portion of the nutrient is not utilized by the plants, but lost to the environment. Thus the excess application of chemical fertilizer not only brings a larger economic cost, but also causes environmental pollution, which makes the fertilizer use efficiencies important indicators of the sustainable use of fertilizers.

Every ton of potato tubers removes about 3.8 kg N, 0.6 kg P and 4.4 kg K from the soil, and insufficient or unbalanced supply of fertilizers has limited the yields in some regions in China (Alva et al., 2011). Compared with other nutrients, N management has been considered the most important for potato yield. The demand for N is the highest among the demands for NPK fertilizers, and it keeps rising across the world (**Figure 1**). Also, while the N surplus largely flows into the environment, the P surplus is reserved in soil (Bouwman et al., 2017). Bouwman et al. argued that making use of accumulated soil P and increasing NUE would allow continuing increase of yield in China.

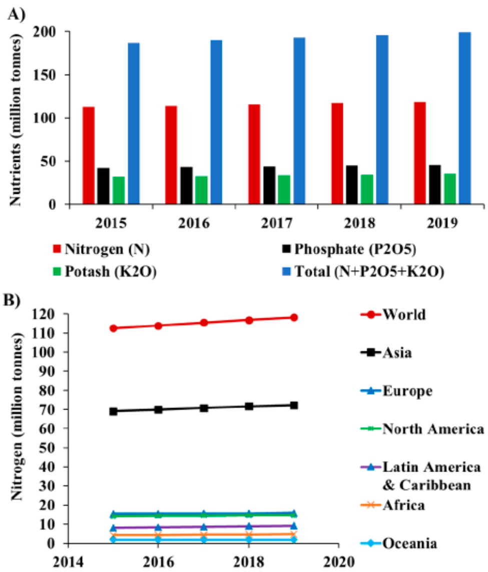

Figure 1: A) The forecasts for the world demand for fertilizers for year 2015 ~ 2019; B) The forecasts for the demand for N fertilizer in different regions around the world for year 2015 ~ 2019. (Sharma & Bali, 2018)

Definitions of NUE

Different definitions of NUE are used in research. Some of them are based on the plant physiological processes, some are established regarding the agronomic management, while others are defined for the local development.

For a same system, different definitions of NUE usually have different values, and describe different aspects of the system.

Based on the mass balance principle, one category of the definitions calculates the ratio of N output over N input, and the definitions of N outputs and N inputs vary for different industries. $NUE_{out/in}$, NUE_{fert}, and NUE_{RE}'s (**Table 1**) show three typical thoughts in adapting it for agricultural systems (EU Nitrogen Expert Panel, 2015; Raun & Johnson, 1999; Dobermann, 2005; Conant et al., 2013). $NUE_{out/in}$ calculates the ratio between the total N output from the system (removed with the harvested products) and the total N input to the system from all sources, and it plays a good role as an indicator of the sustainability of an agroecological system. NUE_{fert} sees soil N stock as a source of N input instead of a part of the system. Since N in harvested crops comes from fertilizers, soil N stock and N deposition in rainfall, NUE_{fert} deducts N from soil N stock and N from deposition from the N output in the numerator and uses N from fertilizer as the denominator to show the conveyance of the fertilizer N.

NUE_{RE}'s (recovery efficiency of fertilizer) ignore the former arguments that the N output in harvested crops come from different sources (fertilizer, soil, rainfall), and calculate the ratio between the N in harvested crops (also called N uptake) and the N from fertilizers. Conant et al. (2013) used a term called "external N inputs", which contains fertilizer, manure and fixed N, as the denominator of the recovery efficiency (NUE_{RE2}, **Table 1**). The "external" sources by Conant et al. were all fertilizer-like sources, while the contributions of soil N stock and rainfall were not considered. Recovery efficiencies of fertilizer are often used as NUE in researches (Yan et al., 2014). One advantage is that they are determined by the equilibrium of the plant's demand for N and the fertilizer's release of N, which is influenced by the crop genotype and the fertilizer application method, and thus very useful in planning fertilization (EU Nitrogen Expert Panel, 2015). Two types of recovery efficiencies are commonly employed in research. One of them (NUE_{RE1}, also called "apparent recovery efficiency") takes the difference in N uptake between fertilized and unfertilized crops as the numerator, while the other (NUE_{RE2}) simply used the N uptake as the numerator.

The second category of NUE maps N input to the crop yield. Moll et al. (1982) defined NUE as the ratio between the crop dry weight and the amount of N available ($NUE_{uptake*utilization}$, **Table 1**). They separated the NUE into two components based on the physiological process: the uptake efficiency from the total N available to N uptake, and the utilization efficiency from N uptake to the crop dry weight. NUE_{PFP} (partial factor productivity of applied N) is distinguished from $NUE_{uptake*utilization}$ by using the amount of fertilizer N as the denominator (EU Nitrogen Expert Panel, 2015; Dobermann, 2005). NUE_{PFP} is one of the most meaningful definitions for agricultural practice, as it shows the efficiency of fertilization in production explicitly. Another widely used NUE, the agronomic efficiency (NUE_{AE}, **Table 1**), is defined as the multiplication of the apparent recovery efficiency of fertilizer (NUE_{RE1}) and the physiological efficiency of applied N (NUE_{physio}) (EU Nitrogen Expert Panel, 2015). NUE_{physio} shows the plant's ability to transform the N uptake into yield. Extremely low NUE_{physio} suggests 'deficiency of other nutrients or mineral toxicity' or too much N application. While $NUE_{uptake*utilization}$ employs the total N available as the denominator, both NUE_{PFP} and NUE_{AE} use the amount of N from fertilizers. The only difference between the equations of NUE_{PFP} and NUE_{AE} is that the yield without N fertilizer application (Y_0) is deducted from the numerator in NUE_{AE}.

NUE_{physio} belongs to the third category of NUEs (NUE_{IE}, NUE_{physio} and $NUE_{N\_prod*res\_time}$, **Table 1**), which shows the transforming of N uptake into crop yield. Internal utilization efficiency of N (NUE_{IE}) is defined as the ratio of crop dry weight over N uptake. The differences between NUE_{IE} and NUE_{physio} lie in whether to deduct the yield and N uptake without N fertilization (Y_0 & U_0) from the numerator and the denominator respectively. $NUE_{N\_prod*res\_time}$ represents "the dry weight which can be produced per unit of N taken up" (Berendse & Aerts, 1987). This NUE definition introduces the concepts of N residence time & N productivity in the plant. $NUE_{N\_prod*res\_time}$ is calculated as the multiplication of N residence time (days) and N productivity in the plant (g dry weight g^{-1} N day^{-1}), where the residence time means the "mean period during which nitrogen can be used for carbon fixation".

There are also other views on the definition of NUE. Chapin (1980) reviewed the crop responses under nutrient stress and showed that the efficiency defined as the amount of dry matter produced per unit of nutrient was also the inverse of tissue concentration. He pointed out that since the NUE could be influenced by processes like development of fibre and sugars, use "respiration, photosynthetic, or net assimilation rate per g nutrient" might be a better measure of efficiency.

Table 1: NUE definitions

Category	Name	Equation
1. From N input to N output	**$NUE_{out/in}$**	$NUE_{out/in}$ = N output in harvested products (kg) / N input (kg) *where N input = N input to the system from all sources (e.g. atmospheric deposition, biological fixation, crop residues, planting materials)* (EU Nitrogen Expert Panel, 2015)
	NUE_{fert}	NUE_{fert} = (N output (kg ha^{-1}) – N from soil N stock (kg ha^{-1}) – N deposited in rainfall (kg ha^{-1})) / fertilizer N (kg ha^{-1}) (Raun & Johnson, 1999)
	NUE_{RE1}	$NUE_{RE1} = (U_N - U_0) / N_{app}$ *where U_N = N uptake with N fertilizer & manure application (kg)* *U_0 = N uptake without N fertilizer & manure application (kg)* *N_{app} = N applied (kg)* *= N from fertilizer (kg) + N from manure (kg)* (Dobermann, 2005)
	NUE_{RE2}	NUE_{RE2} = N in harvested grain (kg)/ external N inputs (kg) *where external N inputs = N from fertilizer (kg) + N from manure (kg) + fixed N (kg)* (Conant et al., 2013)
2. From N input to crop yield	**$NUE_{uptake*utilization}$ [g dry weight g^{-1} N]**	$NUE_{uptake*utilization}$ = N uptake efficiency (%) * utilization efficiency (g dry weight g^{-1} N) $= (N_t / N_a) * (G_w / N_t)$ $= G_w / N_a$ *where G_w = crop dry weight (g dry weight per plant)* *N_a = N available (g N per plant)* *N_t = total N in the plant at maturity (g N per plant)*

		(Moll et al., 1982)
	NUE_{PFP} **[kg yield kg^{-1} N]**	$NUE_{PFP} = Y_N / N_{fert}$ $= Y_0/N_{fert} + NUE_{AE}$ *where PFP = partial factor productivity of fertilizer N* *Y_N = yield with N fertilizer application (kg)* *Y_0 = yield without N fertilizer application (kg)* *N_{fert} = N from fertilizer (kg)* (EU Nitrogen Expert Panel, 2015; Dobermann, 2005)
	NUE_{AE} **[kg yield kg^{-1} N]**	$NUE_{AE} = (Y_N - Y_0) / N_{fert}$ $= RE * PE$ *where AE = agronomic efficiency of fertilizer N* *RE = apparent recovery efficiency of fertilizer N* $= (U_N - U_0) / N_{fert}$ *PE = physiological efficiency of fertilizer N* $= (Y_N - Y_0) / (U_N - U_0)$ *Y_N = yield with N fertilizer application (kg)* *Y_0 = yield without N fertilizer application (kg)* *U_N = N uptake with N fertilizer application (kg)* *U_0 = N uptake without N fertilizer application (kg)* *N_{fert} = N from fertilizer (kg)* (EU Nitrogen Expert Panel, 2015; Dobermann, 2005)
3. From N uptake to crop yield (Utilization efficiencies)	**NUE_{physio}** **[kg dry weight kg^{-1} N]**	$NUE_{physio} = (Y_N - Y_0) / (U_N - U_0)$ *Where Y_N = yield with N fertilizer application (kg)* *Y_0 = yield without N fertilizer application (kg)* *U_N = plant N uptake with N fertilizer application (kg)* *U_0 = plant N uptake without N fertilizer application (kg)* (Chen et al., 2012)
	NUE_{IE} **[kg dry weight kg^{-1} N]**	NUE_{IE} = crop dry weight (kg ha^{-1}) / N uptake (kg ha^{-1}) *where IE = internal utilization efficiency of N* (EU Nitrogen Expert Panel, 2015; Dobermann, 2005; Shaver & Melillo, 1984; Brown, 1978)
	$NUE_{N\_prod*res\_time}$ **[g dry weight g^{-1} N]**	$NUE_{N\_prod*res\_time} = A/L_n$, *where A = N productivity (g dry weight g^{-1} N day^{-1}),* *L_n = the N required per unit of N present in the plant (gN g^{-1}N day^{-1})* *$1/L_n$ = mean residence time (day)* *= the mean period during which N can be used for carbon fixation,* (Berendse & Aerts, 1987)

NUE in China

China is the largest fertilizer user in the world, with a fertilizer nutrient consumption of 47.66 million tons as of year 2005, which equals 32% of the world total consumption (Jin, 2012). But the fertilizer use efficiency in China is low. The NUE_{RE2} was reported to be 30% ~ 35% and the NUE_{AE} was only half of the world average level. And NUEs[1] in China have been decreasing since the year of 1970 (Bouwman et al., 2017). According to Jin (2012), in China approximately 34% of the N from chemical fertilizer was lost through nitrification and denitrification, 11.5% through ammonia volatilization, 5% through soil erosion, and 2% through leaching.

In case of potato production, a research in Guangxi Province (southern China) showed that the NUE_{RE1} was between 35.16% and 39.99%. And the 15N-labeled experiment showed that 46% ~ 52% of the N uptake by potato was from N fertilizers applied in that season, while the other 48% ~ 54% was from soil and seed tubers (Wei et al., 2016). In Heilongjiang Province (north-eastern China), a field experiment fertilized with urea had a NUE_{RE1} of 34.9% (Jiang, 2002), which was similar to the level in Guangxi Province. However, in the same province, the NUE_{RE1} of soil testing formulated fertilization reached 81.7% in a field experiment in 2011 (Liu et al., 2011). According to IPNI (the International Plant Nutrition) cooperative network, the average NUE_{AE} in China was 34 kg tuber fresh yield kg^{-1} N from fertilizer between the year of 2000 and 2006 (Jin, 2012).

1.3.2 Water use efficiency (WUE)

Globally, 6225 m^3 freshwater is available per capita, and 75% of the human water consumption is used on agriculture (Jia et al., 2016; Frenken, 2012). China, with a per capita fresh water availability of only 1/3 of the world level, also has to push up its total agricultural production by 30% in 2030 to meet the needs of the rising population.

With a 4000-year history of irrigation, as of 2006 the area equipped with irrigation in Mainland China reached 62.6 million ha (total arable land & area under permanent crops: 124 million ha), of which 91.2% was covered with annual or food crops (Frenken, 2012). Oher areas with irrigation were used for orchards, forests, pasture and other crops. As of 2016, the irrigated land contributed 80% of the country's food production (Jia et al., 2016).

The water resource allocation in China is extremely imbalanced between the south (25,000 m^3 per year per inhabitant) and the north (500 m^3 per year per inhabitant) (Frenken, 2012). Northern China, with only 20% of the country's water resourses, is producing half of the country's grain and almost all of its maize and wheat on 65% of the country's cultivated land, and contributing 45% to the country's GDP. The water deficiency in northern China is expected to be 25 ~ 46 km^3 in 2030, which is two to four times of the national level. Nowadays, almost 13% of the cultivated land in northern China suffers from droughts every year. Due to the conflict in droughts and large demand for water in production, northern China relies on groundwater (Frenken, 2012). 65% of the water withdrawal in the five northern provinces including Inner Mongolia is from

[1] The definition of NUE that is used by Bouwman et al. is the ratio between the amount of N in harvested crop parts and N inputs (fertilizer, manure, atmospheric deposition, and biological N fixation) (Bouwman et al., 2017).

groundwater, which has largely depleted the groundwater reservoir and caused lower water tables.

The Water and Soil Conservation Law and the Water Law were introduced by the government in 1991 and 2002 repectively for "rational use" of water resources and protecting the environment (Frenken, 2012). Increasing WUE is one of the focuses of the Water Law.
The irrigation WUE[2] in China was about 45%, which was much lower than that in the developed countries (around 70% ~ 80%) (Jia et al., 2016). China has been spending US$2 billion every year to improve the WUE, and the agricultural WUE[3] went up by 10% in the past ten years (Frenken, 2012). The amount of water withdrawal decreased while the total production increased. However, in year 2009, the economic water productivity (WP)[4] in China was still only US$3.6 per m^3, which was very low compared to that in other middle income countries (average US$4.8 per m^3) and was only 1/10 of that in high-income countries (US$35.8 per m^3)

<u>Definitions of WUE and water productivity (WP)</u>

There have been discussions around the definitions of WUE and WP. In a multi-country research report from FAO (Sadras et al., 2011), it was pointed out that the term of "efficiency", especially WUE_{agri} (**Table 2**), was often "misused or used without clear definition" in literature. According to Sadras et al., WUE was originally established "from the viewpoint of engineering and irrigation" as the "conveyance efficiency" ($WUE_{engineer}$, **Table 2**), where the excess of water (water at point 1 minus water at point 2) goes to "spills, leakage and evaporation from the water surface". For agriculture, this report proposed the "field application efficiency" ($WUE_{field\ application}$, **Table 2**) for which the excess of water (total water delivered to the field minus water delivered to the plant root zone) goes to runoff, percolation, or soil surface evaporation.

In the definitions of $WUE_{engineer}$ and $WUE_{field\ application}$, Sadras et al. (2011) regarded "efficiency" as a dimensionless ratio of which the value ranges from 0 to 1, while they defined WP as the ratio of the net benefit from an agricultural system to the water consumption. For example, $WP_{economic}$, which set the economic and social benefits as the numerator, has a unit. But back to the year of 2006, Sadras defined $WUE_{Y/ET}$ as the ratio between the grain yield (kg ha^{-1}) and the seasonal evapotranspiration (mm) (Sadras & Angus, 2006). This definition was later regarded as "evapotranspiration WP" (Sadras et al., 2011). The agronomic efficiency (WUE_{agri}, **Table 2**), also referred to as agronomic WP, is widely used by agronomists for the relationship between crop yield and water usage (Sadras et al., 2011; van Ittersum et al., 2013). A definition that is similar to WUE_{agri} is WUE_{irri}, which uses irrigation water as the denominator instead of the total water used (Fairweather et al., 2003). If the climate (precipitation, temperature, radiation, for example) in an area is stable, the definition WUE_{irri} can be of practical use for agricultural production.

According to Fairweather et al. (2003), WUE, when used for the relationship between water input and agricultural product or economic return, is actually a water use index. They pointed out that WUE is also

[2] A definition of the irrigation WUE used in this paper was not found. Although the term used was "irrigation WUE", it has different definition from WUE_{irri} in **Table 2**.
[3] A definition of the agricultural WUE used in this report was not found. Although the term used was "agricultural WUE", it has different definition from WUE_{agri} in **Table 2**.
[4] A definition of the economic WP used in this report was not found. But we expect it to be similar to $WP_{economic}$ in **Table 2**.

commonly used to describe "the effectiveness of irrigation water delivery and use", which is similar to the idea of $WUE_{engineer}$ and $WUE_{field\ application}$ in **Table 2**. They proposed that WUE should be regarded as a toolbox which included two parts, one of which was dimensionless (based on the water balance), and the other had "a suite of performance indices" like crop yield per mm water input.

Table 2: Definitions of WUE and WP

Name	Equation
$WUE_{engineer}$ **[%]**	$WUE_{engineer}$ = water available at point 1 (mm) / water available at point 2 (mm), *where point 1 & 2 are different points of channels in the irrigation system.* (Sadras et al., 2011)
$WUE_{field\ application}$ **[%]**	$WUE_{field\ application}$ = water delivered to the plant root zone (mm) / total water delivered to the field (mm) (Sadras et al., 2011)
$WP_{economic}$ **[ha^{-1} mm^{-1}]**	$WP_{economic}$ = economic and social benefit / water used (mm) (Sadras et al., 2011)
$WUE_{Y/ET}$, **$WP_{Y/ET}$** **[kg ha^{-1} mm^{-1}]**	$WUE_{Y/ET}$ = grain yield (kg ha^{-1}) / seasonal evapotranspiration (mm) (Sadras & Angus, 2006; Sadras et al., 2011).
WUE_{agri}, **WP_{agri}** **[kg ha^{-1} mm^{-1}]**	WUE_{agri} = grain yield (kg ha^{-1}) / water used (mm) *where water used* = *plant-available soil water at planting* (mm) + *in-season rainfall* (mm) + *applied irrigation* (mm) – *residual plant available water in the root zone at maturity* (mm). (Sadras et al., 2011; van Ittersum et al., 2013)
WUE_{irri} **[kg ml^{-1}]**	WUE_{irri} = yield (kg) / irrigation water applied (ml) (Fairweather et al., 2003)

Relationships among WUE (or WP), NUE and crop yield

Adequate supplies of water and nutrient fill the yield gaps. However, as mentioned above, maximizing only one of WUE (or WP), NUE or crop yield is not commonly preferred due to the tradeoffs. These tradeoffs are inherent features resulted from the biophysical processes and cannot be eliminated (Sadras et al., 2015). Between NUE and WUE (WP), while adequate N input is needed for a high WUE, NUE will be dragged down when more N is supplied according to the law of diminishing returns. A comparison among the flooded and aerobic rice in the Philippines and rainfed and irrigated maize in USA has shown this pattern (**Figure 2**). This data in the Philippines (tropical regime) also showed the tradeoff between WUE and the yield (**Figure 3**). Rice with a higher WUE_{agri} (aerobic) had a lower grain yield than that with a lower WUE_{agri} (flooded). However, there is an example from Japan (temperate regime) where the WUE_{agri} of aerobic rice outperformed that under flooded condition without a penalty on the yield (Sadras et al., 2011). This might be due to that the increase in the grain yield from higher water supply (the numerator in the definition of WUE_{agri}) won over or tied with the increase in the water amount (the denominator in the definition of WUE_{agri}) in this case. Thus although the tradeoffs are inherent in the agricultural systems, the ranges vary for different regions and need to be further explored.

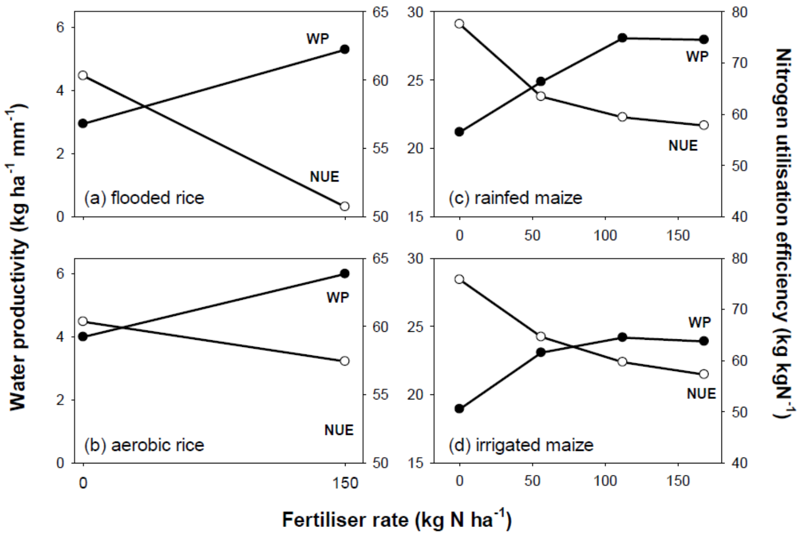

Figure 2: The tradeoff between WUEs (WPs) and NUEs. (a) & (b): WUE_{agri} & NUE_{IE} of flooded & aerobic rice in Philippines; (c) & (d): $WUE_{Y/ET}$ & NUE_{IE} of rainfed & irrigated maize in USA. (Sadras et al., 2015)

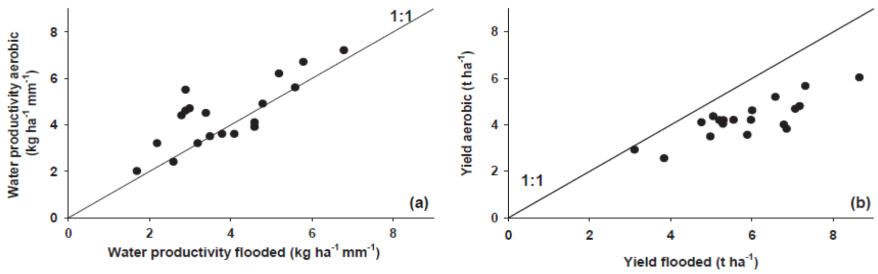

Figure 3: Comparisons between the rice growth under aerobic condition and under flooded condition in the Philippines. (a) WUE_{agri}; (b) grain yield. (Sadras et al., 2015; Sadras et al., 2011)

1.4 Research questions

<u>1.4.1 Major research question</u>

What is the relationship among the NUE, WUE and tuber fresh yield in a field experiment of potato production in Hailar, Inner Mongolia, China conducted in 2017?

Interrelationships among the NUE, WUE and tuber fresh yield have been shown from literature. In our experiment, do the NUE, WUE and tuber fresh yield show tradeoffs? Are there domains within which these three values go up simultaneously?

1.4.2 Sub-questions

1) What are the relationships between N & water inputs and the tuber yield?

   Tuber fresh yields, tuber dry matter contents, and the numbers and sizes of harvested tubers are analyzed.

2) What are the relationships between N & water inputs and the NUE?

3) What are the relationships between N & water inputs and the WUE?

4) What variables can be used to help explaining the relationships between the treatments and the yield, NUE and WUE?

   The explanatory variables to be discussed in this thesis were selected according to the physiological processes and the availability of the experimental data. The sizes, weights and NPK contents of different plant parts were selected due to their possible influences on the plants' ability to uptake and utilize water & nutrients, the photosynthesis and other processes.

5) Based on this field experiment, to what extents can NUE and WUE be improved in Hailar, Inner Mongolia, China? And how?

6) What are the differences in NUEs, WUEs, and tuber yields between the results of our field experiment and other experiments in the same region or the global levels?

2. Materials and methods

2.1 Field experiment

2.1.1 Site description

1) Location

The field experiment was conducted in Hailar, Inner Mongolia, China, which is one of the main potato producing regions in the country. Potato production is not evenly distributed in northern China, where Gansu Province in the west and Inner Mongolia Autonomous Region in the east are outstanding. Most of the land in northern China lies on the plateaus (Qinghai-Tibet Plateau, Loess Plateau, and Inner Mongolian Plateau). Due to the mountains and different distances from the ocean, the effects of the atmospheric circulation and ocean currents on the climate various across northern China. Also, the three plateaus have different topographies and soil conditions.

Hailar (longitude119°28′~120°34′ E, latitude 49°06′~49°28′ N, altitude 603 m ~ 743 m, **Figure 4**) belongs to the Hailar inland fault depression basin in the centre of Hulunbuir Grassland (Hailar, 2017). It is the district where Hailar River and Yimin River confluence, and where Mongolian Plateau meets Greater Khingan Mountains.

Figure 4: The location of Hailar, Inner Mongolia, China is marked in the map with a small circle. Source: Location of Hailar on a map (Worldatlas, 2018).

2) Climate

Summers in Hailar are mild and short, while winters are extreme and long (The Bureau of History Archives of Hailar, 2016). As a result of its medium-temperate semi-arid continental monsoon climate, the inland location and the barrier effect of the Greater Khingan Mountains, Hailar is windy and dry (low precipitation and high evapotranspiration) in spring, and relatively wetter in summer. While the radiation in Hailar is abundant throughout the year, the monthly temperature ranges from -30.8°C in January to 25.84 °C in July (historical average), and the precipitation ranges between 3.36 mm in February and 99.38 mm in July (historical average) (National Meteorological Center of China Meteorological Administration, 2017).

3) Soil conditions

Soil types: Among the five common types of soil in Hailar, Kastanozems and Chernozems are the most common (People's Government of Hailar, 2016). The experimental farm is located on the high plains in eastern Hailar.

Soil physical properties & chemical contents: Physical properties and chemical contents of a soil sample taken in July, 2015 in Hailar (**Table 3**) were used when planning NPK application in the field experiment. Soil samples of 20 cm depth from the experimental field were also taken before sowing and after harvest of this experiment (**Table 4** and **Table 5**). These soil samples were sent to a local laboratory for tests, and the results were received after the experiment.

Table 3: Soil physical properties & chemical contents from the samples taken in Hailar in July, 2015 (Mosaic, 2015).

Content	Amount
Organic Matter (%)	1.64
NH_4-N (kg ha^{-1})	11.8
NO_3-N (kg ha^{-1})	29.2
P (kg ha^{-1})	35
K (kg ha^{-1})	223.2
Ca (kg ha^{-1})	7598.2
Mg (kg ha^{-1})	1133.2
S (kg ha^{-1})	41.4
Cu (kg ha^{-1})	0.4
Mn (kg ha^{-1})	3.8
Zn (kg ha^{-1})	1
B (kg ha^{-1})	4.96
pH	8.05
Ca/Mg	6.7
Mg/K	5.1

* Sample depth: 0~20 cm; soil type: loam.

Table 4: Soil physical properties & chemical contents of the experimental field before planting in May, 2017. One soil sample was taken from each subplot (see Section 2.1.2), the results below show the averages on all subplots, the maximums and the minimums.

	Minimum	Maximum	Average
SOM%	1.83	2.72	2.18
pH	5.80	7.66	6.46
Alkali-hydrolyzable N (kg ha^{-1})	304	634	422
Available P content (kg ha^{-1})	77	224	134
Available K content (kg ha^{-1})	387	659	509

* Sample depth: 0~20 cm; soil bulk density: 1.6 g cm^{-3}; soil dry weight of 20 cm: 3.2*10^{6} kg ha^{-1}; soil type: sandy loam.

Table 5: Soil physical properties & chemical contents of the experimental field after harvest in September, 2017. One soil sample was taken from each subplot (see Section 2.1.2), the results below show the averages on all subplots, the maximums and the minimums.

	Minimum	Maximum	Average
Alkali-hydrolyzable N (kg ha^{-1})	269	720	365
Available P content (kg ha^{-1})	58	163	93
Available K content (kg ha^{-1})	262	93	432

* Sample depth: 0~20 cm; soil bulk density: 1.6 g cm^{-3}; soil dry weight of 20 cm: 3.2*10^{6} kg ha^{-1}.

2.1.2 Field experiment design

The field experiment (Wang, 2017) employed a randomized block split-plot design with three water treatments (three levels of irrigation) and four N treatments (four amounts of N fertilizer). As shown in **Figure 5**, the experimental field (2721 m^2) was divided into four blocks (block index = 1, 2, 3, 4 from north to south), each of which had three wholeplots (wholeplot index = 1, 2, 3 from west to east). Three water treatments were randomly allocated to the three wholeplots of each block (**Table A1**). Each wholeplot consisted of four subplots (subplot index = 1, 2, 3, 4 from west to east), and four N treatments were randomly allocated to the four subplots. It needs to be noticed that N3 was designed to have the largest N input from fertilizers, while N4 has the same amount of N from fertilizers as in the practice of local farmers. Each subplot had an area of 43.2 m^2, and consisted of four 12-metre-long ridges. The cultivar of potatoes planted in the field experiment was Innovator, which was the same as in the local farms. Seed potatoes were entire tubers, and the growing season (from emergence to maturity) was 95 days. Since local farms were seeded with tuber cuts, four subplots A~D seeded with cuts were added on the west of the experimental field. Comparisons between using entire tubers and cuts are not included in the thesis, but the data was collected and available in the database. For further information please read the internship report *Conducting a Field Experiment for Nitrogen and Water use Efficiencies of Potato Production in Hailar, Inner Mongolia, China* of Xiaohan Zhou's MSc program in Wageningen University.

Three water treatments

1) Full irrigation: the soil water contents of wholeplots with full irrigation treatment were kept above 80% of the field capacity from mid-May to mid-August (early and rapid growing period), and between 60% and 65% start from mid-August (late growing period);

2) Local irrigation: the frequencies and amounts of irrigation for wholeplots with local irrigation treatment followed the practice of local farmers. The information on irrigation plan of local farmers was obtained by daily communication with local farmers.

3) No irrigation: wholeplots with this treatment were not irrigated throughout the growing season.

A watermark detector was installed in each wholeplot and soil water potentials (kPa) were measured daily (Section 3.2 in Xiaohan Zhou's MSc Internship Report). The timings and amounts of irrigation were decided according to the soil water potential records, which indicated the soil water contents.

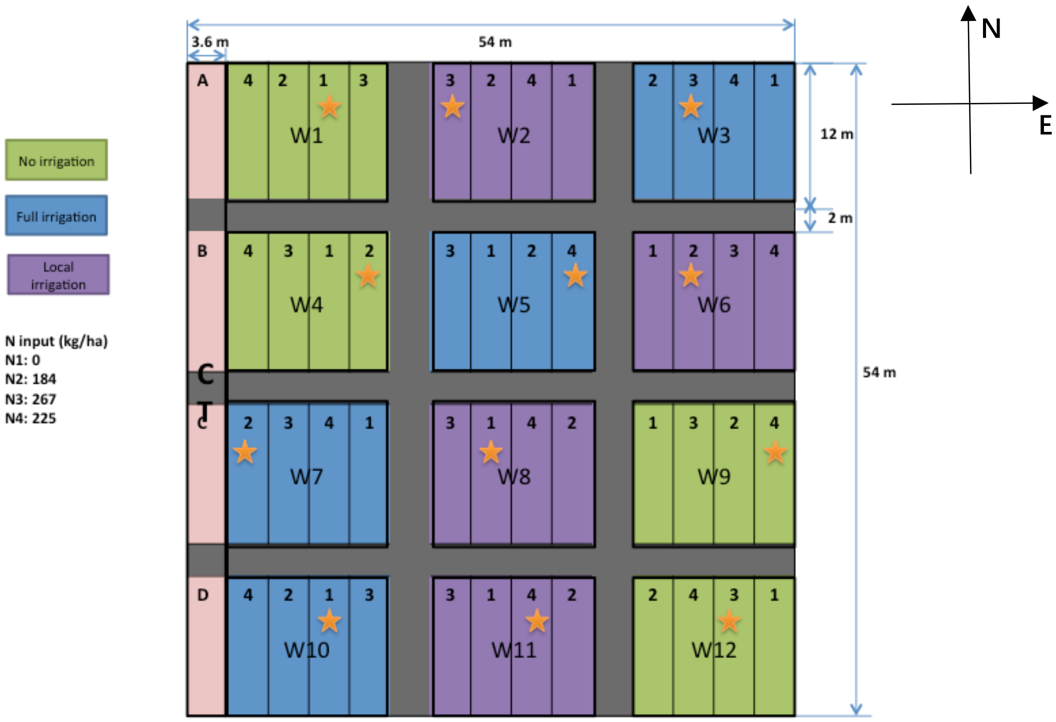

Figure 5: Field experiment design (Wang, 2017). W1 ~ 12 are wholeplots. W1, W4, W9, W12 were treated with no irrigation, W2, W6, W8, W11 were treated with local irrigation and W3, W5, W7, W10 were treated with full irrigation. Each wholeplot was divided into four subplots (each consists of 4 ridges of 12-metre long), and the small number in each subplot in the figure indicates the N treatment that was applied. Each block has three wholeplots: Block 1 consists of W1 ~ 3; Block 2 consists of W4 ~ 6; Block 3 consists of W7 ~ 9; Block 4 consists of W10 ~ 12. Plots A, B, C and D on the left side of the figure were seeded with tuber cuts, fertilized with N3 and watered with full irrigation. The star in a subplot means that the watermark sensor for the wholeplot was buried in this subplot.

Four N treatments

Urea was used as N fertilizer in the field experiment. Base fertilizers were buried in the soil (depth 25 cm) at the time of sowing, and top dressings were carried out twice during the growing season (2nd and 3rd in **Table 6**). The amount of N applied each time for each treatment is shown in **Table 6**. For all the four treatments, N fertilizers were applied at the same time.

Table 6: Nitrogen fertilization (kg N ha^{-1}). Four levels of N treatments (N1, N2, N3, N4) were applied three times (Base fertilization, 2nd fertilization, 3rd fertilization).

	N1	N2	N3	N4	Method
Total	0	184	267	225	---
Base	0	120	174	146	Solid urea buried 25 cm deep in soil
2nd (July 2nd ~ 5th)	0	37	53	45	Root watering
3rd (July 28th ~ 30th)	0	27	40	34	Micro sprinkler irrigation system

2.2 Data collection

Data from the field experiment was collected during Xiaohan Zhou's MSc internship, and the data of other studies in the same area and the global levels were derived from literature. Data collecting methods and equipment used in the field experiment are recorded in Xiaohan Zhou's MSc Internship Report.

According to the original experiment plan, at harvest two 3-metre samples should be taken from the two central ridges of each subplot. But since some of the subplots showed severe lodging in the original 3-metre samples and strange yields compared to other subplots, one or two new 3-metre samples were taken from these subplots. Details are recorded in Xiaohan Zhou's MSc Internship Report.

From the field experiment

1. Soil physical properties and chemical contents: soil organic matter content (SOM), soil bulk density and pH may cause the differences between the field experiment and the literature. They were collected before the field experiment. Soil NPK contents were collected before planting and after harvest. The N measured was in the form of Alkali-hydrolyzable N.

2. NPK contents in tubers, roots, and aboveground parts (main stems, lateral stems and leaves): tested from two original 3-metre samples taken at harvest.

3. Aboveground (main stems, lateral stems and leaves) biomass and sizes: aboveground heights and canopy diameters of three plants randomly selected from each subplot were recorded once a month during the growing season. Aboveground heights were measured three times (June 24th, July 17th and August 16th), while canopy diameters were only measured twice (June 24th and July 17th) because the aboveground parts had lodged in mid-August and thus the canopy diameters could not be measured. Fresh weights of aboveground parts of two original 3-metre samples were measured at harvest;

4. Dry yields and fresh yields: fresh yields and percentages of dry matter contents in harvested tubers were measured from all 3-metre samples (both original and new) taken at harvest. The number and sizes of harvested tubers per sample were also recorded;

5. Precipitation and temperatures: precipitation and temperatures were recorded every day. Precipitation was measured with a rain gauge installed in the experimental field. The highest and lowest temperatures of a day, as well as the local average highest and lowest temperatures of the same day in the past years were derived from the China Weather website;

6. Irrigation and soil water contents: soil water potentials and the timings and amounts of irrigation in each wholeplot were recorded;

7. Diseases, pests and weeds: the phenomena, area of infection and time were recorded;

8. Phenologic stages: emergence, tuber initiation and maturity were recorded when 50 % of the plants in a subplot show certain phenomena;

9. Petiole N contents: measured every 10 days from 16 sample petioles randomly picked from the two side ridges of each subplot (8 samples from each ridge).

From literature

Information on the NUEs, WUEs and yields of potato production in other studies in the same area and globally were collected from literature. Information on the influencing factors (cultivar, climate, soil characteristics, etc.) were also collected this way. Literature used was selected from journals and reports by official institutions such as universities, the United Nations and the governments.

2.3 Data analysis

2.3.1 The main model

The relationship between a result variable and the water & N treatments in the field experiment with randomized block split-plot design was modelled as Equation **1** (Ott & Longnecker, 2008). Result variables include all the variables we measured during or at the end of the field experiment which are results of the treatments. Subplots treated with no irrigation and N1 (no N fertilizer applied) were set as the reference (mean yield = μ). Parameters τ_i and γ_k represent the fixed effects of the ith water treatment and the kth N treatment on the result variable respectively. The effect of block j (β_j) is random.

$$Y_{ijk} = \mu + \tau_i + \beta_j + \tau\beta_{ij} + \gamma_k + \tau\gamma_{ik} + \varepsilon_{ijk}, \qquad \varepsilon_{ijk} \sim N(0, \sigma_\varepsilon^2) \text{ independent} \qquad \text{(Equation 1)}$$

where i = water treatment index = 2, 3 (2 = local irrigation, 3 = full irrigation);

j = block index = 2, 3, 4

k = N treatment index = 2, 3, 4;

Y_{ijk} = the value of the result variable under the i^{th} level of water treatment and the k^{th} level of N treatment in the j^{th} block;

μ = the mean value of the result variable of the reference group (treated with no irrigation & N1 in block 1);

τ_i = main effect for the i^{th} level of water treatment;

β_j = effect due to block j (random effects);

$\tau\beta_{ij}$ = interaction between the i^{th} level of water treatment and the j^{th} block

γ_k = main effect for the k^{th} level of N treatments;

$\tau\gamma_{ik}$ = interaction between the i^{th} level of water treatment and the k^{th} level of N treatment

ε_{ijk} = random error.

2.3.2 Sample selection

As is mentioned in Data Collection (Section 2.2), additional 3-metre samples were taken from subplots with severe lodging and unexpected yields. Only the tuber fresh yields, tuber dry matter contents, average numbers of main stems per m^2, average numbers of tubers per m^2, the numbers of tubers with lengths smaller than 6 cm, and the fresh weights of tubers with lengths smaller than 6 cm were measured from the new 3-metre samples, while other variables were not. Tests of significant differences between the results from the two original 3-metre samples and that from all 3-metre samples were conducted on these six variables by Kruskal-Wallis Tests with 95% CI derived in R (**Appendix 2**). The tests were firstly done on all subplots, and then within the group of each N or water treatment. Since no significant difference was shown, data analyses in this thesis were based on all 3-metre samples. More discussion on lodging is provided in **Appendix 2**.

2.3.3 Selecting definitions of NUE and WUE for data analysis and the calculations of them

The focus of this thesis is on the process from planting to yield, which is the main interest of the producers. Problems like the effect on the environment are not included. Combining this purpose and the limitation by the data we collected from the field experiment, six NUEs from **Table 1** (NUE_{PFP}, NUE_{AE}, NUE_{RE1}, NUE_{RE2}, NUE_{IE} and NUE_{physio}) and two WUEs from **Table 2** (WUE_{agri} and WUE_{irri}) were calculated. As mentioned in Section 1.3.1, the differences in NUE_{PFP} & NUE_{AE}, NUE_{RE1} & NUE_{RE2}, and NUE_{IE} & NUE_{physio} lie in that whether the levels of variables under zero N fertilizer input are deducted. The reasons for calculating both of them are: (1) to avoid that the conclusions become different from the literature due to the choices of NUE definitions; (2) by eliminating the NUEs reached by initial soil N, NUE_{AE}, NUE_{RE1} & NUE_{physio} can help explaining the patterns of NUE_{PFP}, NUE_{RE2} & NUE_{IE}; (3) to show the effects of different NUE definitions on the conclusions through comparisons of these pairs of NUEs,

Calculations of variables in these definitions were modified according to the data collected. N uptake in the definitions NUE_{IE}, NUE_{physio}, NUE_{RE1} and NUE_{RE2} was calculated as the total amount of N contained in the harvested tubers, roots at harvest and aboveground parts at harvest in this thesis, although in NUE_{RE2} the numerator is N in harvested grain according to Conant et al. (2013) and the N uptake was defined as the N in the aboveground parts by Dobermann (2005). Since there was no manure application or N fixation in the field experiment, the "external N inputs" in NUE_{RE2} equals N from fertilizer (N_{fert}).

"Water used" for the definition WUE_{agri} was calculated as the sum of water irrigated and rainfall (**Table 7**). The soil water balances were ignored because during the long transportation of sending soil samples to the laboratories for water content measurements, large portions of water were lost and thus made the results inaccurate. And according to these results, the soil water balances were small compared to the irrigation and precipitation.

According to Fairweather et al. (2003), the unit of irrigation water applied in the definition WUE_{irri} is milliliter (ml) and the unit of yield is kg. In the calculations of WUEs in this thesis, mm for irrigation water and kg ha^{-1} for yield were used (1 ml ha^{-1} equals 100 mm of water irrigated). The units of N_{fert} in all NUE definitions were also modified to kg ha^{-1}. Also, as shown in **Table 1**, in some papers it is not clearly defined whether the yield is dry yield or fresh matter ("yield" in NUE_{physio}, NUE_{AE}, NUE_{PFP} & WUE_{irri}, and "grain yield" in WUE_{agri}). In this thesis, tuber dry yield was used for all definitions in order to eliminate the effect from tuber water content when discussing the influences of water treatments. And the unit of the tuber dry yield in the calculations of NUEs and WUEs was kg ha^{-1}.

Table 7: Water used (mm) was calculated as the sum of precipitation (mm) and irrigation (mm).

Water treatment index	Water treatment name	Precipitation (mm)	Irrigation (mm)	Water used (mm)
1	No irrigation	154	0.0	154
2	Local irrigation	154	235	389
3	Full irrigation	154	280	434

2.3.4 Assumption on the root dry weights and aboveground dry weights

The root dry weights and aboveground dry weights were not measured from the field experiment. They were calculated from the tuber dry yields and a set of assumed dry matter partitioning to tubers, roots and aboveground parts. According to the results of LINTUL growth model ran in the project China Potato GAP 2013 – 2016 (Kempenaar et al., 2017), based on the environmental data of China, around 75% of the dry mass is partitioned to the tubers at the end of the growing season. The experiment by Jenkins & Mahmood (2003) supported the value proposed by China Potato GAP 2013 – 2016. It showed that on the 92th day after emergence, the harvest index ranged from 69% to 80% and the dry weight partitioned to roots ranged from 1.5% to 2.1% no matter whether it was treated with high or low N input. Oliveira et al. (2016) compared the growth of three cultivars (Bondi, Fraser, and Russet Burbank) in non-limiting conditions and showed that the fractions of DM partitioned into tubers of these three cultivars converged as the growing season came to the end, and the fractions were around 70% ~ 80%. In this thesis, it was assumed that 75% of the DM was partitioned into tubers, 23.2% was partitioned into the aboveground parts, and 1.8% was partitioned into roots (the median of the results by Jenkins & Mahmood (2003)).

2.3.5 The relationships between the tuber yield and the water & N treatments

Three groups of result variables were analyzed for this part: (1) tuber fresh yields & tuber dry yields vs. water & N treatments; (2) tuber dry matter contents (DM contents) vs. water & N treatments; (3) the numbers and sizes of tubers at harvest vs. water & N treatments (the number of harvested tubers per m^2 & the fraction of tubers shorter than 6 cm). They were all fitted with the main model (Equation 1) using R. The tuber fresh yield, dry yield, and DM content were analyzed separately because the NUEs and WUEs were calculated based on the tuber dry yield, while the tuber fresh yield is commonly used in the market. Analyzing the DM contents can help explaining the relationships between the tuber fresh yield, NUEs and WUEs.

Whether the change in N or water input has significant effects on the afore mentioned result variables were concluded from the p-values in the ANOVA of the model derived from R. The conclusions were based on a significance level of 0.05. The assumptions on the residual of a linear model were checked. For the comparisons between treatments, figures of the values predicted by the models are provided in the Results (Section 3) rather than plots of the mean values. Because the main model has taken into consideration the blocking effects brought by the randomized block split-plot design of the field experiment, while the mean values were simply averages of the repetitions. Figures will be shown with the result variable on the vertical axis, N treatments on the horizontal axis, and water treatments distinguished with solid or dashed lines. In case water or N treatment significantly influenced the result variable (p value in ANOVA with 95% CI) while the effect is not clearly shown with afore mentioned figure, another figure with the result variable on the vertical axis and this treatment on the horizontal axis will be added. The pairwise comparisons (LSD tests with 95% CI) for predicted values between different N or water treatments were used together with the model parameter estimates and their t-tests to explain the pattern of the changes. It needs to be noted that although an average LSD bar is shown in the figures, the pairwise comparisons were based on the LSD value for each certain pair. Sample means and variances were also reported. In case the variance of a variable was large, it is mentioned in the Results to notice the possible failure of model prediction.

For the sizes of tubers, the fraction of tubers shorter than 6 cm were discussed because such small tubers were rejected by the buyers. Two types of fractions were calculated: (a) the fraction based on the number of tubers; (b) the fraction based on the fresh weights of tubers.

2.3.6 The relationships between NUEs (or WUEs) and the water & N treatments

The relationship between a NUE (or WUE) and the water & N treatments was also fitted with the main model (Equation 1). The analyzing methods were similar to that in Section 2.3.5. Since NUE_{AE}, NUE_{PFP}, NUE_{physio}, NUE_{RE1} & NUE_{RE2} are not defined when the amount of N from fertilizer equals zero, the levels with treatment N2 (184 kg ha^{-1}) and zero irrigation was used as the references in these five models. Similarly, for WUE_{irri}, the level with local irrigation and N1 treatment (0 kg ha^{-1}) was set as the reference.

2.3.7 Analyzing the explanatory variables

Explanatory variables were used to help explaining the relationships between the N & water treatments and the yield, NUEs & WUEs. Firstly, the relationships between the explanatory variables vs. N & water treatments were explored by fitting the explanatory variable into the main model (Equation 1); then, the relationships between the explanatory variables and the NUEs & WUEs were explored.

For the second step, it was tested statistically whether an explanatory variable was correlated to the tuber dry yield or N uptake, because NUEs and WUEs only contain the N or water input, the tuber dry yield or N uptake in their definitions. The explanatory variable was fitted into a linear regression model with the tuber dry yield and the N uptake respectively. The intermediate variable was the predictor and the tuber dry yield or N uptake was set as the predictand. Due to the nature of a randomized block split-plot design, the random effects of blocks and wholeplots were also included in these regression models. Conditional R-squared of these models were reported.

In case an explanatory variable was shown to be related to the tuber dry yield or N uptake by the p-value of the ANOVA (95% CI), a scatter plot of the experimental data with the tuber dry yield or N uptake on the vertical axis and the explanatory variable on the horizontal axis with a linear trend line (intercept and slope derived from the regression model) was plotted. It needs to be noticed that in the physiological processes, the N uptake influences some of the explanatory variables instead of being influenced by them, but in all the linear regressions, N uptake was set as the predictand. Because the purpose for this step is only to get to know whether an explanatory variable was related to the N uptake, and to show the relationships between this explanatory variable and NUEs & WUEs together with the definition equations. Note that how the N uptake changed with the N and water inputs was not statistically tested because the amount of N in roots and aboveground parts were calculated based on the assumption stated in Section 2.3.4, and thus depending on the tuber dry yield and NPK contents (%) in the roots and aboveground parts.

As mentioned in Data Collection (Section 2.2), aboveground heights were measured three times (June 24th, July 17th and August 16th) and canopy diameters were measured twice (June 24th and July 17th). Also, petiole N contents were measured six times during the field experiment (July 13th, July 23rd, August 2nd, August 12th, August 22nd, and September 1st). The regression models were established separately for each date to see which stages of the aboveground growth were important in influencing the tuber dry yield and N uptake.

2.3.8 The relationship among NUE, WUE, and yield in this field experiment

The interactions between NUEs & WUEs: linear regressions were run in R with an NUE as the predictand and a WUE as the predictor, the random effects of blocks and wholeplots were considered. The conditional R-squared and p-values of the ANOVAs were reported. In case an ANOVA p-value was smaller than 0.05, a scatter plot with this NUE on the vertical axis and WUE on the horizontal axis was plotted with the experimental data. A trend line with the intercept and slope derived from the linear regression was drawn.

Tuber fresh yield vs. NUEs & WUEs: Linear regressions run in Rwith an NUE or a WUE as the predictand and the tuber fresh yield as the predictor were used to show the relationship between this NUE or WUE and the fresh yield. A scatter plot of the experimental data with a trend line showing the regression equation was plotted when the ANOVA p-value of a regression was smaller than 0.05.

3. Results

3.1 The relationship between the tuber yield and water & N treatment

To show the pattern of tuber yield in this experiment and to help explain the relationships between the tuber fresh yield, NUEs and WUEs, three groups of variables were analyzed for their relationships with N & water treatments: (1) Tuber fresh yields (Section 3.1.1) & tuber dry yields (Section 3.1.2); (2) tuber DM contents (Section 3.1.3); (3) the numbers and sizes of tubers at harvest (Section 3.1.4). As mentioned in Section 2.3.5, while the tuber fresh yield is commonly used as the indicator of potato yield in both research and market, the tuber dry yield is used in the definitions of NUEs and WUEs. The tuber DM content will be used to help explain the relationships between the tuber fresh yield, NUEs, and WUEs. The number of tubers harvested per m^2 can show the pattern of tuber yield from another aspect. For the sizes of tubers, since tubers shorter than 6 cm were rejected by the main buyers, the fraction of small tubers was calculated (based on both the numbers and the fresh weights).

3.1.1 Tuber fresh yields vs. water and N treatments

The factors that had significant effect on the tuber fresh yield were the main effect of water and N treatments, while the interactions between water and N treatments were not significant (ANOVA, **Table A3-1**). The sample means of the fresh yields with no irrigation, local irrigation (235 mm irrigation) and full irrigation (280 mm irrigation) were 15.7, 42.9 and 43.5 ton ha^{-1} respectively (**Table A3-2**), which showed a big gap between non-irrigated and irrigated situations. This pattern was proved statistically by the pairwise comparisons (LSD tests with 95% CI) of the values predicted by the model (**Figure 6-(a)**). The sample mean tuber fresh yields with 0 (N1), 184 (N2), 225 (N4), and 267 kg ha^{-1} (N3) N from fertilizer ranged between 30.6 and 36.1 ton ha^{-1}. The pattern of predicted fresh yields vs. N treatments is shown in **Figure 6-(b)**: 1) the application of 184 kg ha^{-1} N brought a lower predicted fresh yield than zero N fertilization, but the difference was not significant; 2) while application of 225 kg ha^{-1} N resulted in significantly higher fresh yield than 184 kg ha^{-1} N, increase N fertilization to 267 kg ha^{-1} did not push up the fresh yield further. It needs to be noticed that the assumption of constant variance on the error term for the linear regression was not satisfied (**Figure A3-1**) and that the variance of fresh yields under each N treatment was big (**Table A3-3**).

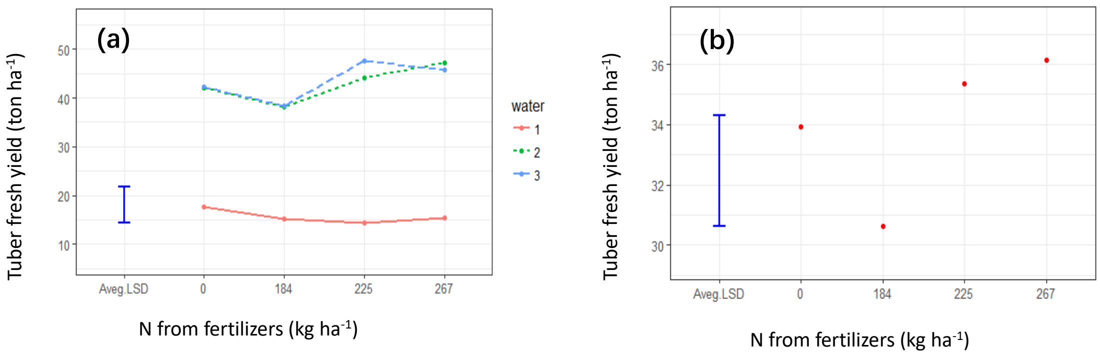

Figure 6: (a) Predicted means of tuber fresh yield (ton ha^{-1}) for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments. (b) Predicted means of tuber fresh yield (ton ha^{-1}) for N treatments with average LSD bar (95% Confidence interval).

3.1.2 Tuber dry yields vs. water and N treatments

As is shown with the p-values in ANOVA (**Table A3-4**), water treatments had significant effects on the tuber dry yield while N treatments did not. The difference in tuber dry yields between non-irrigated and irrigated plots was big, but there was no significant difference between the model predicted means for 'local' and 'full' irrigation (**Figure 7**). In other words, the tuber dry yield went up from zero irrigation to 235 mm irrigation, while further increase in irrigation did not make any difference. Tuber dry yields (ton ha^{-1}) were calculated from the fresh yields (ton ha^{-1}) and tuber DM contents (%), and are reported in **Appendix 1**.

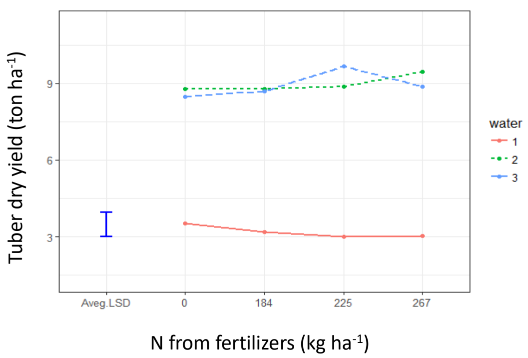

Figure 7: Predicted means of tuber dry yield (ton ha^{-1}) based on all 3-metre samples for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments.

3.1.3 Tuber dry matter contents vs. water & N treatments

The sample mean tuber dry matter content (DM content, %) across all treatments was 20.0% (variance = 0.3 ‰) (**Table A4-1 & A4-2**). Both N and water treatments significantly influenced the tuber DM contents (p-value < 0.05), while the interactions between water and N treatments were not significant (ANOVA, **Table A4-3**). The pairwise comparisons of predicted mean DM contents showed that, for water treatments, both the increase from 0 mm to 235 mm irrigation and the decrease from 235 mm to 280 mm irrigation were significant (**Figure 8-(a)**). As for N treatments, the decrease of DM content from 0 kg ha^{-1} to 184 kg ha^{-1} N fertilizer input was significant (**Figure 8-(b)**). The predicted mean tuber DM content for each combination of N and water treatments are shown in **Figure 9**.

The tuber DM content decreased with N input while the tuber fresh yield increased with N input, although between different pairs of N treatments. It suggests that a higher N input enhanced tuber's ability to uptake or store water. The fact that DM content increased with irrigation amount from 0 to 235 mm, which was the same as the change in tuber fresh yield, can explain the increase in dry yield between the same pair of water treatments.

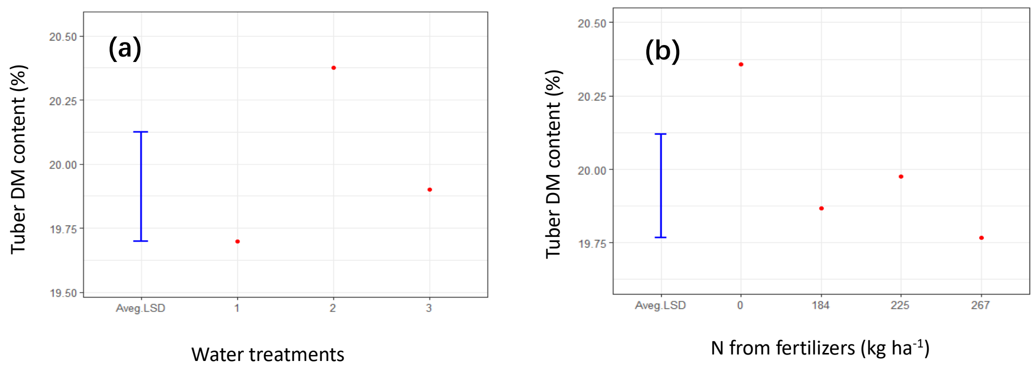

Figure 8: Predicted means of tuber dry matter content (%) with average LSD bar (95% CI) for (a) Water treatments. Water treatment 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively; (b) N treatments.

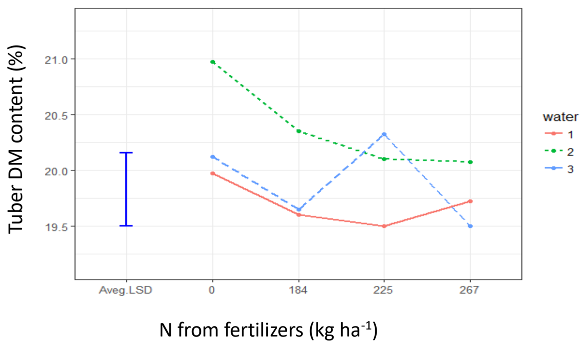

Figure 9: Predicted means of tuber dry matter content (%) for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments.

3.1.4 The numbers & sizes of tubers at harvest vs. water & N treatments

The sample mean number of harvested tubers per m^2 in the irrigated plots (local & full irrigation) almost doubled that in the non-irrigated plots (**Table A5-1**), while the means for different N treatments stayed between 22.5 and 23.6 per m^2 (**Table A5-2**). The main effects of water treatments and the effects of the interactions between water and N treatments were both significant for the number of harvested tubers per m^2 (ANOVA, **Table A5-3**). The mean numbers of harvested tubers predicted by the model are shown in **Figure 10**. Without separating the interactions from the main effects, the pairwise comparisons of predicted means showed that the increases in the number of harvested tubers per m^2 from 0 mm to 235 mm irrigation and from 235 mm to 280 mm irrigation were both significant (**Figure 11**). N input only influenced the number of harvested tuber per m^2 when the irrigation was 235 mm (p-value for t-test, **Table A5-3**). At 235 mm irrigation, the number of harvested tubers per m^2 with 267 kg ha^{-1} N fertilization was higher than that with other N treatments, since other N treatments did not make a significant difference from the reference level, while 267 kg ha^{-1} N fertilization had positive effects (Estimate of parameters, **Table A5-3**).

As for the fraction of harvested tubers with lengths smaller than 6 cm, irrigation was the only significant factor for both the results based on the numbers and that based on the fresh weights (ANOVA, **Table A5-4 & A5-5**). Based on the numbers (**Figure 12-(a)**), the predicted mean fraction of small tubers significantly decreased with irrigation from 0 mm to 235 mm (local), and did not show significant change when irrigation continued increasing. But the fraction under 0 mm and 280 mm irrigation (full) were not significantly different. However, when based on the fresh weights (**Figure 12-(b)**), the predicted mean fraction of small tubers under full irrigation was significantly lower than that under zero irrigation.

As shown in Section 3.1.1, the tuber fresh yields under irrigation (local & full) were nearly three times of that under rain-fed condition. Compared to the changes in the number of harvested tubers, it suggests that the average fresh weight of each tuber increased with irrigation from 0 to 235 mm. It agrees with the decrease in the fraction of small tubers based on fresh weights, which is favored

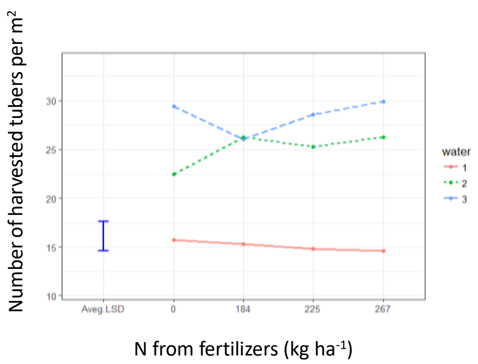

Figure 10: Predicted means of the number of harvested tubers per m^2 for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments.

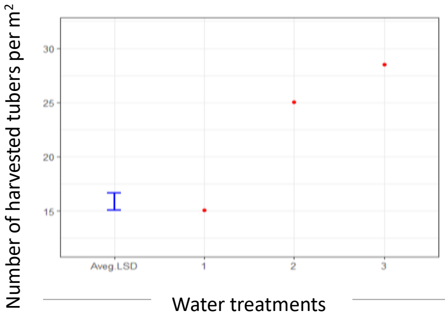

Figure 11: Predicted means of the number of harvested tubers per m^2 for water treatments with average LSD bar (95% CI). Water treatments 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively.

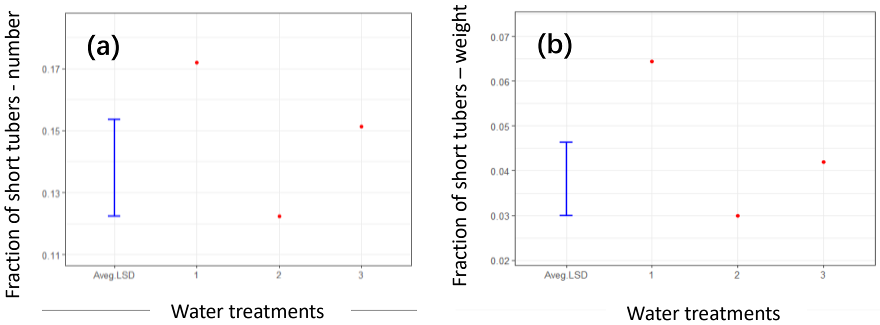

Figure 12: Predicted means of the fraction of harvested tubers shorter than 6 cm for water treatments with average LSD bar (95% CI). Water treatments 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. (a) Based on numbers; (b) based on fresh weights.

3.2 The relationships between the NUEs and water & N treatment

NUEs of six definitions are analyzed in this section for their relationships with water and N treatments. NUE_{AE} & NUE_{PFP} show the entire process from the N input to the tuber dry yield (Section 3.2.1), NUE_{RE1} & NUE_{RE2} show the process from the N input to the N uptake (Section 3.2.2), while NUE_{IE} & NUE_{physio} show the utilization of N uptake to produce tuber dry mass (Section 3.2.3). The six NUEs will be used to explain the potato growth. And analyzing the pair of NUEs for each process can avoid unfair conclusion due to whether the value with zero N fertilizer input was deducted from the definition.

3.2.1 NUE_{AE} and NUE_{PFP}

The sample means of NUE_{AE} ranged from -0.27 to 1.15 kg kg^{-1} for different N treatments, and from -2.04 to 2.64 kg kg^{-1} for different water treatments (**Table A6-1 & A6-2**). Negative NUE_{AE} occurred when the tuber dry yield without N fertilization (Y_0) exceeded those with N fertilization (Y_N). Fitted with the main model, neither water nor N treatment significantly influenced NUE_{AE} (F-test p-value for the main effects of water treatments = 0.151, p-value for the main effects of N treatments = 0.539, p-value for the effects of interactions between water and N treatments = 0.359). This can be explained by the fact that the differences between the tuber dry yield without N fertilization (Y_0) and those with N fertilization (Y_N) were close to zero (**Table A3-3**), and thus the a change in the denominator (N_{fert}) did not make a difference.

For NUE_{PFP}, the influences of water treatments, N treatments, and the interactions between them were all significant (ANOVA, **Table A6-5**). As shown in **Figure 13**, NUE_{PFP} decreased with N fertilizer input from 184 kg ha^{-1} to 267 kg ha^{-1}, and increased with irrigation amount from 0 mm to 235 mm (local irrigation). There was no significant change on NUE_{PFP} by increasing the irrigation from 235 mm to 280 mm (full irrigation). According to the pairwise comparisons of predicted mean NUE_{PFP}'s, both the change from 184 kg ha^{-1} to 225 kg ha^{-1} N fertilizer input and the change from 225 kg ha^{-1} to 267 kg ha^{-1} N fertilizer input were significant. This pattern of change is due to that the numerator of NUE_{PFP} (Y_N) increased with irrigation from 0 to 235 mm (Section 3.1.2), while the denominator equals the amount of N fertilization (N_{fert}). The interaction between water and N treatments was only significant at the highest N input (p-value for t-test, **Table A6-5**). At 267 kg ha^{-1} N treatment, increase in irrigation from 235 to 280 mm brought a lower NUE_{PFP} (Estimate of parameter, **Table A6-5**).

It needs to be noticed that the variances of NUEs within each treatment group were big. Especially for NUE_{AE}, the standard deviation under each N treatment ranged from 5 to 15 times of the mean value (**Table A6-1 & A6-2**).

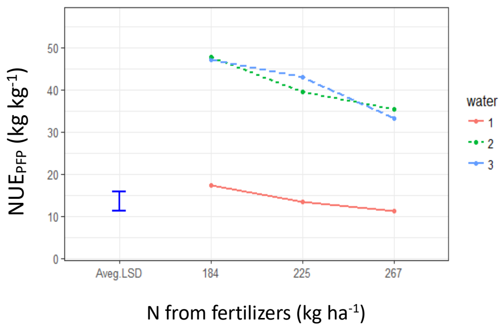

Figure 13: Predicted means of NUE_{PFP} (kg dry yield kg^{-1} N) for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments.

3.2.2 Recovery efficiencies: NUE_{RE1} and NUE_{RE2}

Samples means of NUE_{RE1} ranged from 4.5% to 11.8% for all N treatments and from -1.8% to 14.4% for all water treatments. Negative NUE_{RE1} occurred when the N uptake with N fertilization (U_N) was smaller than that without N fertilization (U_0), which suggests that the soil N stock before sowing was adequate for growth. No treatment significantly influenced NUE_{RE1} (F-test p-value for the main effects of water treatments = 0.104, p-value for the main effects of N treatments = 0.639, p-value for the effects of interactions between water and N treatments = 0.747). Similar to NUE_{AE}, this is due to that the differences between U_N and U_0 were close to zero. The N amounts in plant parts can explain it further (explanatory variables, Section 3.4.1-(3)).

The sample mean of NUE_{RE2} for zero irrigation was 40.6%, which was smaller than half of that with irrigation (**Table A6-2**). NUE_{RE2} was only influenced by water treatments (ANOVA, **Table A6-6**). As shown in **Figure 14**, the increase of NUE_{RE2} from no irrigation to local irrigation (235 mm) was obvious, while there was no significant difference between local and full irrigation (280 mm). Similar to NUE_{AE} and NUE_{PFP}, the variances of NUE_{RE1} and NUE_{RE2} under each treatment were also large (**Table A6-1 & A6-2**).

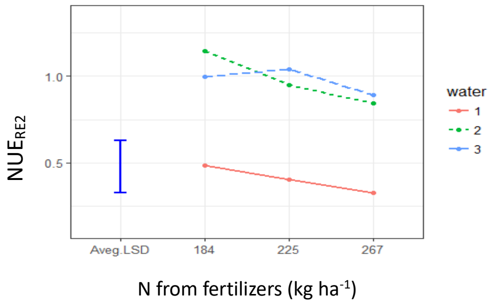

Figure 14: Predicted means of NUE_{RE2} for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments.

3.2.3 Utilization efficiencies: NUE_{physio} and NUE_{IE}

Fitted with the main model, the ANOVAs showed that neither NUE_{physio} nor NUE_{IE} was influenced by the treatments (**Table A6-7**). Explanations will be made with the N amounts in plant parts at harvest (explanatory variable, Section 3.4.1-(3)). Similar to what was shown in Section 3.2.1 & 3.2.2, the sample variances of NUE_{physio} and NUE_{IE} under a certain treatment were large (**Table A6-1 & A6-2**). The sample mean NUE_{physio} was 24.5 kg kg^{-1} across all treatments, while the mean NUE_{IE} was 42.8 kg kg^{-1}.

3.3 The relationships between the WUEs and water & N treatment

WUE_{irri} was only influenced by the water treatments (ANOVA in **Table A6-8**, **Figure 15-(a)**), while WUE_{agri} was influenced by both the main effect of water treatments and the interaction between N and water treatments (ANOVA in **Table A6-9**, **Figure 15-(b)**). WUE_{irri} decreased with irrigation from 235 mm (sample mean 38.2 kg ha^{-1} mm^{-1}) to 280 mm (sample mean 31.8 kg ha^{-1} mm^{-1}), because the tuber dry yield stayed the same as the water input increased in this range. Since WUE_{irri} is not defined at zero irrigation, the change with irrigation from 0 mm to 235 mm is unknown.

As shown in **Figure 16-(a)**, the increase of WUE_{agri} from 0 (sample mean 20.6 kg ha^{-1} mm^{-1}) to 235 mm irrigation (sample mean 23.0 kg ha^{-1} mm^{-1}) and the decrease from 235 mm to 280 mm irrigation (sample mean 20.5 kg ha^{-1} mm^{-1}) were both significant. The increase of WUE_{agri} from zero to local irrigation was due to that the percentage increase in the tuber dry yield was higher than that in the water used. As for N treatments (**Figure 16-(b)**), the pairwise comparisons showed that WUE_{agri}'s were the same between any pair of the N treatments. The t-tests on the estimates of model parameters however showed that the interactions of treatments 235 mm irrigation & N3 (267 kg ha^{-1} N from fertilizer), 280 mm irrigation & N3, and 280 mm irrigation & N4 (225 kg ha^{-1} N from fertilizer) made WUE_{agri} different from the reference level (under zero irrigation & zero N input). In other words, interactions between water and N treatments became effective on WUE_{agri} when the input of water and N were both high. The increase in WUE_{agri} from 0 to 235 mm irrigation was larger at 267 kg ha^{-1} N treatment compared to other N treatments, because the estimate of parameter of the interaction between 235 mm irrigation & N3 was larger than 0, while the interaction between 235 mm irrigation & N2 and that between 235 mm irrigation & N4 did not bring significant difference from the reference level (**Table A6-9**). Similarly, the decrease in WUE_{agri} from 235 to 280 mm irrigation was also larger at 267 kg ha^{-1} N input. At 280 mm irrigation, WUE_{agri} increased with N input from 0 to 225 kg ha^{-1}, and decreased with N input from 225 to 267 kg ha^{-1} (Estimate of parameter & p-value for t-test, **Table A6-9**).

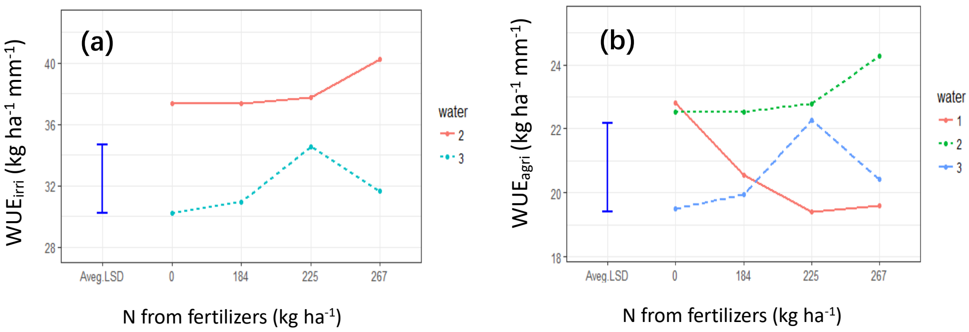

Figure 15: Predicted means of WUEs (kg ha^{-1} mm^{-1}) for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments. (a) WUE_{irri}; (b) WUE_{agri}.

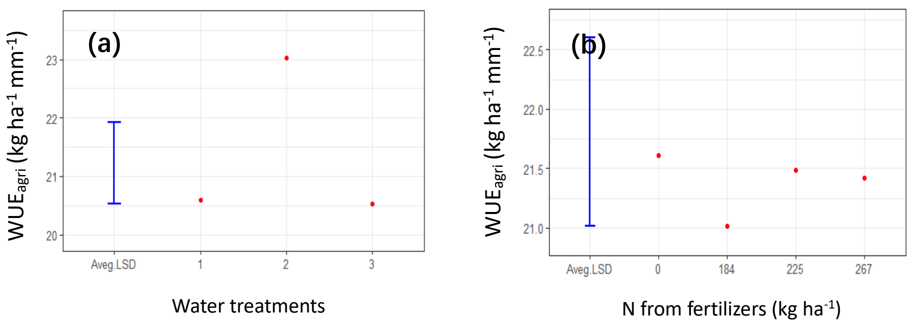

Figure 16: Predicted means of WUE_{agri} (kg ha^{-1} mm^{-1}) with average LSD bar (95% CI) for (a) water treatments. Water treatment 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively.; (b) N treatments.

3.4 Explanatory variables

Explanatory variables were employed to explain how the water & N treatments influenced the tuber yield, NUEs, and WUEs. Firstly, the relationships between the explanatory variables and the treatments were analyzed (Section 3.4.1). Then, it was explored how these explanatory variables were connected with the tuber dry yield or the N uptake (Section 3.4.2). Since the tuber dry yield and the N uptake were the only variables contained in the definitions of NUEs and WUEs besides the N & water input, the relationships between the explanatory variables and the NUEs & WUEs can be inferred this way.

3.4.1 The relationships between the explanatory variables and N & water treaments

1) Sizes and weights of plant parts (aboveground height, canopy diameter, the fresh weight of aboveground part, and the fresh weight of roots)

Aboveground heights measured in July showed different patterns from those measured in June and August. In June and August, aboveground heights were not influenced by N treatments (ANOVA, **Table A7-3**), and only increased with irrigation from 0 to 235 mm (**Figure 17**). **Figure 17-(a)** shows a slight drop of model-predicted aboveground height from 235 to 280 mm irrigation on June 24th. The drop was not significant and the aboveground height on June 24th with 280 mm irrigation was still significantly bigger than that with 0 mm irrigation. In July, however, the aboveground height kept increasing as irrigation increased from 235 to 280 mm (**Figure 18-(a)**), and was positively related to N input between 0 and 184 kg ha^{-1}. The decrease of aboveground height from 225 to 267 kg N ha^{-1} shown in **Figure 18-(b)** was not significant, and the difference between 0 and 267 kg ha^{-1} was significant.

Canopy diameters were not measured in August due to lodging. In June, the model-predicted canopy diameter significantly increased when irrigation went up from 0 to 235 mm (**Figure 19**). In July, the canopy diameter not only significantly increased with irrigation from 0 to 235 mm (**Figure 20-(a)**), but also significantly increased with N input from 184 to 225 kg ha^{-1} (**Figure 20-(b)**). The increase from 0 to 184 kg ha^{-1} and the decrease from 225 to 267 kg ha^{-1} shown in **Figure 20-(b)** were not significant.

The fresh weights of aboveground parts and roots were not influenced by the treatments (ANOVA, **Table A7-4**). The increase of aboveground size (aboveground height & canopy diameter) with irrigation from 0 to 235 mm and the unchanged aboveground fresh weight indicates a decrease in the density of aboveground parts (fresh weight per unit volume). And since the aboveground and root dry weights were calculated based on the assumption of fixed dry matter partitioning (Section 2.3.4) and the tuber dry weight increased with irrigation from 0 to 235 mm, it suggests that the aboveground and root dry weights increased while the aboveground and root water contents decreased.

The sample means and standard deviations of the sizes and fresh weights of plant parts are reported in **Table A7-1 & 7-2**. The variances are acceptable.

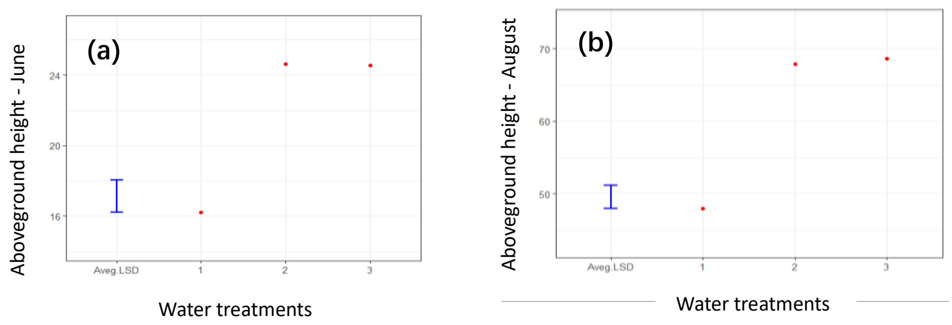

Figure 17: Predicted means of the aboveground heights (cm) for water treatments with average LSD bar (95% CI). Water treatments 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. (a) Aboveground heights measured on June 24th; (b) Aboveground heights measured on August 16th.

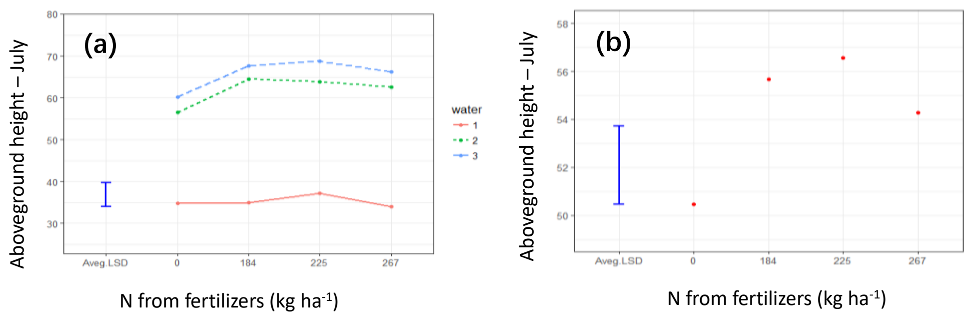

Figure 18: (a) Predicted means of the aboveground heights (cm) measured on July 17th for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI). 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. (b) Predicted means of the aboveground heights (cm) measured on July 17th for N treatments with average LSD bar (95% CI). The lines connecting points do not mean continuous data, they show which four points are under a same water treatments.

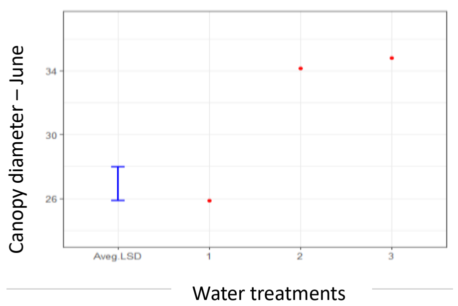

Figure 19: Predicted means of the canopy diameters (cm) measured on June 24th for water treatments with average LSD bar (95% CI). Water treatments 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively.

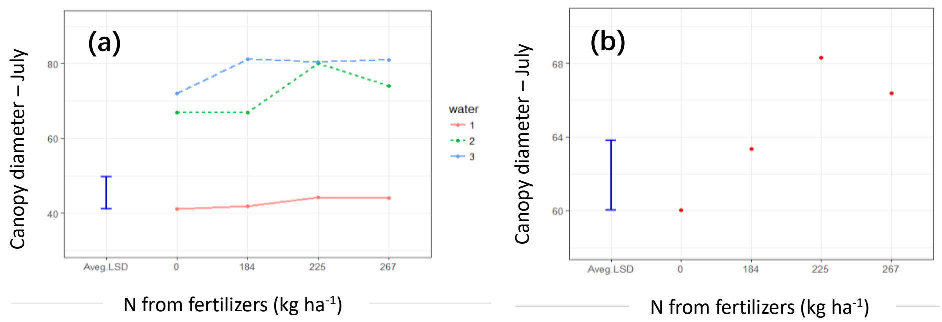

Figure 20: (a) Predicted means of the canopy diameters (cm) measured on July 17th for different combinations of water and nitrogen treatments by the model with average LSD bar (95% CI); (b) Predicted means of the canopy diameters (cm) measured on July 17th for N treatments with average LSD bar (95% CI).

2) The number of main stems per m^2

As shown in **Table 8**, the number of main stems per m^2 was not influenced by water or N treatments. The variance under each treatment is acceptable. Thus the number of main stems will be regarded was an irrelevant variable in this experiment.

Table 8: The means and standard deviations, and the p-values for F-test from ANOVA of the number of main stems per m^2. W1, W2 and W3 means 0, 235 and 280 mm irrigation respectively; N1, N2, N3 and N4 means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively. 'Interaction' represents the effects of the interactions between water and N treatments.

	W1	W2	W3	N1	N2	N3	N4	Interactions
Mean	12.9	13.0	13.0	12.8	12.9	13.4	12.9	---
Sd	1.30	1.34	1.19	1.32	1.11	1.22	1.44	---
p-value (ANOVA)	0.961			0.722				0.832

3) NPK contents (%) in different plant parts (tubers, aboveground parts and roots), and the amount of NPK in tubers (kg ha^{-1})

P contents (%) in tubers, aboveground parts and roots were not influenced by the water or N treatments (ANOVA, **Table A8-2**). N contents (%) in tubers and roots were influenced by both the water and N treatments, while in aboveground parts it was only influenced by N treatments. The interactions between water and N treatments significantly influenced N content in roots. K contents (%) in aboveground parts and roots were influenced by both the water and N treatments, as well as the interactions between the two treatments. The K content in tubers was influenced by water treatments only. The samples means and standard deviations of NPK contents in each plant part for different treatments are reported in **Table A8-1**. The variance of the data under each treatment was acceptable.

As shown in **Figure 21**, the effective change of irrigation was between 0 and 235 mm. Tuber N & K content, aboveground K content, and roots N & K content all went down when irrigation increased from 0 to 235 mm. The effects of N treatments are plotted in **Figure A8-1**, since they are not clearly shown in **Figure 21**. Tuber N content went up when N input from fertilizer increased from 0 to 225 kg ha^{-1}, while the change between 0 & 184 kg ha^{-1} and that between 184 & 225 kg ha^{-1} were not significant (**Figure A8-1(a)**). Aboveground and root N contents went up as N input increased from 0 to 184 kg ha^{-1} (**Figure A8-1(b)&(c)**), while aboveground K content went up from 225 to 267 kg ha^{-1} N input (**Figure A8-1(d)**). Root K content, however, was negatively related to N input between 0 and 184 kg ha^{-1} (**Figure A8-1(e)**).

The levels of NPK contents might be influenced by the dry weights of the plant parts. But since the dry weights of aboveground parts and roots were calculated from a set of assumed dry matter partitioning, only the tuber NPK amounts (kg ha^{-1}) were analyzed here to complement the analysis of NPK contents. According to the ANOVA, the amount of N in tubers at harvest was influenced by both the water and the N treatments, as well as the interactions between the two treatments (ANOVA, **Table A8-3**). As shown in **Figure 22-(a)**, the tuber N amount increased with irrigation from 0 to 235 mm, which contradicted the results of the tuber N content (%). But the change with N treatments in tuber N amount was similar to that in tuber N content, namely going up as N input increased from 0 to 225 kg ha^{-1} and no significant changes between 0 & 184 kg ha^{-1} or between 184 & 225 kg ha^{-1} (**Figure A8-2**). As shown in **Figure 22-(b) & (c)**, the tuber P & K amounts also significantly increased with irrigation from 0 to 235 mm (F-test p-value for P = 0.000, F-test p-value for K = 0.000).

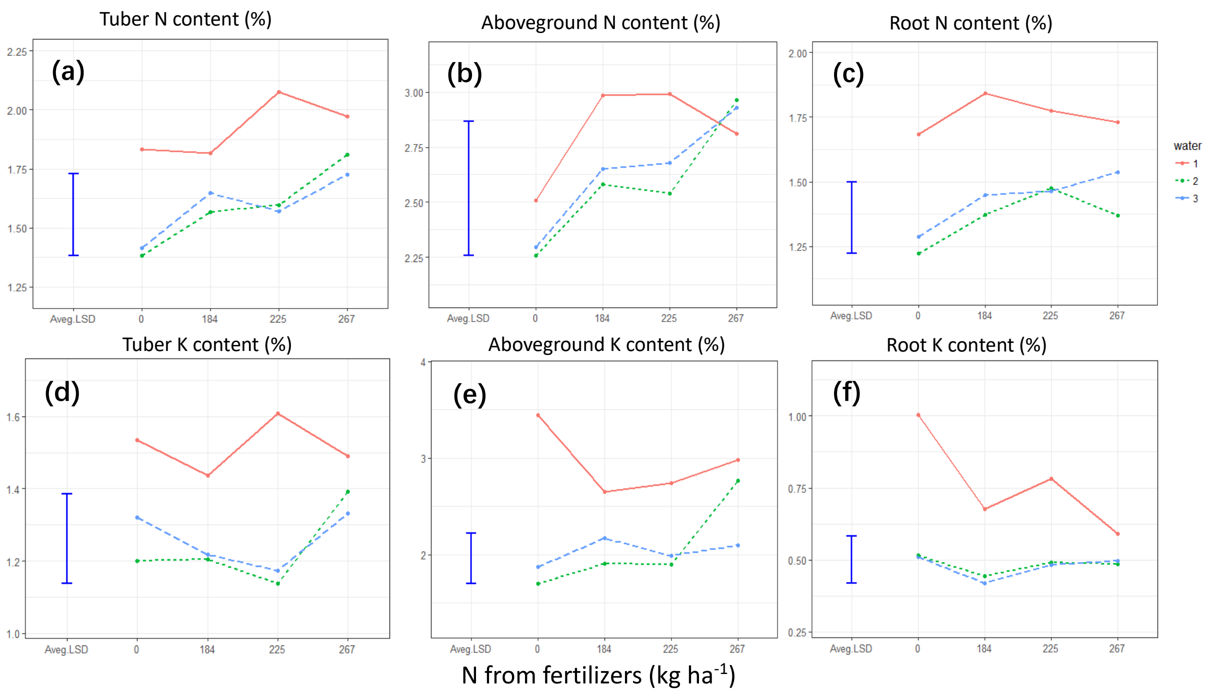

Figure 21: Model predicted means of NPK contents (%) in different plant parts at harvest for different combinations of water and nitrogen treatments with average LSD bar (95% CI). The horizontal axes are N treatments. 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments. (a), (b) and (c) shows N% in tubers, aboveground parts and roots respectively; (d), (e) and (f) shows K% in tubers, aboveground parts and roots respectively.

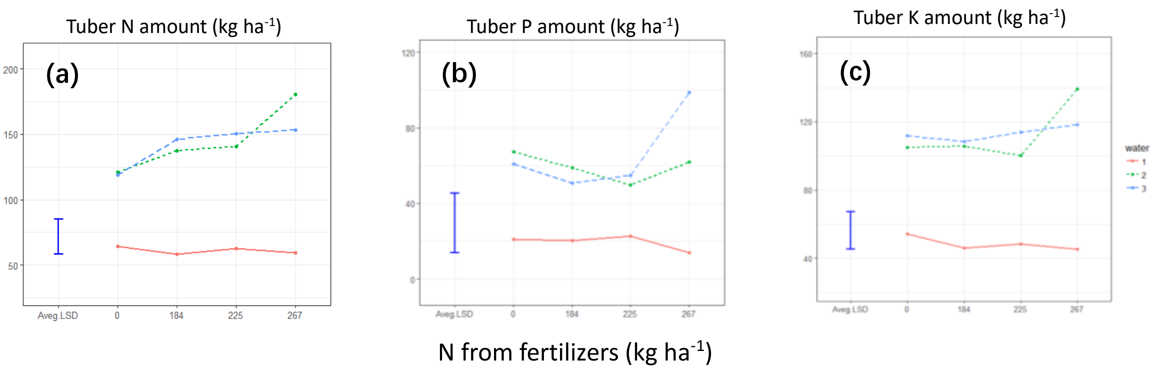

Figure 22: Model predicted means of the amount of NPK in tubers (kg ha^{-1}) at harvest for different combinations of water and nitrogen treatments with average LSD bar (95% CI). The horizontal axes are N treatments. 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. (a) tuber N amount; (b) tuber P amount; (c) tuber K amount.

4) The fluctuation of petiole N contents

Petiole N contents (NO_3-N, ppm) were measured on July 13th, July 23rd, August 2nd, August 12th, August 22nd and September 1st, 2017. The sample means ranged from 4058 (full irrigation, September 1st) to 11288 ppm (no irrigation, August 2nd) for different water treatments, and from 1639 (N1, September 1st) to 8892 ppm (N3, August 2nd) for different N treatments (**Table A9-1**). They are high compared to other experiments. According to a research on the white potato production in Virginia, USA, the yield does not respond to additional N application when the petiole N content is higher than 1500 ppm (Reiter et al., 2009).

The fluctuations of mean petiole N contents for each treatment from July 13th to September 1st were shown in **Appendix 13**. N fertilizers were applied on July 2nd ~ 5th and July 28th ~ 30th. The reason for the rise in petiole N contents from July 13th to July 23rd might be due to the continuing uptake of N that was applied during July 2nd ~ 5th. And the second fertilization explains why on August 2nd the petiole N contents were higher than that on July 23rd under some treatments. On August 13th, Cyazofamid (C13H13ClN4O2S), which contains N, was applied for potato late blight. It might be the reason for the increase in petiole N contents between August 12th and August 22nd under some treatments. But the amount of N applied with Cyzofamid was only 10.37 g ha^{-1}, which was small compared to N fertilization.

On all the six dates, petiole N contents increased with N treatments from 0 to 184 kg ha^{-1} (**Figure A9-1**), and decreased with irrigation from 0 to 235 mm (**Figure 23**). There were also some other significant changes: on July 23rd petiole N content decreased with irrigation from 235 to 280 mm, on August 22nd it increased with N input from 225 to 267 kg ha^{-1}, and on August 2nd and September 1st it increased with N input from 184 to 225 kg ha^{-1}, but these changes were small, although they were statistically significant. The effect from the interactions between N and water treatments were significant in August (ANOVA, **Table A9-2**).

The significant increases of petiole N contents with N input from 0 to 184 kg ha^{-1} were consistent with the results of the aboveground N content (%, Section 3.4.1-(3)). But the aboveground N content was not influenced by water treatments.

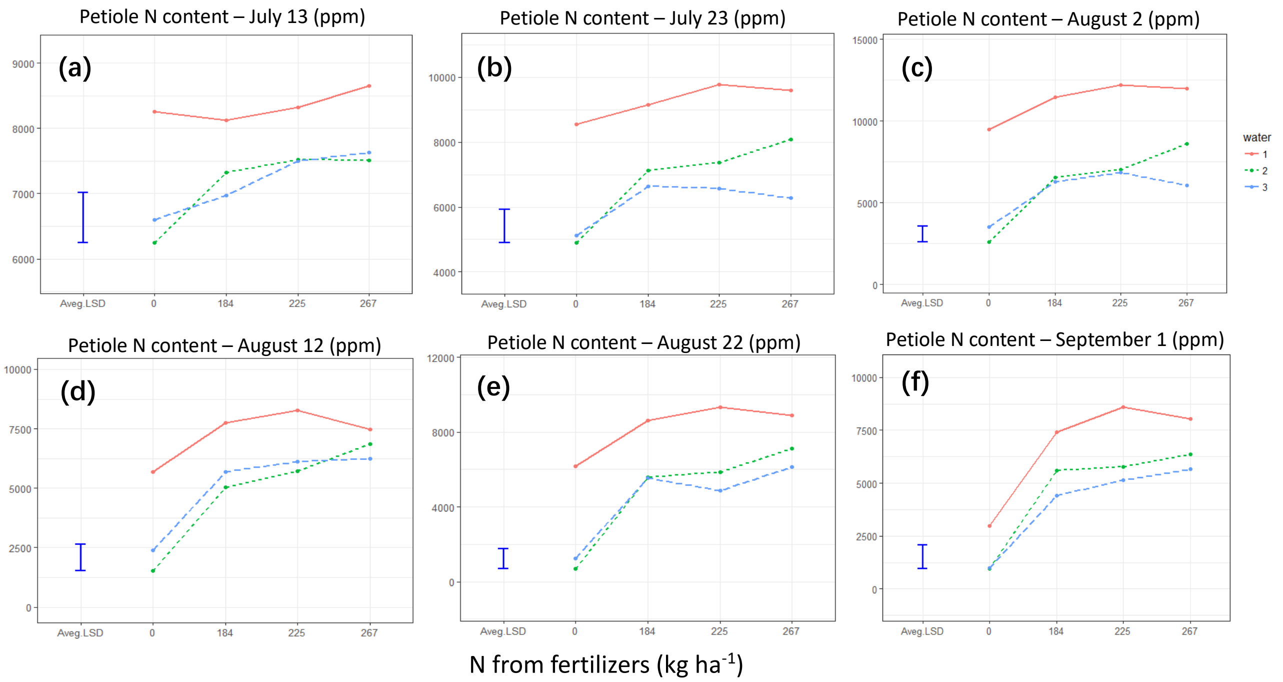

Figure 23: Model predicted means of petiole N contents (NO_3-N, ppm) measured on six dates for different combinations of water and nitrogen treatments with average LSD bar (95% CI). The horizontal axes are N treatments. 'water' 1, 2 & 3 means zero irrigation, local irrigation (235 mm) and full irrigation (280 mm) respectively. The lines connecting points do not mean continuous data, they show which four points are under a same water treatments. (a) July 13th; (b) July 23rd; (c) August 2nd; (d) August 12th; (e) August 22nd; (f) September 1st, 2017.

3.4.2 The relationships between the explanatory variables and the tuber dry yield & N uptake

The root fresh weight (kg ha^{-1}), the number of main stems per m^2, the NPK contents (%) of the roots and the aboveground parts at harvest, the P amount in harvested tubers (kg ha^{-1}), and the petiole N contents measured during growth (NO_3-N, ppm) were not related to the tuber dry yield (ton ha^{-1}) or the N uptake (kg ha^{-1}). The fresh weight of aboveground parts (ton ha^{-1}), the aboveground heights in July and August (cm), the canopy diameter in July (cm) and the amounts of N & K in harvested tubers (kg ha^{-1}) were positively related to the tuber dry yield (**Figure 24**). The fresh weight of aboveground parts, the aboveground heights and canopy diameters in all months, the tuber N content (%), and N & K amounts in harvested tubers (kg ha^{-1}) were positively related to the N uptake (**Figure 25**). The N uptake was positively related to the tuber N content (%) & tuber N amount (kg ha^{-1}) because it was calculated based on these variables.

The data points are shown to be divided into two groups in each scatter plot, which indicates the significant increases of these variables with water treatments: the values of the variables were similar with local (235 mm) and full (280 mm) irrigation (2/3 of the data points), while much higher than that with zero irrigation (1/3 of the data points). The conditional R-squared and ANOVA p-values of the regression models are reported in **Table A10-1 & A10-2**.

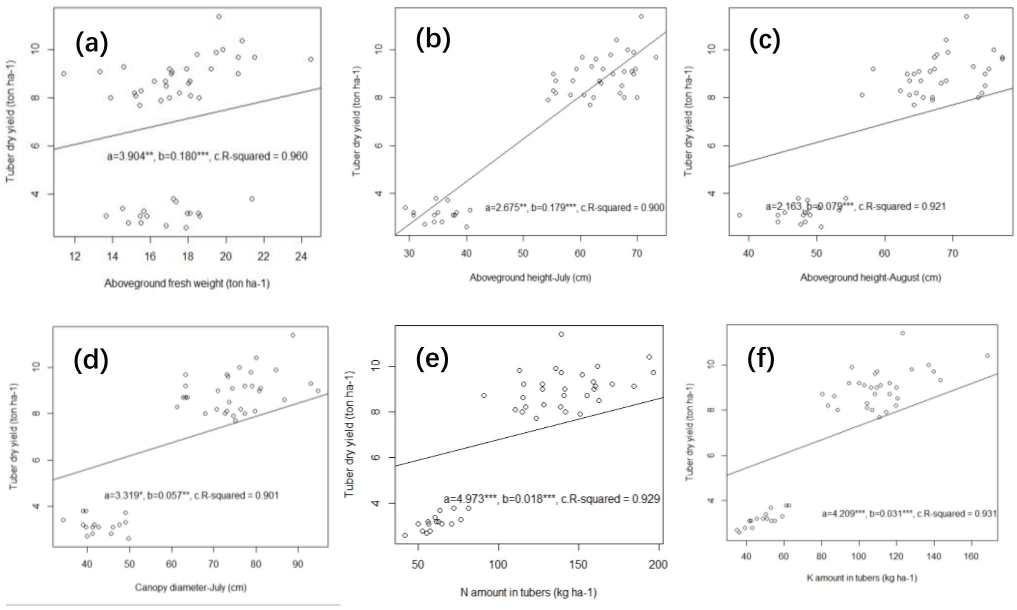

Figure 24: Scatter plots of the experimental data of the tuber dry yield (ton ha^{-1}) vs. the explanatory variables which were shown to be related to it with the ANOVA of the regression models (Table A10-1). The intercepts and slopes of the trend lines were derived with the regression models in which the random effects of the blocks and wholeplots were considered. (a) Aboveground fresh weight (ton ha^{-1}); (b) Aboveground height measured in July (cm); (c) Aboveground height measured in August (cm); (d) Canopy diameter measured in July (cm); (e) The amount of N in harvested tubers (kg ha^{-1}); (f) The amount of K in harvested tubers (kg ha^{-1}).

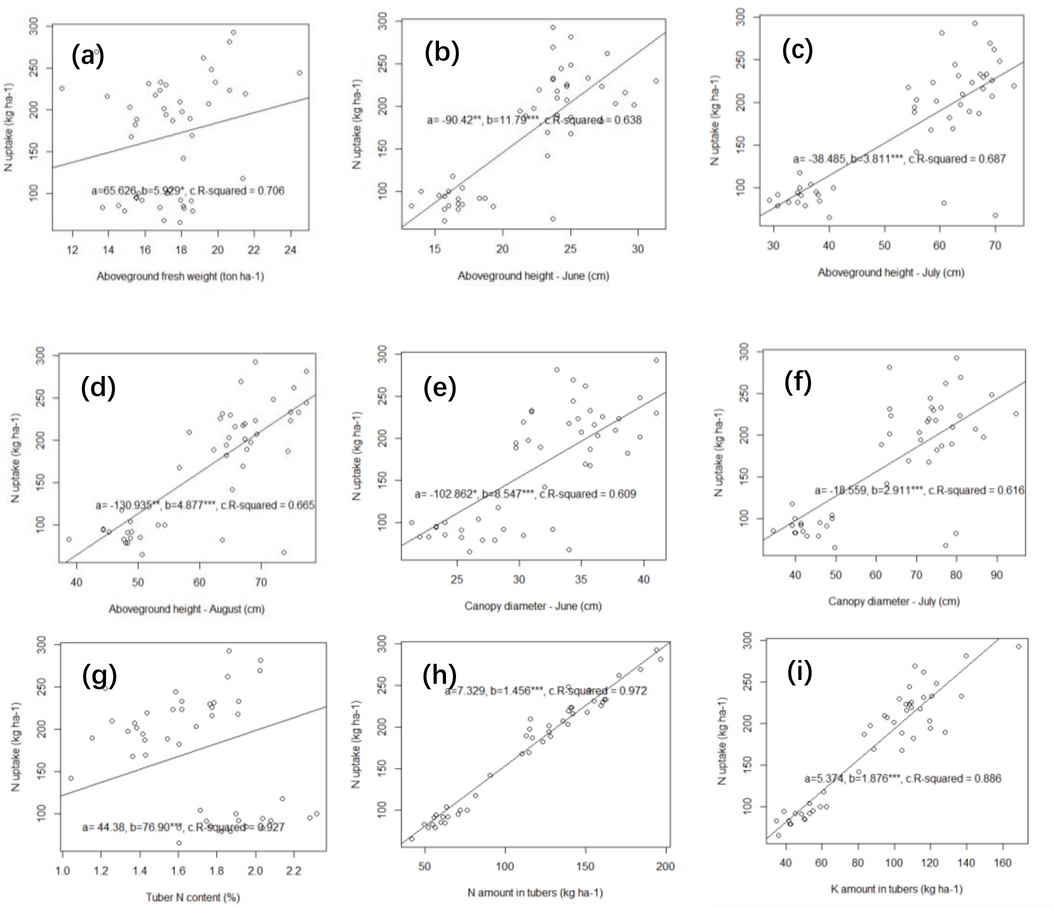

Figure 25: Scatter plots of the experimental data of the N uptake (ton ha^{-1}) vs. the explanatory variables which were shown to be related to it with the ANOVA of the regression models (Table A10-2). The intercepts and slopes of the trend lines were derived with the regression models in which the random effects of the blocks and wholeplots were considered. (a) Aboveground fresh weight (ton ha^{-1}); (b) Aboveground height measured in June (cm); (c) Aboveground height measured in July (cm); (d) Aboveground height measured in August (cm); (e) Canopy diameter measured in June (cm); (f) Canopy diameter measured in July (cm); (g) Tuber N content (%); (h) The amount of N in harvested tubers (kg ha^{-1}); (i) The amount of K in harvested tubers (kg ha^{-1}).

3.5 The relationships among NUEs, WUEs, and the tuber fresh yield in this field experiment

3.5.1 The interactions between NUEs and WUEs

The regressions showed that out of the 12 combinations of NUE & WUE (six NUEs with two WUEs), five pairs of NUE & WUE were positively related with each other (**Figure 26**): NUE_{AE} (kg kg^{-1}) & WUE_{irri} (kg ha^{-1} mm^{-1}), NUE_{AE} & WUE_{agri} (kg ha^{-1} mm^{-1}), NUE_{PFP} (kg kg^{-1}) & WUE_{agri}, NUE_{RE1} & WUE_{agri}, and NUE_{RE2} & WUE_{agri}, while the other seven pairs did not show a correlation (ANOVA, **Table A11-1**). No tradeoff was shown between any pair of NUE and WUE. NUE_{physio} and NUE_{IE} were not correlated to any WUE. It agrees with the results that WUE_{irri} and WUE_{agri} changed with the water treatment (Section 3.3), while NUE_{IE} and NUE_{physio}

did not (Section 3.2.3). The conditional R-squared of the regressions on the uncorrelated pairs were small, which means that the regression models were not able to well explain the varieties of the response data.

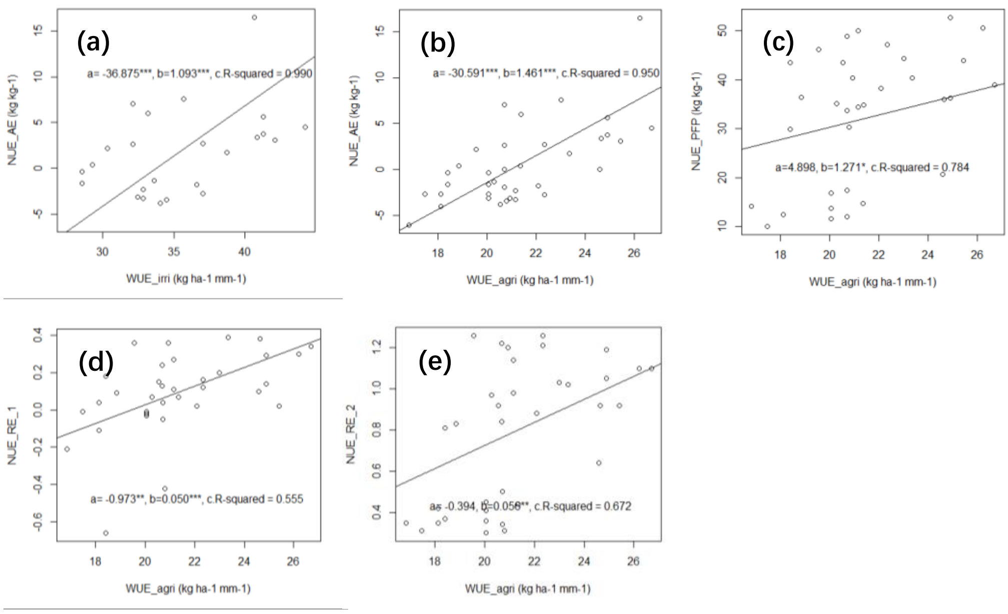

Figure 26: Scatter plots of the experimental data of the NUEs vs. the WUEs which were shown to be related with the ANOVA of the regression models (Table A11-1). The intercepts and slopes of the trend lines were derived with the regression models in which the random effects of the blocks and wholeplots were considered. (a) NUE_{AE} (kg kg^{-1}) vs. WUE_{irri} (kg ha^{-1} mm^{-1}); (b) NUE_{AE} (kg kg^{-1}) vs. WUE_{agri} (kg ha^{-1} mm^{-1}); (c) NUE_{PFP} (kg kg^{-1}) vs. WUE_{agri} (kg ha^{-1} mm^{-1}); (d) NUE_{RE1} vs. WUE_{agri} (kg ha^{-1} mm^{-1}); (e) NUE_{RE2} vs. WUE_{agri} (kg ha^{-1} mm^{-1}).

3.5.2 Tuber fresh yield vs. NUEs and WUEs

The regressions of an NUE or WUE on the fresh yield showed that NUEs and WUEs were positively related to the fresh yield except NUE_{physio}, which was not related to the fresh yield (ANOVA, **Table A11-2**, **Figure 27**). The conditional R-squared of the regressions of NUE_{RE1}, NUE_{physio} and NUE_{IE} were small.

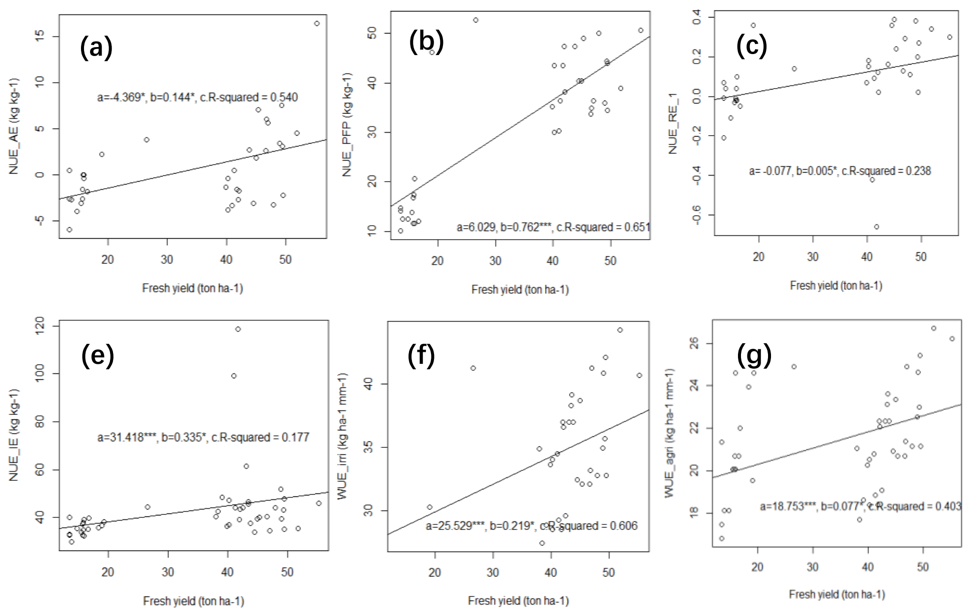

Figure 27: Scatter plots of the experimental data of the NUEs or the WUEs vs. t he tuber fresh yield (ton ha^{-1}) which were shown to be related with the ANOVA of the regression models (Table A11-2). The intercepts and slopes of the trend lines were derived with the regression models in which the random effects of the blocks and wholeplots were considered. (a) NUE_{AE} (kg kg^{-1}); (b) NUE_{PFP} (kg kg^{-1}); (c) NUE_{RE1}; (d) NUE_{RE2}; (e) NUE_{IE} (kg kg^{-1}); (f) WUE_{irri} (kg ha^{-1} mm^{-1}); (g) WUE_{agri} (kg ha^{-1} mm^{-1}).

4. Discussion

4.1 The relationships between the tuber yield and the water & N treatments

The tuber fresh yield (ton ha^{-1}), tuber dry yield (ton ha^{-1}), tuber DM content (%), number of harvested tubers per m^2, and the fraction of harvested tubers shorter than 6 cm (based on the numbers and the fresh weights) were analyzed to evaluate the tuber yield. Most variables showed significant differences between zero irrigation and 235 mm irrigation (local irrigation treatments): the tuber fresh yield, dry yield, DM content, and the number of harvested tubers per m^2 increased with the water input from 0 to 235 mm, while the fraction of small tubers decreased. The sample mean of tuber fresh yield with local irrigation was 42.9 ton ha^{-1}, while with zero irrigation it was only 15.7 ton ha^{-1}. The fresh yields with local and full irrigation in our experiment were higher than the local average yield and the yields in other experiments in the same region, and they were similar to the average yield of North America (Chen et al., 2012; Xie et al., 2012; FAOSTAT, 2008; Kempenaar et al., 2017). But it is still far from reaching the "attainable yield" for Inner Mongolia (72 ton ha^{-1}) proposed by China Potato GAP 2013-2016 (Kempenaar et al., 2017). Since the consumers prefer tubers longer than 6 cm, the decrease in the fraction of small tubers is preferred by the producers. The number of harvested tubers per m^2 continued increasing when irrigation increased from 235 mm to 280 mm (full irrigation), while the DM content significantly decreased. The DM content with full irrigation (19.9%) was similar to that with zero irrigation (19.7%). In other words, the highest tuber DM content showed up with local irrigation (20.4%). But all of the three levels of DM contents were acceptable by the consumers.

One explanation for the pattern of change that no irrigation was significantly different from local irrigation while full irrigation was not is that water is not limiting anymore when the irrigation reaches 235 mm. It is supported by the findings of China Potato Gap 2013-2016 (Kempenaar et al., 2017), which put that the local irrigation in Inner Mongolia is higher than the needed amount calculated from the LINTUL model. However, the full irrigation treatment (280 mm) in our field experiment, which was designed according to the WOFOST model, was higher than the local irrigation (235 mm). This difference in the model results suggests the importance of choosing a suitable model and the possibility of improve the modelling.

Another explanation for the pattern is that the gap between the amounts of water input of no irrigation and local irrigation is much larger than that between local irrigation and full irrigation. Taking precipitation into consideration, the water used (precipitation plus irrigation) for local irrigation doubled that of no irrigation, while the relative difference between the amounts of water used for local and full irrigation was only about 0.12 (**Table 7**). Thus the pattern might be a result of the difference between the two amount gaps. In other words, the irrigation applied by local farmers has almost reached the level of full irrigation (80% of the field capacity in early and rapid growing season, 60~65% in the late growing period).

As for the effects of the N treatments, the fresh yield increased significantly from 30.6 to 35.4 ton ha^{-1} as N input was raised from 184 to 225 kg ha^{-1}, while the tuber DM content went down from 20.4% to 19.9% when N input increased from 0 to 184 kg ha^{-1}. Although these two significant changes occurred with different ranges of N inputs, a linkage between them might be that the fresh yield increased with N input, while the dry yield did not change, and thus the DM content decreased. In other words, the water content in tubers increased with N input. This indicates that the increase in N fertilization can increase the plant's ability to uptake or store water. Similar results were observed in some other experiments (Ahmed et al., 2009; Leszczyński & Lisińska, 1988), and the same explanation was given by Ahmed et al. (2009). This view is supported by Schippers (1968), who found that the fresh yield increase from N fertilizer was mostly from the increasing in tuber water content. However, the increase in N application brings significant increase in the protein content (Ahmed et al., 2009).

An explanation for the ineffectiveness of N fertilization on the tuber dry yield is that the soil N content was already very high at sowing. The N treatments were designed based on the soil N contents tested in July 2015 in the same area (**Table 3**), because the soil N content in the experimental field at the time of sowing in 2017 was not available before planting. In 2015, the total amount of NH_4-N and NO_3-N was 41 kg ha^{-1}, but in 2017 before planting, the average amount of soil N (Alkali-hydrolyzable nitrogen) tested from the soil samples taken from the experimental field reached 426 kg ha^{-1} (Xiaohan Zhou's MSc Internship Report, Section 3.2, **Table 10**). The amount of N fertilizer used on this field might have been very high in the former cultivation season in the year of 2016. As shown in **Figure A12**, the amount of NPK in soil decreased after the 2017 growing season. Before planting, soil N (Alkali-hydrolyzable nitrogen), P and K contents ranged between 305 & 634 (average = 426), 77 & 224 (average = 134), and 387 & 660 (average = 514) kg ha^{-1} respectively. While after harvest, they lied between 269 & 719 (average = 366), 59 & 164 (average = 94), and 262 & 1051 (average = 433) kg ha^{-1} respectively. This result indicates that the NPK uptake might have exceeded the amount of NPK applied from fertilizer. The different N treatments did not influence the tuber dry yield because plants received enough nutrients from the soil stock. The comparisons between the N uptakes and the amounts of N from fertilizer in all subplots support this inference. 25 out of the 48 subplots had N uptakes which were higher than the N from fertilization (NUE_{RE2} larger than one or not defined, **Table A1**). However, the N amount in tubers and the petiole N contents increased with N treatments, which indicates that the N uptake was not the same for all N treatments. The relationships will be further explained with the NUEs for different processes and the explanatory variables.

4.2 The relationships between the NUEs and the water & N treatments

The NUEs on the process from the N input to N uptake (NUE_{RE1} & NUE_{RE2}), the process from the N uptake to tuber dry yield (NUE_{physio} & NUE_{IE}), and the whole process from the N input to tuber dry yield (NUE_{AE} & NUE_{PFP}) were analyzed. NUE_{AE}, NUE_{RE1}, NUE_{physio} and NUE_{IE} were not significantly influenced by the water or N treatments. Both NUE_{PFP} and NUE_{RE2} increased with irrigation from 0 to 235 mm, but NUE_{PFP} decreased with irrigation from 235 to 280 mm when N fertilization was 267 kg ha^{-1}. NUE_{PFP} was the only one which was significantly influenced by the interaction between N and water treatments, as well as the N treatment itself. NUE_{PFP} decreased as N fertilizer input went up from 184 to 225 kg ha^{-1}, and from 225 to 267 kg ha^{-1}.

The increase of NUE_{RE2} when irrigation went up from 0 to 235 mm indicates that with 235 mm irrigation, more N can be taken up per unit of available N. For NUE_{RE1}, this effect was offset by deducting the uptake in plots without N fertilization from the numerator. The efficiencies of utilizing the N uptake (NUE_{physio} and NUE_{IE}) did not change, and thus NUE_{PFP}, which measures the whole process from the N fertilization to the tuber dry yield, increased in the same way as NUE_{RE2}. The significant increase in the tuber dry yield with irrigation from 0 to 235 mm was also consistent with this change. On the other hand, the increase in NUE_{PFP} can also be explained with NUE_{AE}. As put by Dobermann (2005), to improve NUE_{PFP}, increasing Y_0 (the dry yield without N fertilizer application) is as important as increasing NUE_{AE}. Since Y_0 increased with irrigation (from 0 to 235 mm) and NUE_{AE} did not change, NUE_{PFP} went up.

NUE_{PFP} decreased with N input because the tuber dry yield, which is the numerator in the definition of NUE_{PFP}, did not change, while the denominator (amount of N from fertilizer) increased. Decomposed into two steps, although NUE_{RE2} did not significantly change with N input, it slightly decreased (**Table A6-1**), and thus the increase in N uptake was smaller than that in N input. And as a result, an unchanged (no significant change) NUE_{IE} brought an unchanged dry yield. As shown in **Table A6-1** & **A6-2**, the mean levels of NUE_{RE2} for different N treatments were all larger than 50%, and that for different water treatments were close to one except zero irrigation. According to Alva et al. (2011), NUE_{RE2} for potatoes usually lies between 33% and 50%. The high NUE_{RE2} in our experiment can explain the changes in soil N contents shown in **Figure A12-(a)**, where the soil N contents decreased in most subplots, except those with no irrigation.

4.3 The relationships between the WUEs and the water & N treatments

WUE_{agri} significantly increased with the water treatment from 0 to 235 mm and decreased from 235 to 280 mm. WUE_{irri} also decreased with irrigation from 235 to 280 mm, but since it is not defined at zero irrigation, the change between 0 and 235 mm irrigation is unknown. This pattern of change might be a direct result from the definitions of the WUEs. The tuber dry yield, as the numerator of the WUEs, increased with irrigation from 0 to 235 mm, and stayed the same between 235 and 280 mm. While the denominator (water used, mm) went up with irrigation. The relative increase in the tuber dry yield with irrigation from 0 to 235 mm wins over the relative increase in the amount of water used, and thus WUE_{agri} increased. Since it is unclear whether the relative increase in the tuber dry yield can win over the relative increase in the irrigation amount (denominator of WUE_{irri}), no inference can be made on the difference between WUE_{irri} for 235 mm and a smaller irrigation (bigger than 0 mm). Note that although N treatments did not have significant effect on the WUEs, the interactions between N and water treatments were shown to have significantly influenced WUE_{agri}. Compared to other N treatments, 267 kg ha^{-1} N input enhanced the positive effect of water input on WUE_{agri} from 0 to 235 mm. However, this enhancement was not observed for the tuber dry yield, the numerator of WUE_{agri}.

4.4 Explain the patterns of the tuber yield, NUEs & WUEs with the explanatory variables

The fresh weights of roots and aboveground parts at harvest, the sizes of aboveground parts during the growing season, the number of main stems per m^2 at harvest, the NPK contents (%) in different plant parts at harvest, the NPK amounts (kg ha^{-1}) in tubers at harvest, and the petiole N contents during the growing season were selected to help explaining the relationships between the N & water treatments and the tuber yield, NUEs & WUEs. Besides the N and water inputs, the tuber dry yield and the N uptake were the only two variables in the definitions of NUEs and WUEs, and thus the relationships between the explanatory variables and the tuber dry yield & the N uptake were analyzed.

The N uptake was positively related to the aboveground heights in all months (June, July & August), the canopy diameters in both months (June & July), the tuber N content (%), the amount of N & K in tubers (kg ha^{-1}) and the fresh weight of aboveground parts (ton ha^{-1}). The aboveground heights in all months, the canopy diameters in both months, and the N & K amounts in tubers increased with irrigation from 0 to 235 mm, while the tuber N content decreased. The decrease in tuber N content (%) was due to that the increase in tuber dry yield was larger than that in tuber N amount with the rise in irrigation, and this is the reason why both the tuber N amount and the percentage of tuber N content were analyzed. The bigger canopy with 235 mm irrigation could bring higher transpiration and thus enhancing the uptake and transport of N in the plant body. The N uptake is the summation of the N amounts in tubers, roots and aboveground parts. The amounts of N in roots and aboveground parts were not statistically analyzed (although they were calculated for the calculation of N uptake) because they were calculated from the N contents (%) in roots & aboveground parts and an assumed dry matter partitioning (Section 2.3.4). But since the tuber dry yield increased with irrigation from 0 to 235 mm, the root dry weight and aboveground dry weight used in the calculation of N uptake also increased, because the dry matter partitioning was assumed to stay the same across all treatments. The N amount in aboveground parts thus increased because the N content in aboveground parts did not change with water input. The change of the N amount in roots is unclear since the root N content was shown to be decreasing with irrigation in this range. The increases of the N amounts in tubers and aboveground parts pushed up the N uptake, and NUE_{RE2} increased as a result. The N contents in roots and aboveground parts increased with N fertilizer input from 0 to 184 kg ha^{-1}, and the N content in tubers increased with N input between 0 and 225 kg ha^{-1}, all of which could have improved the N uptake. But recovery efficiencies (NUE_{RE1} & NUE_{RE2}) did not show increase with N input due to the increase in the denominator (N fertilizer input).

The tuber dry yield was positively related to the fresh weight of the aboveground parts, the aboveground heights in July and August, the canopy diameter in July, and the amount of N & K in tubers. As irrigation increased from 0 to 235 mm, the canopy was bigger and intercepted more light, and thus enhancing the photosynthesis and pushed up the tuber dry yield. The increase in the tuber N amount might be in the form of protein or other matters which are parts of the dry matter in tubers. The changes in the K amounts in roots and aboveground parts are unclear because the K contents (%) decreased with irrigation from 0 to 235 mm while the dry weights of roots & aboveground parts went up. But the K amount in tubers significantly increased according to ANOVA. The uptake of K, an element of many important enzymes, was positively related to the starch production (Lindhauer & De Fekete, 1990), and thus positively related to the tuber dry yield. This is one of the reason for the increase of NUE_{PFP} and WUE_{agri} with irrigation between 0 and 235 mm (they are positively related to the tuber dry yield by definition). Although the canopy diameter in July increased with N fertilizer input between 184 and 225 kg ha^{-1}, and the amount of N in tubers went up with N input between 0 and 225 kg ha^{-1}, the positive effects of them on the tuber dry yield (numerator of NUE_{PFP}) were not significant, and could not compete with the increase in the amount of N input (denominator of NUE_{PFP}), and thus NUE_{PFP} decreased with N input. The fresh weight of aboveground parts was not influenced by water or N treatments, but it was positively correlated with the N uptake and the tuber dry yield. This supports our assumption of a constant dry matter partitioning among plant parts, based on which we calculated the aboveground dry weight from the tuber dry yield.

It needs to be noticed that the root fresh weights, the number of main stems per m^2, the P contents in plant parts, the tuber P amount, and the petiole N contents measured every 10 days from July 13th to September 1st were not significantly related to the tuber dry yield or the N uptake in this experiment. The tuber P amount and the petiole N contents were significantly different for different N or water treatments though. Many studies have pointed out that the number of main stems per m^2 changes with irrigation (Tolessa et al., 2016), and is positively related to the tuber yield and the number of tubers per m^2, and negatively related to the tuber size (Wiersema, 1987). There were also papers which observed the same results as our experiment. Fleisher et al. (2011) concluded that the stem density does not influence the total leaf area and the dry matter productions of both the vegetative parts and tubers. The P in tubers should have been important for the starch phosphorylation (Houghland, 1960), and the reason why it was not related to the tuber dry yield in this experiment is unclear yet. As for the petiole N content for each date of measurement, the reason for which it was not correlated with the tuber dry yield might be that it was high under all treatments. According to a paper on the white potato production in Virginia, USA, when the petiole N content is higher than 1500 ppm, the yield does not respond to additional N application anymore (Reiter et al., 2009). In an experiment in Israel (Cohen et al., 2010), the petiole N content ranged from 200 to 3000 ppm through the growing season, while the tuber yield reached above 60 ton ha^{-1}. Although the cultivar and location in this experiment were different, with the means for different water treatments ranging from 4058 to 11288 ppm and for N treatments ranging from 1639 to 8892 ppm, the petiole N contents in this experiment were high, and thus did not limit the growth of tubers (**Table A9-1, Figure A13**). The reason for which the petiole N contents on all the measurement dates were not correlated with the N uptake might be that the biggest portion of N uptake was in tubers, and not all the N in tubers was derived from the aboveground parts. According to Lin et al. (2006), as much as 40% of the tuber NO_3^- uptake can be derived through the tuber skin. However, the petiole N contents also showed a trend of decreasing with time even though fertilization was done twice during the growing season (**Figure A13**), which indicates the transportation of N from the petioles to other plant parts (Ziadi et al., 2012).

The significant increases of petiole contents with N input from 0 to 184 kg ha^{-1} were consistent with the results of aboveground N content (%). But the aboveground N content was not influenced by water treatments. It might be due to that: (1) the aboveground N contents were calculated based on a set of assumed dry matter partitioning and thus the results might not be accurate; (2) the petiole N contents were measured from the juice of petioles, while the aboveground N contents at harvest were measured from the dry matter. The decrease in petiole N content with water treatments might be a result of the dilution of water. The reason for which it did not further decrease when the irrigation was increased from 235 to 280 mm might be that the plant has reached its upper limit of water uptake.

4.5 The relationships among NUEs, WUEs and the tuber fresh yield in this experiment

No tradeoff was shown between any pair of NUE and WUE. WUE_{agri} was positively correlated with NUE_{AE}, NUE_{PFP}, NUE_{RE1} and NUE_{RE2}, while not correlated with the two NUEs for the process from the N uptake to the tuber dry yield (NUE_{physio} & NUE_{IE}). The positive correlations between WUE_{agri} and NUE_{AE} & NUE_{PFP} were direct results of the definitions (tuber dry yield in the numerator). The reason for the positive correlation between WUE_{agri} and NUE_{RE2} might be that both of them increased with irrigation from 0 to 235 mm, and this was resulted from the positive effect of irrigation within this range on the N uptake and the tuber dry yield. As shown in **Figure 26-(d) & (e)**, the slope of the regression of NUE_{RE1} on WUE_{agri} is smaller than that of NUE_{RE2} on WUE_{agri}, which is consistent with the difference in the definitions of NUE_{RE1} and NUE_{RE2}. WUE_{irri} was positively correlated with NUE_{AE}. Both of their definitions have tuber dry yield in the numerator.

The tuber fresh yield was shown to be positively related to all NUEs and WUEs except NUE_{physio}. The facts that the tuber fresh yield was not related to NUE_{physio}, and the slope of the regression between NUE_{IE} and the fresh yield was small (the process from N uptake to tuber dry yield) support the inference that the N uptake was too large and thus not limiting the tuber production. This inference is also supported by the observation that although the N uptake was bigger than the amount of N from fertilizer and thus the N fertilization was not influencing the tuber dry yield, the N uptake was still changing with N fertilization (tuber N amount increased with N fertilization from 0 to 225 kg ha^{-1}). The increase in the N uptake was not utilized for the tuber dry matter production, but stored in the plant.

The tuber fresh yield equals the division of the tuber dry yield by the tuber DM content. The numerator (tuber dry yield) is in positive relations with WUE_{agri} and WUE_{irri} by definition. When irrigation increased from 0 to 235 mm, both the tuber fresh yield and WUE_{agri} went up. When irrigation increased from 235 to 280 mm, WUE_{irri}, WUE_{agri}, and the tuber DM content went down, while the tuber fresh yield did not significantly change. The drop in tuber DM content should have indicated an increase in the tuber fresh yield, but the absolute drop was very small, although it was significant due to the scale of the DM content (sample mean tuber DM content is 20.4% for 235 mm irrigation, and 19.9% for 280 mm irrigation). Thus the tuber fresh yield did not increase with irrigation from 235 to 280 mm, and the tuber fresh yields for all water treatments showed positive relationship with WUE_{agri} and WUE_{irri}.

4.6 Compare the NUEs, WUEs, and yields from our field experiments to other experiments

Most researches used one to three definitions of NUE for an analysis. And WUE_{agri} was commonly used. Some researches calculated the NUE or WUE based on the fresh yields, while others based on the dry yields. Many papers on the local potato production did not include an explicit definition of NUE or WUE. In this section, studies which had a clear definition of NUE or WUE were selected to be compared with the results of our experiments. The fresh yields from these experiments were also compared with those in our experiment. The tuber fresh yield with irrigation (local & full) in our experiment was higher than the yields in most of the selected experiments. It was also slightly higher than the average yield in North America at 41.2 ton ha^{-1}, and is approaching three times of the world average at 16.8 ton ha^{-1} (FAOSTAT, 2008).

4.6.1 Local NUE

An experiment performed in Heilongjiang Province (Liu et al., 2011), which is also located in northeastern China, reached an NUE_{RE1} of 81.7%, which is much higher than the level resulted from our experiment (ranged from 4.5% for N2 to 11.8% for N4). Similar to our experiment, the fertilizer application in this Heilongjiang experiment in 2011 was also based on the soil tests. The large difference might be due to that our fertilizer application was based on the soil test from the year of 2015, and the soil chemical contents before sowing in

2017, which we received later, showed that the soil N content was much higher than the level in 2015. And thus the N uptake in plots without N fertilizer application, namely the N uptake from N stored in soil, was high, which dragged down the level of NUE_{RE1}.

In an experiment of the effects of water and N treatments on the NUE of potato production in Inner Mongolia, China (Chen et al., 2012), the results showed that with increasing N application, NUE_{AE} and NUE_{PFP} went down. But NUE_{physio} first went up and then went down with the increase in N fertilization under high and low water treatment, while kept going down under medium water treatment.[5] With increasing irrigation, both NUE_{AE} and NUE_{physio} went down, while NUE_{PFP} went up. The decrease of NUE_{PFP} with N fertilization was observed in our experiment when N application increased from 184 to 225 and from 225 to 267 kg ha^{-1}. Also, the change with irrigation was only shown by NUE_{PFP} in our experiment, which went up with irrigation from 0 to 235 mm.

The five N fertilizations in Chen et al. (2012) were 0, 75, 150, 225 and 300 kg ha^{-1}, which is similar to our treatments (0, 184, 225 and 267 kg ha^{-1}). The soil was also sandy loam with a pH 6, which is similar to that in our experiment (**Table 4**). Our soil had a higher soil organic matter content (SOM% = 2.18) compared to Chen et al. (2012) (SOM% = 0.8), and more Alkali-hydrolyzable nitrogen (132 mg kg^{-1} for our experiment before sowing, 32.4 mg kg^{-1} for Chen et al. (2012)), which might be the reason why NUE_{AE} and NUE_{physio} did not show the changes with N treatments as in Chen et al. (2012). In the definitions of NUE_{AE} and NUE_{physio}, the difference in tuber dry yield or N uptake between the plot with N application and without N application were used, while the definition of NUE_{PFP} only considers the dry yield with N fertilization and does not deduct the level with zero fertilization. The NUEs in Chen et al. (2012) were calculated based on the tuber fresh weight, and the tuber DM contents were only around 8%. When converting the NUEs in our experiment (based on tuber dry yield) with our tuber DM contents (around 20%, **Table A4-2**) to that based on tuber fresh yields, the NUE_{AE} in our experiment tended to be lower than that from Chen et al. (2012), while NUE_{PFP} and NUE_{physio} were similar. The small NUE_{AE} in our experiment can be explained by the high tuber dry yield without N fertilization (deducted in the numerator). However, when converting the NUEs in Chen et al. (2012) to that based on the tuber dry yield with their low tuber DM content, the NUE_{AE} (maximum of 2.17 kg kg^{-1}) was slightly lower than that in our experiment (sample mean of 2.64 kg kg^{-1} with full irrigation). This shows that using dry yield and fresh yield in the definition of NUE leads to different conclusions.

The three amounts of irrigation designed in the experiment of Chen et al. (2012) were 120 mm for W1, 180 mm for W2 and 240 mm for W3. The precipitation is not provided in the paper of Chen et al. (2012). If we assume that the precipitation was the same as in our experiment, then it can be shown that the water used for W2 (235 mm irrigation) and W3 (280 mm irrigation) in our experiment were very high compared to the design of Chen et al. (2012). The W2 treatment in our experiment, which is the same as local practice, is close to the highest irrigation of Chen et al. (2012), while the W3 treatment in our experiment was even higher, and this might be the reason why the trends of NUE's with increasing irrigation shown by Chen et al. (2012) was not observed in our experiment. However, the fresh yield with 235 mm irrigation in our experiment (sample mean of 42.9 ton ha^{-1}) was higher than that in Chen et al. (2012) with 240 mm irrigation (ranged from 27.8 to 31.1 ton ha^{-1} for different N treatments).

[5] In the experiment by Chen et al. (2012), high, medium and low water treatments are 2400 m^3 hm^{-2}, 1800 m^3 hm^{-2}, 1200 m3 hm^{-2} respectively.

4.6.2 Local WUE

For the WUEs in our experiment, no significant effect from N treatments was shown on WUE_{irri}, while on WUE_{agri} the interactions between water & N treatments showed slight positive effects with a p-value of 0.045 (**Table A6-9**), although the N treatments alone did not have significant effects. Another experiment (Xie et al., 2012) in Inner Mongolia (Hohhot) showed a low WUE_{agri} of the local water management. From this experiment, the WUE_{agri} following the local conventional irrigation plan was only 9.3 kg ha^{-1} mm^{-1} (based on tuber dry yield) with a total water used of 565.8 mm (416.8 mm irrigation & 149 mm precipitation). The total water used in our experiment was 389.5 mm for local irrigation and 434.8 mm for full irrigation, with WUE_{agri} of 23.0 kg ha^{-1} mm^{-1} and 20.5 kg ha^{-1} mm^{-1} respectively. According to Xie et al. (2012), when the irrigation was reduced to 50% of the local conventional plan (208.4 mm irrigation), the WUE_{agri} increased to 11.7 kg ha^{-1} mm^{-1}, and under rain-fed condition the WUE_{agri} was 15.9 kg ha^{-1} mm^{-1}, which were still lower than the WUE_{agri}'s in our experiment. The local conventional irrigation plan in Xie et al. (2012) used more water than our full irrigation, and received a lower tuber fresh yield (32.9 ton ha^{-1} in Xie et al. (2012) & 43.5 ton ha^{-1} in our experiment), which leads to a lower WUE_{agri}. When irrigated 50% of the conventional planned amount, the water used by Xie et al. (2012) was 357.4 mm, which is slightly lower than our local irrigation treatment, but resulted in a much lower tuber fresh yield (28.5 ton ha^{-1} in Xie et al. (2012) & 42.9 ton ha^{-1} in our experiment). The reason for these differences in yields are unclear yet. It might be due to nutrient management, disease control or cultivars. For the rain-fed condition, Xie et al. (2012) had a similar amount of rainfall to us during the growing season (149 mm for Xie et al. (2012) and 154.5 mm for us) and a higher tuber fresh yield (22.0 ton ha^{-1} for Xie et al. (2012) & 15.7 ton ha^{-1} for us). The lower WUE_{agri} of Xie et al. (2012) under rain-fed condition might be due to a lower tuber DM content, which is not mentioned in their paper. Calculated from the tuber fresh yield and WUE_{agri} given by Xie et al. (2012), the tuber DM contents were 16.0%, 14.7% and 10.8% for 416.8 mm irrigation, 208.4 mm irrigation and rain-fed condition respectively, which were all lower than that in our experiment (**Table A4-1**).

4.6.3 China NUE

IPNI (the International Plant Nutrition) cooperative network did a research in China from year 2000 to 2006 (Jin, 2012). According to 13 trials, the average NUE_{AE} was 34 kg kg^{-1} based on the tuber fresh yield, which is much higher than the levels in our experiment (-1.367, 5.75 and 3.626 kg kg^{-1} for 184, 225 and 267 kg ha^{-1} N input respectively based on the tuber fresh yields). The average yield increase for N fertilizer application compared to zero N application was 26.9 % according to IPNI, with an average N application rate of 116.9 kg ha^{-1}. While in our experiment, the only difference in tuber fresh yield was between N treatments of 184 and 225 kg ha^{-1} (15.7% increase).

4.6.4 China WUE

Xie et al. (2012) did the same experiment in Lanzhou, Gansu (northwestern China) as they did in Hohhot, Inner Mongolia for the effects of water treatments on tuber yield and WUE_{agri}. Lanzhou was drier than Hohhot, with only 68 mm rainfall during the growing season. However, the local conventional irrigation was similar (444.4 mm), which means a lower amount of water used (512.4 mm) than that in Hohhot, but still higher than the full irrigation in our experiment. The potato fresh yield in Lanzhou under local conventional irrigation was only half of that in Hohhot, and did not significantly change with the decrease in water input to 50% irrigation plan (290.2 mm water used). The amount of rainfall was slightly lower than half of that in our experiment, while the fresh yield under rain-fed condition in Lanzhou (7.97 ton ha^{-1}) was slightly higher than half of that in our experiment. As a result, WUE_{agri} under rain-fed condition in Lanzhou was higher than that in our experiment. WUE_{agri}'s in Lanzhou for local conventional irrigation and 50% of local conventional irrigation were 6.1 and 11.7 kg ha^{-1} mm^{-1} (based on tuber dry yields) respectively, which were lower than the WUE_{agri}'s under all conditions in our experiment. Both Gansu and Inner Mongolia are in northern China. A more general conclusion on the WUE in China cannot be made due to the limitation of literature.

4.6.5 Global NUE & WUE

An experiment was conducted in New Zealand in the growing season of 2010 ~ 2011 by Fandika et al. (2016), where they compared the tuber yields, WUE_{agri}'s and NUE_{PFP}'s for different water and N treatments. The tuber fresh yield increased with water input and decreased with N input, with no significant interaction between water and N treatments. The tuber fresh yield for full irrigation ("refilling 25 mm of the soil's moisture deficit on the day that soil moisture deficit equated to or exceeded 30 mm") was 36.3 ton ha^{-1}, and that for lower N application (80 kg ha^{-1}) was 34.1 ton ha^{-1}, which were lower than that for local irrigation (42.9 kg ha^{-1}) but similar to that for all the four N treatments in our experiment. WUE_{agri} based on tuber fresh yield by Fendika et al. (2016) did not significantly change (80 kg ha^{-1} mm^{-1}) with water input from rain-fed to partial irrigation ("irrigated at every second full irrigation"), but decreased when water input went up to full irrigation (70 kg ha^{-1} mm^{-1}), both of which were lower than the WUE_{agri}'s in our experiment for all water treatments. As a result of the decreasing tuber fresh yield with N input, the WUE_{agri} by Fendika et al. (2016) also decreased with N input. NUE_{PFP} by Fendika et al. (2016) significantly decreased with N input and increased with water input. NUE_{PFP} of 80 kg ha^{-1} N input by Fendika et al. (2016) reached 425.9 kg kg^{-1} (based on tuber fresh yield), which doubled the levels in our experiment.

A similar field experiment was done in Egypt (Badr et al., 2012), where interactions between N and water treatments were shown. When water input was smaller, the highest tuber fresh yield occurred at a lower N input. With full irrigation, the highest tuber fresh yield appeared with the highest N input (340 kg ha^{-1}) at 47.8 ton ha^{-1}, which is slightly higher than the yields for local and full irrigation in our experiment. The highest NUE_{AE} by Badr et al. (2012) (176 kg kg^{-1}, based on tuber fresh yield) occurred at the highest irrigation (328 mm) with the lowest N input (160 kg ha^{-1}), while the lowest NUE_{AE} (55 kg kg^{-1}) occurred at the lowest irrigation (131 mm) with the highest N input (340 kg ha^{-1}), both of which are higher than the NUE_{AE}'s in our experiment because of the high yield with zero N fertilization in our experiment. The rainfall in this area in Egypt was only 16.5 mm, and thus the total water used for the lowest irrigation plan by Badr et al. (2012) was slightly lower than the zero irrigation plan in our experiment. NUE_{RE1}'s by Badr et al. (2012) ranged from 26% to 72%, which are all higher than the NUE_{RE1}'s in our experiment. These comparisons justified the inference that the N amount in soil in our experiment was too high and the N from fertilizers was redundant. The highest WUE_{agri} (based on tuber fresh yield) occurred with 131 mm irrigation and 220 kg ha^{-1} N fertilization at 195 kg ha^{-1} mm^{-1}, which was higher than the highest WUE_{agri} in our experiment which occurred with local irrigation plan. Badr et al. (2012) reached a conclusion that there is a tradeoff between WUE_{agri} and NUE_{AE}, and the maximization of WUE_{agri} has to be built on a sacrifice of the yield. This conclusion contradicts our results that NUE_{AE} and WUE_{agri} were positively related, and WUE_{agri} was positively related to the yield.

4.7 Based on this field experiment, to what extent can local NUEs and WUEs be improved?

The mean NUE_{RE2} ranged from 66.5% for N3 (267 kg ha^{-1} N fertilization) to 87.6% for N2 (184 kg ha^{-1} N fertilization) (it is not defined at zero N fertilization N1) (**Table A6-1**). NUE_{RE1}, which shows the increase in N uptake corresponding to the application of N fertilizer, ranged between 4.5% for N2 and 11.8% for N4. The N uptake in tubers with zero fertilization was provided with the N in soil and the N from precipitation. While the N amount in tubers significantly increased from N1 to N4 (225 kg ha^{-1} N fertilization), this effect was offset by the increase in the denominator (N from fertilizers), and thus NUE_{RE1} & NUE_{RE2} did not show significant differences for different N treatments. However, without irrigation, the mean NUE_{RE2}, which was close to 100% with irrigation, fell to 41% (**Table A6-2**). Thus according to this experiment, the highest NUE_{RE2} can be achieved with an irrigation of 235 mm, which is the same as the local practice. NUE_{RE1} did not significantly change with irrigation. No N fertilizer should be used as it will be wasted and do no good to NUE_{RE1} & NUE_{RE2}. The level of NUE_{RE2} can go infinitely large (zero denominator). And as shown in Section 4.6.1, an experiment in this area has achieved an NUE_{RE1} of 81.7% (Liu et al., 2011). The soil N content should be measured before and after every growing season to make sure that the soil N is not over used. When the soil N content decreases to a level that is not enough to satisfy the needs of a growing season, N fertilizers should be applied and the NUEs should be re-measured.

The process of utilizing the N uptake to produce tuber dry yield (NUE_{physio} & NUE_{IE}) was not influenced by N or water treatments based on this experiment. However, the sample variances of the NUE_{physio} and NUE_{IE} under each water or N treatment were large (**Table A6-1 & A6-2**), and thus reliable predictions for them cannot be made based on this experiment.

As for the whole process from N fertilization to the production of tuber dry yield, NUE_{AE} did not show significant changes with N or water treatments, while NUE_{PFP} significantly increased with irrigation from the sample mean of 14 kg dry yield kg^{-1} N for zero irrigation to 40.8 kg kg^{-1} for 235 mm irrigation (local practice), and decreased with N fertilization from 37.4 kg kg^{-1} under N2 (184 kg N ha^{-1}) to 31.9 kg kg^{-1} under N4 (225 kg N ha^{-1}), and further decreased to 26.7 kg kg^{-1} under N3 (267 kg N ha^{-1}). According this experiment, the optimal NUE_{PFP} in this area can be achieved with 235 mm irrigation. But the maximal level of NUE_{PFP} is unknown, because NUE_{PFP} is not defined with zero N fertilization, and thus its difference for N1 and N2 treatments is unclear. Since from the former analyses we conclude that no fertilizer should be applied, NUE_{PFP} can increase to infinitely large with the denominator approaches zero.

Mean WUE_{agri} increased with irrigation from 20.6 kg ha^{-1} mm^{-1} for zero irrigation to 23.0 kg ha^{-1} mm^{-1} for 235 mm irrigation, and then decreased to 20.5 kg ha^{-1} mm^{-1} for 280 mm irrigation (**Table A6-3**). Mean WUE_{irri} is not defined for zero irrigation, and it decreased from 38.16 kg ha^{-1} mm^{-1} for 235 mm irrigation to 31.84 kg ha^{-1} mm^{-1} for 280 mm irrigation. Neither did WUE_{agri} nor did WUE_{irri} show significant differences for different N treatments. Thus based on this experiment, WUE_{agri} can reach a maximum of 23.0 kg ha^{-1} mm^{-1} with 235 mm irrigation, which is the same as the practice of local farmers. And N fertilization is not needed. However, as shown in Section 4.6.2, WUE_{agri} in another experiment in Inner Mongolia reached above 80 kg ha^{-1} mm^{-1} with adequate fertilization based on the soil test[6] (Li et al., 2011). The amount of water used in this experiment is unclear though. No conclusion can be made on the optimal WUE_{irri} since its change with irrigation lower than 235 mm is unclear.

The highest values of NUEs and WUEs achieved in our experiment were higher than or similar to those in other local experiments shown in Section 4.6.1 & 4.6.2, except NUE_{RE1} from Liu et al. (2011) and WUE_{agri} from Li et al. (2011). Based on the limited literature review, most of the boundaries of local NUEs and WUEs drawn from our experiment can represent this region.

[6] The calculation of WUE_{agri} in Li et al. (2011) was based on the tuber fresh yield. Since the tuber dry matter content is not available in Li et al. (2011), the WUE_{agri} was converted to that based on the tuber dry yield according to the average tuber dry matter content in our experiment.

5. Conclusion

In the field experiment on potato production in Hailar, Inner Mongolia, China in 2017, the tuber fresh yield increased with irrigation from 0 to 235 mm (sample mean 15.7 to 42.9 ton ha^{-1}) and increased with N fertilization from 184 to 225 kg N ha^{-1} (sample mean 30.6 to 35.4 ton ha^{-1}). The fresh yield with local or full irrigation has reached the average level of North America (FAOSTAT, 2008). The increases in the aboveground sizes (height and canopy diameter) from 0 to 235 mm irrigation might have enhanced the photosynthesis and starch production in tubers. Due to the high soil N content at sowing, the tuber dry yield did not change N from zero to higher levels of input. The decrease in tuber DM content (sample mean 20.4% with zero N fertilization to 19.9% with 184 kg ha^{-1} N fertilization) with unchanged dry yield suggests that the N input pushed up the plants' ability to uptake or store water. The N uptake, which increased with N input, did not benefit the tuber dry yield.

Six definitions of NUE and two definitions of WUE were calculated and analyzed. NUE_{PFP} increased with irrigation from 0 to 235 mm (sample mean 14.0 to 40.8 kg kg^{-1}) while decreased with N fertilization from 184 to 267 kg ha^{-1} (sample mean 37.4 to 26.7 kg kg^{-1}), and NUE_{RE2} also increased with irrigation from 0 to 235 mm (sample mean 40.6% to 97.9%). NUE_{PFP} can increase to infinitely large when N fertilization approaches zero due to its definition, but the optimal irrigation for both NUE_{PFP} and NUE_{RE2} is 235 mm. Other NUEs did not vary with treatments, and thus the ranges of them cannot be found from this experiment. WUE_{irri} can increase to infinitely large when irrigation approaches zero due to its definition, while WUE_{agri} reached its optimum at 23 kg ha^{-1} mm^{-1} with 235 mm irrigation. Since the full irrigation (280 mm) in our experiment, which was derived from the WOFOST model, showed no benefit compared to the local irrigation (235 mm), while based on the LINTUL model the China Potato Gap 2013-2016 suggested a level of irrigation which was lower than the local practice in Inner Mongolia, modelling of potato production for this region needs to be further explored.

The increase in NUE_{PFP} and WUE_{agri} with irrigation was resulted from the rise in tuber dry yield, and the increase in NUE_{RE2} was due to the rise in N uptake. The result that NUE_{IE} (the process of utilizing N uptake to produce tubers) did not change with water input suggests that the contribution from water to the NUE_{PFP} (the whole process from N input to tuber production) occurred in the N uptake process (NUE_{RE2}), while the utilization of N could not be further improved by adding water. The result that the tuber dry yield did not change with N input explains why NUE_{PFP} decreased with N input, while NUE_{AE} & NUE_{physio} did not change. The interactions between N and water treatments were only significant for NUE_{PFP} and WUE_{agri} (only a few combinations of treatments). They were not significant for other NUEs, WUE_{irri}, tuber fresh yield or tuber dry yield.

Although the field experiment achieved a competitive tuber fresh yield, the NUE_{RE1} and NUE_{AE} in this experiment were much lower than those in other experiments (local, national or global) due to the high N uptake and tuber dry yield with zero N fertilization. One of the local experiments and an experiment in Egypt had higher WUE_{agri}'s than our experiment (Li et al., 2011; Badr et al., 2012), while other experiments had lower WUE_{agri}'s than us. The NUE_{PFP} in an experiment in New Zealand doubled the levels in our experiment.

As for the relationships among NUEs, WUEs and the tuber fresh yield, regressions showed that: 1) there was no tradeoff between any pair of NUE & WUE, they were either positively related or unrelated; 2) the tuber fresh yield was positively related to all NUEs & WUEs, except NUE_{physio}.

Since according to the results of the research the soil N content might be very high at sowing in this region due to the local rotation management, it is recommended to test the soil before each sowing for a proper N fertilization plan. Also, since the N uptake increased with N input while it was not efficiently used in the N utilization process to produce tuber dry yield (dry yield did not change with N input), NUE_{IE} needs to be improved to further increase the yield. It was observed from this study that NUE_{IE} cannot be improved with more water input, which suggests that to fill the yield gap in this region, not only the resource (fertilizers and water) supply should be adequate, but the efficiency yield gap (for example timing & method of resource application) should be narrowed. It also points out a direction for breeding that a cultivar with potential for a higher NUE_{IE} can further increase the yield in this region.

This study also showed the importance of choosing proper definitions of NUE and WUE in a research. The definitions should be commonly used in science so that the result of the research can be compared with other studies. Making good use of different NUEs and WUEs can also help explaining the data pattern.

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Appendices

Appendix 1: Dry yields, NUEs and WUEs

Table A1: Dry yields, NUEs and WUEs based on all 3-metre samples

	Block[7]	Whole -plot[8]	Sub -plot[9]	Water	N	Dry yield (ton ha^{-1})	NUE_{AE} (kg kg^{-1})	NUE_{PFP} (kg kg^{-1})	NUE_{physio} (kg kg^{-1})	NUE_{IE} (kg kg^{-1})	NUE_{RE1}	NUE_{RE2}	WUE_{irri} (kg ha^{-1} mm^{-1})	WUE_{agri} (kg ha^{-1} mm^{-1})
1	1	1	1	1	4	2.8	-2.67	12.44	-71.06	29.82	0.04	0.42	---	18.12
2	1	1	2	1	2	3.1	-1.63	16.85	129.77	37.29	-0.01	0.45	---	20.06
3	1	1	3	1	1	3.4	---	---	---	39.79	---	---	---	22.01
4	1	1	4	1	3	2.7	-2.62	10.11	268.17	32.60	-0.01	0.31	---	17.48
5	1	2	1	2	3	8.1	-3.37	30.34	8.03	99.00	-0.42	0.31	34.47	20.80
6	1	2	2	2	2	9.7	3.80	52.72	28.00	44.32	0.14	1.19	41.28	24.90
7	1	2	3	2	4	8.6	-1.78	38.22	-110.78	43.55	0.02	0.88	36.60	22.08
8	1	2	4	2	1	9.0	---	---	---	46.43	---	---	38.30	23.11
9	1	3	1	3	2	8.0	-1.63	43.48	2.48	118.72	-0.66	0.37	28.54	18.40
10	1	3	2	3	3	9.0	2.62	33.71	19.90	40.27	0.13	0.84	32.11	20.70
11	1	3	3	3	4	10.0	7.56	44.44	38.53	43.02	0.20	1.03	35.68	23.00
12	1	3	4	3	1	8.3	---	---	---	44.07	---	---	29.61	19.09
13	2	1	1	1	4	2.8	-4.00	12.44	36.06	35.42	-0.11	0.35	---	18.12
14	2	1	2	1	3	3.2	-1.87	11.99	38.99	35.09	-0.05	0.34	---	20.71
15	2	1	3	1	1	3.7	---	---	---	35.57	---	---	---	23.95
16	2	1	4	1	2	2.6	-5.98	14.13	28.06	40.12	-0.21	0.35	---	16.83

[7] Blocks were numbered from north to south (j = 1, 2, 3, 4).

[8] Wholeplots were numbered from west to east (1, 2, and 3), and three water treatments (W1 = 0 mm, W2 = 235 mm, W3 = 280 mm) were randomly allocated to them.

[9] Subplots were numbered from west to east (1, 2, 3, and 4), and four N treatments (N1 = 0 kg ha^{-1}, N2 = 184 kg ha^{-1}, N3 = 267 kg ha^{-1}, N4 = 225 kg ha^{-1}) were randomly allocated to them.

17	2	2	1	3	3	8.0	-0.37	29.96	-2.07	37.09	0.18	0.81	28.54	18.40
18	2	2	2	3	1	8.1	---	---	---	48.41	---	---	28.90	18.63
19	2	2	3	3	2	8.5	2.17	46.20	6.12	36.52	0.36	1.26	30.32	19.55
20	2	2	4	3	4	8.2	0.44	36.44	5.17	43.93	0.09	0.83	29.25	18.86
21	2	3	1	2	1	8.2	---	---	---	40.48	---	---	34.89	21.05
22	2	3	2	2	2	8.7	2.72	47.28	17.36	37.60	0.16	1.26	37.02	22.34
23	2	3	3	2	3	9.7	5.62	36.33	19.08	34.50	0.29	1.05	41.28	24.90
24	2	3	4	2	4	7.9	-1.33	35.11	-19.78	36.28	0.07	0.97	33.62	20.28
25	3	1	1	3	2	9.0	7.07	48.91	29.85	39.97	0.24	1.22	32.11	20.70
26	3	1	2	3	3	9.3	5.99	34.83	---	---	---	---	33.18	21.39
27	3	1	3	3	4	11.4	16.44	50.67	55.58	45.93	0.30	1.10	40.67	26.22
28	3	1	4	3	1	7.7	---	---	---	42.39	---	---	27.47	17.71
29	3	2	1	2	3	10.4	4.49	38.95	13.10	35.51	0.34	1.10	44.26	26.70
30	3	2	2	2	1	9.2	---	---	---	45.71	---	---	39.15	23.62
31	3	2	3	2	4	9.9	3.11	44.00	130.55	47.91	0.02	0.92	42.13	25.42
32	3	2	4	2	2	8.7	-2.72	47.28	-23.24	39.05	0.12	1.21	37.02	22.34
33	3	3	1	1	1	3.2	---	---	---	37.74	---	---	---	20.71
34	3	3	2	1	3	3.1	-0.37	11.61	17.10	39.27	-0.02	0.30	---	20.06
35	3	3	3	1	2	3.2	0.00	17.39	0.00	34.80	0.04	0.50	---	20.71
36	3	3	4	1	4	3.3	0.44	14.67	6.52	32.96	0.07	0.44	---	21.36
37	4	1	1	3	4	9.1	-3.11	40.44	-8.76	33.80	0.36	1.20	32.47	20.93
38	4	1	2	3	2	9.2	-3.26	50.00	-29.90	43.94	0.11	1.14	32.82	21.16
39	4	1	3	3	1	9.8	---	---	---	51.77	---	---	34.96	22.54
40	4	1	4	3	3	9.2	-2.25	34.46	-8.25	35.11	0.27	0.98	32.82	21.16
41	4	2	1	2	3	9.6	3.37	35.96	8.80	39.29	0.38	0.92	40.85	24.65
42	4	2	2	2	1	8.7	---	---	---	61.25	---	---	37.02	22.34
43	4	2	3	2	4	9.1	1.78	40.44	4.55	39.58	0.39	1.02	38.72	23.36
44	4	2	4	2	2	8.0	-3.80	43.48	-25.68	47.25	0.15	0.92	34.04	20.54
45	4	3	1	1	2	3.8	0.00	20.65	0.00	32.45	0.10	0.64	---	24.60

46	4	3	2	1	4	3.1	-3.11	13.78	90.77	33.75	-0.03	0.41	---	20.06
47	4	3	3	1	3	3.1	-2.62	11.61	153.79	32.63	-0.02	0.36	---	20.06
48	4	3	4	1	1	3.8	---	---	---	38.17	---	---	---	24.60

Appendix 2: Compare the results based on the two original 3-metre samples only and that calculated from all 3-metre samples.

As mentioned in Section 2.2, additional 3-metre samples were taken from subplots with severe lodging and unexpected yields. Lodging can disrupt the transport of nutrients and water inside a plant, and result in bad yield (Struik & Wiersema, 1999). The reason for lodging is unknown yet. According to Struik & Wiersema (1999) and Ondieki (1982), lodging might be caused by diseases like Black Scurf, which results from the infection of Rhizoctonia solani. And different water and fertilization management might have resulted in different immunity, and thus the possibilities of diseases. CM Agu (2004) has found that the interaction between nitrogen and phosphorus application significantly affected the incidence of potato late blight. On the other hand, the report of China Potato Gap 2013-2016 project (Kempenaar et al., 2017) proposed that early plant lodging might be a result of excess N input, which makes plants grow too high. Thus the observations of lodging can be considered as an explanatory variable through which water and N treatments influence the yield, NUE and WUE. For this reason, we first tested whether there was significant difference between the two sets of results (one based on the two original 3-metre samples and the other based on all 3-metre samples) by Krukal-Wallis Test with 95% CI (**Table A2-1 ~ A2-6**). No significant difference was shown between the two sets of results for tuber fresh yield, tuber dry matter content, the number of main stems per m^2, the number of tubers per m^2, the fraction of harvested tubers shorter than 6 cm based on numbers, and the fraction of harvested tubers shorter than 6 cm based on weights.

Table A2-1: Significances of differences between the tuber fresh yields (ton ha^{-1}) calculated from the two original 3-metre samples only and that calculated from all 3-metre samples.

		P-value	Conclusion
All plots		0.655	No significant difference
N treatments	**N1**	0.931	No significant difference
	N2	1.000	No significant difference
	N3	0.340	No significant difference
	N4	1.000	No significant difference
Water treatments	**Zero**	1.000	No significant difference
	Local	0.571	No significant difference
	Full	0.509	No significant difference

Table A2-2: Significances of differences between the tuber dry matter contents (%) calculated from the two original 3-metre samples only and that calculated from all 3-metre samples.

		P-value	Conclusion
All plots		0.883	No significant difference
N treatments	**N1**	0.907	No significant difference
	N2	1.000	No significant difference

	N3	0.727	No significant difference
	N4	1.000	No significant difference
Water treatments	**Zero**	1.000	No significant difference
	Local	0.985	No significant difference
	Full	0.791	No significant difference

Table A2-3: Significances of differences between the numbers of main stems per m² calculated from the two original 3-metre samples only and that calculated from all 3-metre samples.

		P-value	**Conclusion**
All plots		0.974	No significant difference
N treatments	**N1**	0.954	No significant difference
	N2	1.000	No significant difference
	N3	0.930	No significant difference
	N4	1.000	No significant difference
Water treatments	**Zero**	1.000	No significant difference
	Local	0.761	No significant difference
	Full	0.894	No significant difference

Table A2-4: Significances of differences between the numbers of tubers per m² calculated from the two original 3-metre samples only that calculated from all 3-metre samples.

		P-value	**Conclusion**
All plots		0.886	No significant difference
N treatments	**N1**	1.000	No significant difference
	N2	1.000	No significant difference
	N3	0.685	No significant difference
	N4	1.000	No significant difference
Water treatments	**Zero**	1.000	No significant difference
	Local	0.791	No significant difference
	Full	0.894	No significant difference

Table A2-5: Significances of differences between the fractions of harvested tubers shorter than 6 cm (based on numbers) calculated from the two original 3-metre samples only and that calculated from all 3-metre samples.

		P-value	**Conclusion**
All plots		0.918	No significant difference
N treatments	**N1**	1.000	No significant difference
	N2	1.000	No significant difference
	N3	0.862	No significant difference
	N4	0.931	No significant difference

Water treatments	**Zero**	0.940	No significant difference
	Local	0.849	No significant difference
	Full	0.939	No significant difference

Table A2-6: Significances of differences between the fractions of harvested tubers shorter than 6 cm (based on weights) calculated from the two original 3-metre samples only and that calculated from all 3-metre samples.

		P-value	**Conclusion**
All plots		1.000	No significant difference
N treatments	**N1**	1.000	No significant difference
	N2	1.000	No significant difference
	N3	1.000	No significant difference
	N4	1.000	No significant difference
Water treatments	**Zero**	1.000	No significant difference
	Local	1.000	No significant difference
	Full	1.000[10]	No significant difference

[10] The average fraction of harvested tubers shorter than 6 cm (based on weights) of each subplot calculated from the two original 3-samples was the same as that calculated from all 3-metre samples by coincidence.

Appendix 3: Fresh & Dry yields vs. treatments

Table A3-1: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between tuber fresh yield (ton ha^{-1}) and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	17.600	2.750	0.000	---
water	**water 2 (235 mm irrigation)**	24.400	3.744	0.000	0.000
	water 3 (280 mm irrigation)	24.625	3.744	0.000	
N	**N2 (184 kg ha^{-1})**	-2.325	3.105	0.461	0.024
	N3 (267 kg ha^{-1})	-2.150	3.105	0.495	
	N4 (225 kg ha^{-1})	-3.175	3.105	0.316	
Interaction between water and N treatment	**water 2 & N2**	-1.525	4.392	0.731	0.209
	water 3 & N2	-1.425	4.392	0.748	
	water 2 & N3	7.350	4.392	0.106	
	water 3 & N3	5.675	4.392	0.207	
	water 2 & N4	5.275	4.392	0.240	
	water 3 & N4	8.525	4.392	0.063	

Table A3-2: Means and standard deviations of tuber yields (ton ha^{-1}) for each water treatment. "no", "local" and "full" means 0, 235 and 280 mm irrigation respectively.

	Mean-no	Sd-no	Mean-local	Sd-local	Mean-full	Sd-full
Fresh yield	15.7	1.66	42.9	5.73	43.5	7.94
Dry yield	3.18	0.132	8.97	0.549	8.93	0.891

Table A3-3: Means and standard deviations of tuber yields (ton ha^{-1}) for each N treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively.

	Mean-N1	Sd-N1	Mean-N2	Sd-N2	Mean-N3	Sd-N3	Mean-N4	Sd-N4
Fresh yield	33.9	12.4	30.6	13.9	36.1	15.6	35.4	16.0
Dry yield	6.92	2.57	6.88	2.78	7.12	3.09	7.18	3.22

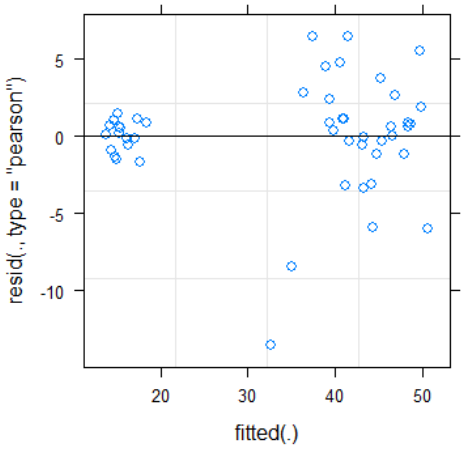


Figure A3-1: Residuals vs. fitted values of the main model with tuber fresh yield. It might be due to that the tuber fresh yields under no irrigation were much lower than that under local and full irrigation, while they did not show significant differences across N treatments. Thus 1/3 of the data points are located together while the other 2/3 of the data points are located together, and the group with more data points shows a bigger range of residuals.

Table A3-4: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between tuber dry yield (ton ha^{-1}) and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	3.525	0.357	0.000	---
water	**water 2 (235 mm irrigation)**	5.250	0.468	0.000	0.000
	water 3 (280 mm irrigation)	4.950	0.468	0.000	
N	**N2 (184 kg ha^{-1})**	-0.350	0.468	0.460	0.618
	N3 (267 kg ha^{-1})	-0.500	0.468	0.293	
	N4 (225 kg ha^{-1})	-0.525	0.468	0.270	
Interaction between water and N treatment	**water 2 & N2**	0.350	0.662	0.600	0.150
	water 3 & N2	0.550	0.662	0.412	
	water 2 & N3	1.175	0.662	0.085	
	water 3 & N3	0.900	0.662	0.183	
	water 2 & N4	0.625	0.662	0.352	
	water 3 & N4	1.725	0.662	0.014	

Appendix 4: Dry matter contents (%) vs. treatments

Table A4-1: Means and standard deviations of dry matter contents (%) for each water treatment. "no", "local" and "full" means 0, 235 and 280 mm irrigation respectively.

Mean-no	Sd-no	Mean-local	Sd-local	Mean-full	Sd-full
19.7	0.41	20.4	0.58	19.9	0.56

Table A4-2: Means and standard deviations of dry matter contents (%) for each N treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively.

Mean-N1	Sd-N1	Mean-N2	Sd-N2	Mean-N3	Sd-N3	Mean-N4	Sd-N4
20.4	0.61	19.9	0.57	19.8	0.51	20.0	0.53

Table A4-3: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between tuber dry matter content (%) and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	19.98	0.233	0.000	---
water	**water 2 (235 mm irrigation)**	1.000	0.329	0.005	0.025
	water 3 (280 mm irrigation)	0.150	0.329	0.652	
N	**N2 (184 kg ha^{-1})**	-0.375	0.297	0.218	0.010
	N3 (267 kg ha^{-1})	-0.250	0.297	0.408	
	N4 (225 kg ha^{-1})	-0.475	0.297	0.122	
Interaction between water and N treatment	**water 2 & N2**	-0.250	0.420	0.557	0.117
	water 3 & N2	-0.100	0.420	0.814	
	water 2 & N3	-0.650	0.420	0.134	
	water 3 & N3	-0.375	0.420	0.380	
	water 2 & N4	-0.400	0.420	0.350	
	water 3 & N4	0.675	0.420	0.120	

Appendix 5: The numbers and sizes of tubers vs. treatments

Table A5-1: Means and standard deviations of numbers and sizes of tubers of each water treatment. "no", "local" and "full" means 0, 235 and 280 mm irrigation respectively.

	Mean-no	Sd-no	Mean-local	Sd-local	Mean-full	Sd-full
Total number of tubers per m^2	15.1	1.71	25.1	2.07	28.5	3.22
Fraction of tubers with length smaller than 6 cm (number)	0.172	0.054	0.122	0.041	0.151	0.033
Fraction of tubers with length smaller than 6 cm (weight)	0.064	0.022	0.030	0.011	0.042	0.014

Table A5-2: Means and standard deviations of numbers and sizes of tubers of each N treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively.

	Mean-N1	Sd-N1	Mean-N2	Sd-N2	Mean-N3	Sd-N3	Mean-N4	Sd-N4
Total number of tubers per m^2	22.5	6.43	22.5	5.63	23.6	7.04	22.9	6.44
Fraction of tubers with length smaller than 6 cm (number)	0.135	0.049	0.146	0.046	0.153	0.040	0.160	0.054
Fraction of tubers with length smaller than 6 cm (weight)	0.043	0.024	0.048	0.024	0.046	0.019	0.045	0.022

Table A5-3: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between the number of harvested tubers per m^2 and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	15.733	1.139	0.000	---
water	**water 2 (235 mm irrigation)**	6.750	1.484	0.000	0.000
	water 3 (280 mm irrigation)	13.685	1.484	0.000	
N	**N2 (184 kg ha^{-1})**	-0.465	1.484	0.756	0.573
	N3 (267 kg ha^{-1})	-1.150	1.484	0.444	
	N4 (225 kg ha^{-1})	-0.935	1.484	0.533	
Interaction between water and N treatment	**water 2 & N2**	4.223	2.099	0.053	0.038
	water 3 & N2	-2.900	2.099	0.176	
	water 2 & N3	4.928	2.099	0.025	
	water 3 & N3	1.668	2.099	0.433	

water 2 & N4	3.733	2.099	0.085	
water 3 & N4	0.073	2.099	0.973	

Table A5-4: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between the fraction of harvested tubers shorter than 6 cm (based on numbers) and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	0.163	0.021	0.000	---
water	**water 2 (235 mm irrigation)**	-0.070	0.030	0.026	-0.009
	water 3 (280 mm irrigation)	-0.013	0.030	0.680	
N	**N2 (184 kg ha^{-1})**	0.033	0.030	0.286	0.521
	N3 (267 kg ha^{-1})	0.010	0.030	0.741	
	N4 (225 kg ha^{-1})	-0.005	0.030	0.869	
Interaction between water and N treatment	**water 2 & N2**	-0.010	0.042	0.815	0.231
	water 3 & N2	-0.055	0.042	0.204	
	water 2 & N3	0.013	0.042	0.770	
	water 3 & N3	0.013	0.042	0.770	
	water 2 & N4	0.080	0.042	0.068	
	water 3 & N4	0.010	0.042	0.815	

Table A5-5: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between the fraction of harvested tubers shorter than 6 cm (based on fresh weights) and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	0.063	0.008	0.000	---
water	**water 2 (235 mm irrigation)**	0.040	0.012	0.003	0.013
	water 3 (280 mm irrigation)	0.018	0.012	0.151	
N	**N2 (184 kg ha^{-1})**	0.015	0.010	0.147	0.910
	N3 (267 kg ha^{-1})	0.003	0.010	0.806	
	N4 (225 kg ha^{-1})	0.005	0.010	0.623	
Interaction between water and	**water 2 & N2**	0.005	0.014	0.728	0.166

N treatment	**water 3 & N2**	0.028	0.014	0.064
	water 2 & N3	0.008	0.014	0.602
	water 3 & N3	0.008	0.014	0.602
	water 2 & N4	0.020	0.014	0.171
	water 3 & N4	0.000	0.014	1.000

Appendix 6: The NUEs and WUEs vs. treatments

Table A6-1: Means and standard deviations of NUEs for each N treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively.

	Mean-N1	Sd-N1	Mean-N2	Sd-N2	Mean-N3	Sd-N3	Mean-N4	Sd-N4
NUE_{AE} (kg kg^{-1})	---	---	-0.272	3.68	0.718	3.48	1.15	5.82
NUE_{PFP} (kg kg^{-1})	---	---	37.4	15.1	26.7	11.6	31.9	14.3
NUE_{IE} (kg kg^{-1})	44.3	7.15	46.0	23.3	41.9	19.1	38.8	5.91
NUE_{physio} (kg kg^{-1})	---	---	13.6	42.1	48.8[11]	85.1	13.1	65.3
NUE_{RE1} (%)	---	---	4.5	26.1	9.7	23.3	11.8	15.9
NUE_{RE2} (%)	---	---	87.6	38.2	66.5	33.7	79.8	30.6

Table A6-2: Mean and standard deviation of NUEs for each water treatments. "no", "local" and "full" means 0, 235 and 280 mm irrigation respectively.

	Mean-no	Sd-no	Mean-local	Sd-local	Mean-full	Sd-full
NUE_{AE} (kg kg^{-1})	-2.04	1.88	0.991	3.36	2.64	5.80
NUE_{PFP} (kg kg^{-1})	14.0	3.01	40.8	6.32	41.1	7.13
NUE_{IE} (kg kg^{-1})	35.5	3.03	46.1	15.6	47.0	20.4
NUE_{physio} (kg kg^{-1})	58.2	90.0	4.17	54.3	9.88	24.3
NUE_{RE1} (%)	-1.8	8.3	13.8	22.0	14.4	28.2
NUE_{RE2} (%)	40.6	9.5	97.9	24.6	98.0	25.9

Table A6-3: Mean and standard deviation of WUEs for each water treatment. "no", "local" and "full" means 0, 235 and 280 mm irrigation respectively.

	Mean-no	Sd-no	Mean-local	Sd-local	Mean-full	Sd-full
WUE_{irri} (kg ha^{-1} mm^{-1})	---	---	38.16	3.15	31.84	3.37
WUE_{agri} (kg ha^{-1} mm^{-1})	20.6	2.36	23.0	1.90	20.5	2.17

[11] There were two subplots with extremely large NUE_{physio}'s. One of them was block 1 wholeplot 1 subplot 4 (NUE_{physio} = 268.17 kg kg^{-1}), and the other was block 4 wholeplot 3 subplot 3 (153.79 kg kg^{-1}). Both of them were treated with zero irrigation and 267 kg ha^{-1} N fertilization. When the two terms are eliminated, the sample mean NUE_{physio} is 12.74 kg kg^{-1}. These two large NUE_{physio} occurred due to that the N uptakes without N fertilization in these two subplots (U_0) were very close to the N uptakes with N fertilization (U_N), and thus resulting in small denominators.

Table A6-4: Mean and standard deviation of WUEs for each N treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively.

	Mean-N1	Sd-N1	Mean-N2	Sd-N2	Mean-N3	Sd-N3	Mean-N4	Sd-N4
WUE_{irri} (kg ha^{-1} mm^{-1})	33.79	4.53	34.14	4.13	35.94	5.49	36.14	4.32
WUE_{agri} (kg ha^{-1} mm^{-1})	21.6	2.21	21.0	2.32	21.4	2.70	21.5	2.65

Table A6-5: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between NUE_{PFP} (kg kg^{-1})and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	17.255	1.675	0.000	---
water	water 2 (235 mm irrigation)	30.435	2.122	0.000	0.000
	water 3 (280 mm irrigation)	29.893	2.122	0.000	
N	N2 (184 kg ha^{-1})	---	---	---	0.000
	N3 (267 kg ha^{-1})	-5.925	2.122	0.010	
	N4 (225 kg ha^{-1})	-3.923	2.122	0.077	
Interaction between water and N treatment	water 2 & N2	---	---	---	0.041
	water 3 & N2	---	---	---	
	water 2 & N3	-6.370	3.001	0.044	
	water 3 & N3	-7.983	3.001	0.014	
	water 2 & N4	-4.325	3.001	0.163	
	water 3 & N4	-0.228	3.001	0.940	

Table A6-6: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between NUE_{RE2} and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	0.485	0.105	0.000	---
water	water 2 (235 mm irrigation)	0.660	0.139	0.000	0.000
	water 3 (280 mm irrigation)	0.513	0.139	0.001	
N	N2 (184 kg ha^{-1})	---	---	---	0.096
	N3 (267 kg ha^{-1})	-0.158	0.139	0.270	
	N4 (225 kg ha^{-1})	-0.080	0.139	0.572	

Interaction between water and N treatment	**water 2 & N2**	---	---	---	0.779
	water 3 & N2	---	---	---	
	water 2 & N3	-0.143	0.197	0.477	
	water 3 & N3	0.050	0.206	0.811	
	water 2 & N4	-0.118	0.197	0.557	
	water 3 & N4	0.123	0.197	0.541	

Table A6-7: P-values of F-tests (ANOVA) of the randomized block split-plot design model (Equation 1) of the relationships between the utilization efficiencies (kg kg^{-1}) and the treatments.

	Water treatments	**N treatments**	**Interaction between water & N treatments**
NUE_{physio}	0.088	0.400	0.407
NUE_{IE}	0.229	0.897	0.930

Table A6-8: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between WUE_{irri} (kg ha^{-1} mm^{-1}) and treatments.

		Estimate of parameter	**Std.error of parameter**	**P-value (for t-test)**	**P-value (for F-test from ANOVA)**
	Intercept	37.34	1.627	0.000	---
water	**water 2 (235 mm irrigation)**	---	---	---	0.000
	water 3 (280 mm irrigation)	-7.11	2.107	0.003	
N	**N2 (184 kg ha^{-1})**	0.00	2.107	1.000	0.295
	N3 (267 kg ha^{-1})	2.88	2.107	0.187	
	N4 (225 kg ha^{-1})	0.43	2.107	0.841	
Interaction between water and N treatment	**water 2 & N2**	---	---	---	0.360
	water 3 & N2	0.71	2.979	0.813	
	water 2 & N3	---	---	---	
	water 3 & N3	-1.45	2.979	0.632	
	water 2 & N4	---	---	---	
	water 3 & N4	3.86	2.979	0.210	

Table A6-9: Coefficients and ANOVA of the randomized block split-plot design model (Equation 1) of the relationship between WUE_{agri} (kg ha^{-1} mm^{-1}) and treatments.

		Estimate of parameter	Std.error of parameter	P-value (for t-test)	P-value (for F-test from ANOVA)
	Intercept	22.818	1.030	0.000	---
water	**water 2 (235 mm irrigation)**	-0.288	1.341	0.832	0.001
	water 3 (280 mm irrigation)	-3.325	1.341	0.018	
N	**N2 (184 kg ha^{-1})**	-2.268	1.341	0.100	0.878
	N3 (267 kg ha^{-1})	-3.240	1.341	0.021	
	N4 (225 kg ha^{-1})	-3.403	1.341	0.016	
Interaction between water and N treatment	**water 2 & N2**	2.268	1.896	0.240	0.045
	water 3 & N2	2.728	1.896	0.160	
	water 2 & N3	4.973	1.896	0.013	
	water 3 & N3	4.160	1.896	0.035	
	water 2 & N4	3.658	1.896	0.062	
	water 3 & N4	6.163	1.896	0.003	

Appendix 7: Sizes and weights of roots and aboveground parts

Table A7-1: The means and standard deviations of the sizes of plant parts (cm) for each N and water treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively. "W1", "W2" and "W3" means 0, 235 and 280 mm irrigation respectively.

			N1	N2	N3	N4	W1	W2	W3
Above-ground height	**June 24th**	**Mean**	22.3	21.9	21.1	22.0	16.2	24.6	24.6
		Sd	4.82	4.10	5.24	5.03	1.36	3.11	2.64
	July 17th	**Mean**	50.5	55.7	54.3	56.6	35.2	61.8	65.7
		Sd	12.1	15.9	15.3	15.0	3.30	5.43	4.43
	August 16th	**Mean**	59.6	59.9	63.7	62.8	48.0	67.8	68.7
		Sd	7.36	11.8	13.0	11.0	3.69	4.14	6.38
Canopy diameter	**June 24th**	**Mean**	31.3	32.4	30.7	32.1	25.8	34.2	34.8
		Sd	5.65	4.84	5.97	5.57	3.20	4.37	2.86
	July 17th	**Mean**	60.0	63.3	66.4	68.3	42.9	72.0	78.6
		Sd	15.2	18.0	17.9	18.4	4.48	7.82	8.15

Table A7-2: The means and standard deviations of the fresh weights of plant parts for each N and water treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively. "W1", "W2" and "W3" means 0, 235 and 280 mm irrigation respectively.

		N1	N2	N3	N4	W1	W2	W3
Aboveground (ton ha^{-1})	**Mean**	16.6	17.3	18.5	17.0	16.8	18.5	16.7
	Sd	1.35	2.80	3.01	2.05	1.94	2.39	2.61
Roots (kg ha^{-1})	**Mean**	301	379	336	305	337	371	283
	Sd	126	154	67.1	109	138	91.8	113

Table A7-3: P-values of F-tests (ANOVA) of the randomized block split-plot design model (Equation 1) of the relationships between the sizes of plant parts (cm) and the treatments.

		Water treatments	N treatments	Interactions between water & N treatments
Above-ground height	June 24th	0.000	0.693	0.906
	July 17th	0.000	0.003	0.403
	August 16th	0.000	0.059	0.073
Canopy diameter	June 24th	0.000	0.471	0.928
	July 17th	0.000	0.001	0.065

Table A7-4: P-values of F-tests (ANOVA) of the randomized block split-plot design model (Equation 1) of the relationships between the fresh weights of plant parts and the treatments.

	Water treatments	N treatments	Interactions between water & N treatments
Aboveground (ton ha^{-1})	0.104	0.210	0.374
Roots (kg ha^{-1})	0.403	0.183	0.734

Appendix 8: NPK% in different plant parts at harvest

Table A8-1: The means and standard deviations of the NPK% in different plant parts for each N and water treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively. "W1", "W2" and "W3" means 0, 235 and 280 mm irrigation respectively.

			N1	N2	N3	N4	W1	W2	W3
Tuber	**N%**	**Mean**	1.54	1.68	1.84	1.75	1.92	1.58	1.59
		Sd	0.282	0.256	0.209	0.350	0.216	0.264	0.263
	P%	**Mean**	0.700	0.616	0.738	0.634	0.603	0.653	0.765
		Sd	0.265	0.243	0.400	0.196	0.225	0.217	0.365
	K%	**Mean**	1.35	1.29	1.41	1.31	1.52	1.22	1.26
		Sd	0.203	0.168	0.196	0.280	0.158	0.206	0.149
Above-ground	**N%**	**Mean**	2.36	2.74	2.90	2.74	2.82	2.59	2.62
		Sd	0.378	0.361	0.365	0.539	0.586	0.370	0.346
	P%	**Mean**	0.810	0.853	0.785	0.807	0.777	0.827	0.840
		Sd	0.081	0.215	0.082	0.131	0.077	0.149	0.170
	K%	**Mean**	2.34	2.24	2.67	2.21	2.96	2.07	2.03
		Sd	0.854	0.350	0.498	0.625	0.480	0.565	0.229
Roots	**N%**	**Mean**	1.40	1.55	1.55	1.57	1.76	1.36	1.43
		Sd	0.292	0.265	0.263	0.229	0.169	0.240	0.193
	P%	**Mean**	1.36	1.41	1.34	1.23	1.42	1.27	1.32
		Sd	0.277	0.181	0.209	0.179	0.238	0.232	0.170
	K%	**Mean**	0.676	0.514	0.525	0.586	0.764	0.484	0.477
		Sd	0.297	0.130	0.078	0.174	0.230	0.059	0.062

Table A8-2: P-values of F-tests (ANOVA) of the randomized block split-plot design model (Equation 1) of the relationships between the NPK% of plant parts and the treatments.

		Water treatments	N treatments	Interactions between water & N treatments
Tuber	**N%**	0.013	0.025	0.670
	P%	0.273	0.670	0.052
	K%	0.014	0.268	0.284
Aboveground	**N%**	0.511	0.010	0.720
	P%	0.561	0.625	0.884
	K%	0.000	0.046	0.003
Roots	**N%**	0.017	0.023	0.664
	P%	0.137	0.157	0.107
	K%	0.001	0.001	0.009

Table A8-3: The means and standard deviations for each N and water treatment, and the p-values for F-test from ANOVA of the amount of N in tubers (kg ha^{-1}). “N1”, “N2”, “N3” and “N4” means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively. “W1”, “W2” and “W3” means 0, 235 and 280 mm irrigation respectively. “Interactions” represents the effects of the interactions between water and N treatments.

	N1	N2	N3	N4	W1	W2	W3	Interactions
Mean	101	111	127	118	61.3	143	142	---
Sd	29.8	45.4	56.3	45.3	10.2	28.0	23.5	---
p-value (ANOVA)	0.000				0.003			0.032

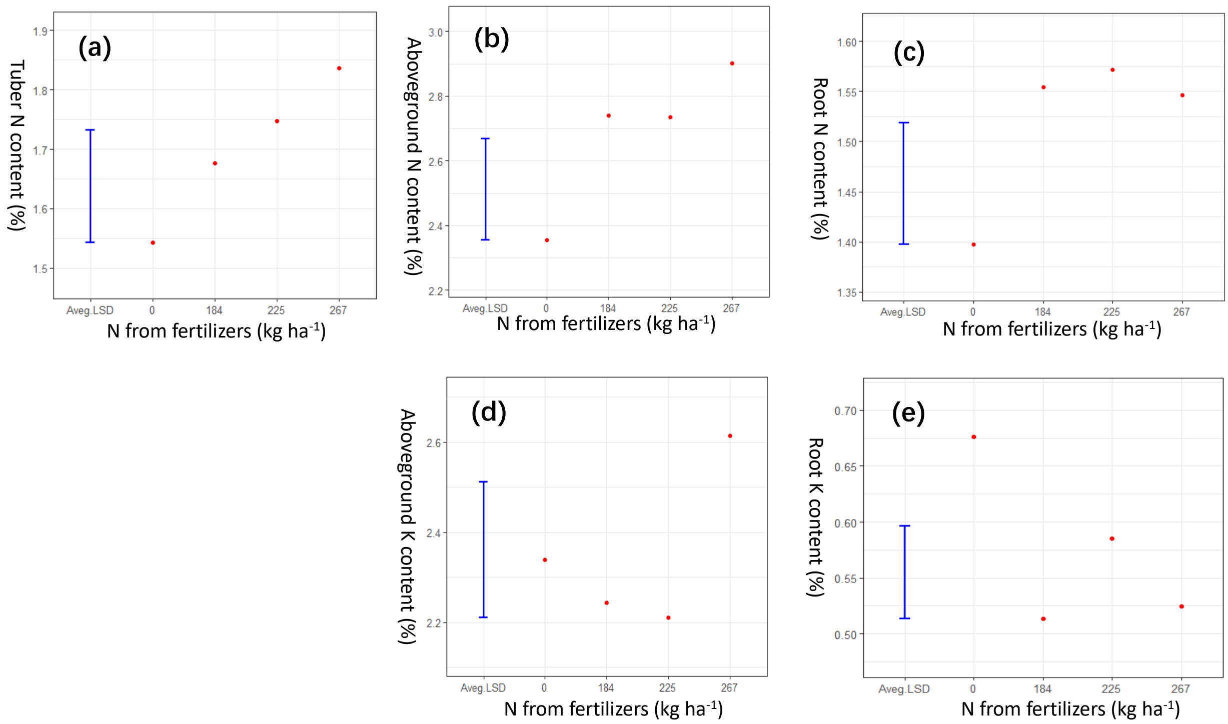


Figure A8-1: Predicted means of the N & K contents (%) in different plant parts at harvest for different N treatments with average LSD bar (5%). (a), (b) and (c): N content in tubers, aboveground parts and roots respectively; (d) & (e): K content in aboveground parts and roots respectively. Tuber K content did not change with N fertilization.

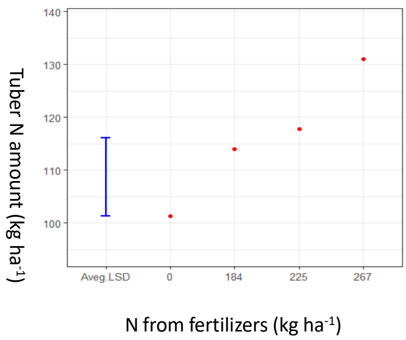


Figure A8-2: Predicted means of the amount of N in tubers (kg ha^{-1}) at harvest for different N treatments with average LSD bar (5%).

Appendix 9: The means and standard deviations of petiole N contents

Table A9-1: The mean and standard deviation of petiole N contents (ppm) for each N and water treatment. "N1", "N2", "N3" and "N4" means 0, 184, 267 and 225 kg ha^{-1} N fertilization respectively. "W1", "W2" and "W3" means 0, 235 and 280 mm irrigation respectively.

		N1	N2	N3	N4	W1	W2	W3	Average
July 13th	**Mean**	7033	7475	7929	7783	8338	7153	7175	7555
	Sd	1090	703	731	577	594	751	590	847
July 23rd	**Mean**	6192	7633	7983	7908	9269	6869	6150	7429
	Sd	1796	1220	1588	1661	956	1380	712	1696
August 2nd	**Mean**	5208	8100	8892	8692	11288	6194	5688	7723
	Sd	3246	2548	2594	2675	1230	2368	1449	3078
August 12th	**Mean**	3202	6150	6858	6708	7300	4782	5106	5730
	Sd	2001	1427	874	1324	1140	2175	1812	2061
August 22nd	**Mean**	2706	6575	7367	6675	8250	4804	4438	5831
	Sd	2609	1721	1359	2109	1368	2572	2137	2679
September 1st	**Mean**	1639	5808	6692	6508	6750	4678	4058	5162
	Sd	1113	1618	1254	1643	2332	2361	2072	2498

Table A9-2: P-values of F-tests (ANOVA) of the randomized block split-plot design model (Equation 1) of the relationships between the petiole N contents and the treatments.

	Water treatments	N treatments	Interaction between water & N treatments
July 13th	0.004	0.000	0.134
July 23rd	0.000	0.000	0.060
August 2nd	0.000	0.000	0.000
August 12th	0.000	0.000	0.006
August 22nd	0.000	0.000	0.001
September 1st	0.000	0.000	0.384

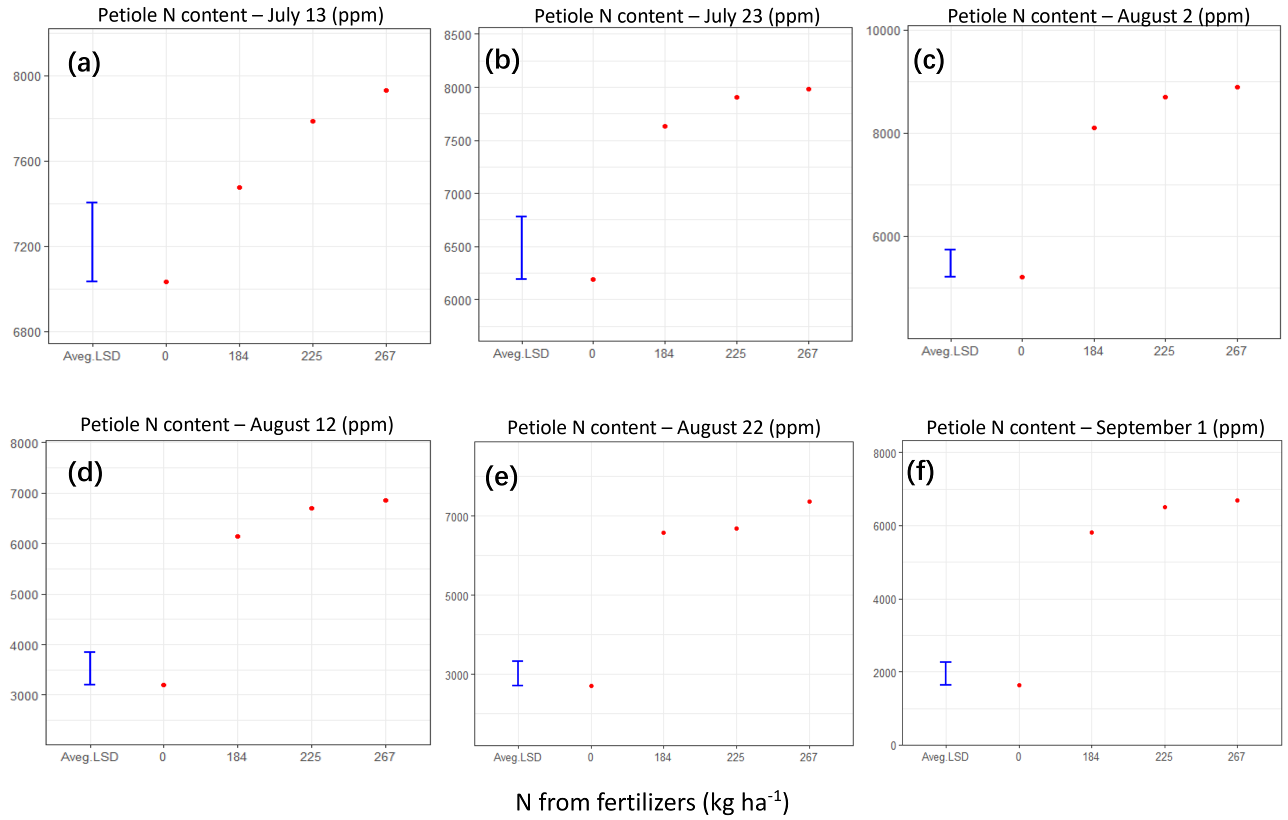


Figure A9-1: Predicted means of the petiole N contents (ppm) measured on six dates for different N treatments with average LSD bar (5%). (a) July 13th; (b) July 23rd; (c) August 2nd; (d) August 12th; (e) August 22nd; (f) September 1st.

Appendix 10: The tuber dry yield & N uptake vs. explanatory variables

Table A10-1: The conditional R-squared and ANOVA p-values of the regression models with the tuber dry yield (ton ha^{-1}) as the predictand, and an explanatory variable as the predictor. The random effects of blocks and wholeplots were considered. Significance codes: 0 '*' 0.001 '**' 0.01 '*' 0.05.**

			Conditional R-squared	P-value
Sizes & weights of plant parts	**Aboveground fresh weight (ton ha^{-1})**		0.960	0.000 ***
	Root fresh weight (kg ha^{-1})		0.941	0.671
	Aboveground height (cm)	**June**	0.935	0.506
		July	0.900	0.000 ***
		August	0.921	0.000 ***
	Canopy diameter (cm)	**June**	0.933	0.313
		July	0.901	0.002 **
Number of main stems per m^2			0.945	0.095
NPK in plant parts	**Tuber**	**N%**	0.942	0.402
		P%	0.946	0.465
		K%	0.942	0.592
		N amount (kg ha^{-1})	0.929	0.001 ***
		P amount (kg ha^{-1})	0.943	0.767
		K amount (kg ha^{-1})	0.931	0.000 ***
	Aboveground	**N%**	0.941	0.642
		P%	0.943	0.361
		K%	0.942	0.723
	Root	**N%**	0.935	0.073
		P%	0.941	0.293
		K%	0.945	0.578
Petiole N content (ppm)	**July 13th**		0.942	0.882
	July 23rd		0.941	0.915
	August 2nd		0.943	0.807
	August 12th		0.949	0.175
	August 22nd		0.944	0.600
	September 1st		0.942	0.811

Table A10-2: The conditional R-squared and ANOVA p-values of the regression models with the N uptake (kg ha^{-1}) as the predictand, and an explanatory variable as the predictor. The random effects of blocks and wholeplots were considered. Significance codes: 0 '*' 0.001 '**' 0.01 '*' 0.05.**

			Conditional R-squared	P-value
Sizes & weights of plant parts	**Aboveground fresh weight (ton ha^{-1})**		0.706	0.033 *
	Root fresh weight (kg ha^{-1})		0.688	0.189
	Aboveground height (cm)	**June**	0.638	0.000 ***
		July	0.687	0.000 ***
		August	0.665	0.000 ***
	Canopy diameter (cm)	**June**	0.609	0.000 ***
		July	0.616	0.000 ***
Number of main stems per m^2			0.672	0.783
NPK in plant parts	**Tuber**	**N%**	0.927	0.000 ***
		P%	0.811	0.958
		K%	0.855	0.178
		N amount (kg ha^{-1})	0.972	0.000 ***
		P amount (kg ha^{-1})	0.757	0.104
		K amount (kg ha^{-1})	0.886	0.000 ***
	Aboveground	**N%**	0.701	0.298
		P%	0.674	0.932
		K%	0.680	0.918
	Root	**N%**	0.675	0.970
		P%	0.666	0.649
		K%	0.601	0.128
Petiole N content (ppm)	**July 13th**		0.788	0.065
	July 23rd		0.630	0.507
	August 2nd		0.699	0.769
	August 12th		0.764	0.057
	August 22nd		0.752	0.135
	September 1st		0.712	0.268

Appendix 11: The relationships among the tuber fresh yield, NUEs and WUEs

Table A11-1: The conditional R-squared and ANOVA p-values of the regression models with one NUE as the predictand, and one WUE as the predictor. The random effects of blocks and wholeplots were considered. Significance codes: 0 '*' 0.001 '**' 0.01 '*' 0.05.**

	WUE_{irri}		WUE_{agri}	
	Conditional R-squared	**P-value**	**Conditional R-squared**	**P-value**
NUE_{AE}	0.990	0.000 ***	0.950	0.000 ***
NUE_{PFP}	0.056	0.255	0.784	0.048 *
NUE_{RE1}	0.422	0.071	0.555	0.001 ***
NUE_{RE2}	0.242	0.183	0.672	0.004 **
NUE_{physio}	0.150	0.120	0.037	0.651
NUE_{IE}	0.204	0.232	0.160	0.435

Table A11-2: The conditional R-squared and ANOVA p-values of the regression models with one NUE or WUE as the predictand, and the tuber fresh yield (ton ha^{-1}) as the predictor. The random effects of blocks and wholeplots were considered. Significance codes: 0 '*' 0.001 '**' 0.01 '*' 0.05.**

	Conditional R-squared	**P-value**
NUE_{AE}	0.540	0.015 *
NUE_{PFP}	0.651	0.000 ***
NUE_{RE1}	0.238	0.036 *
NUE_{RE2}	0.498	0.000 ***
NUE_{physio}	0.086	0.082
NUE_{IE}	0.177	0.029 *
WUE_{irri}	0.606	0.028*
WUE_{agri}	0.403	0.020*

Appendix 12: Changes in soil NPK contents

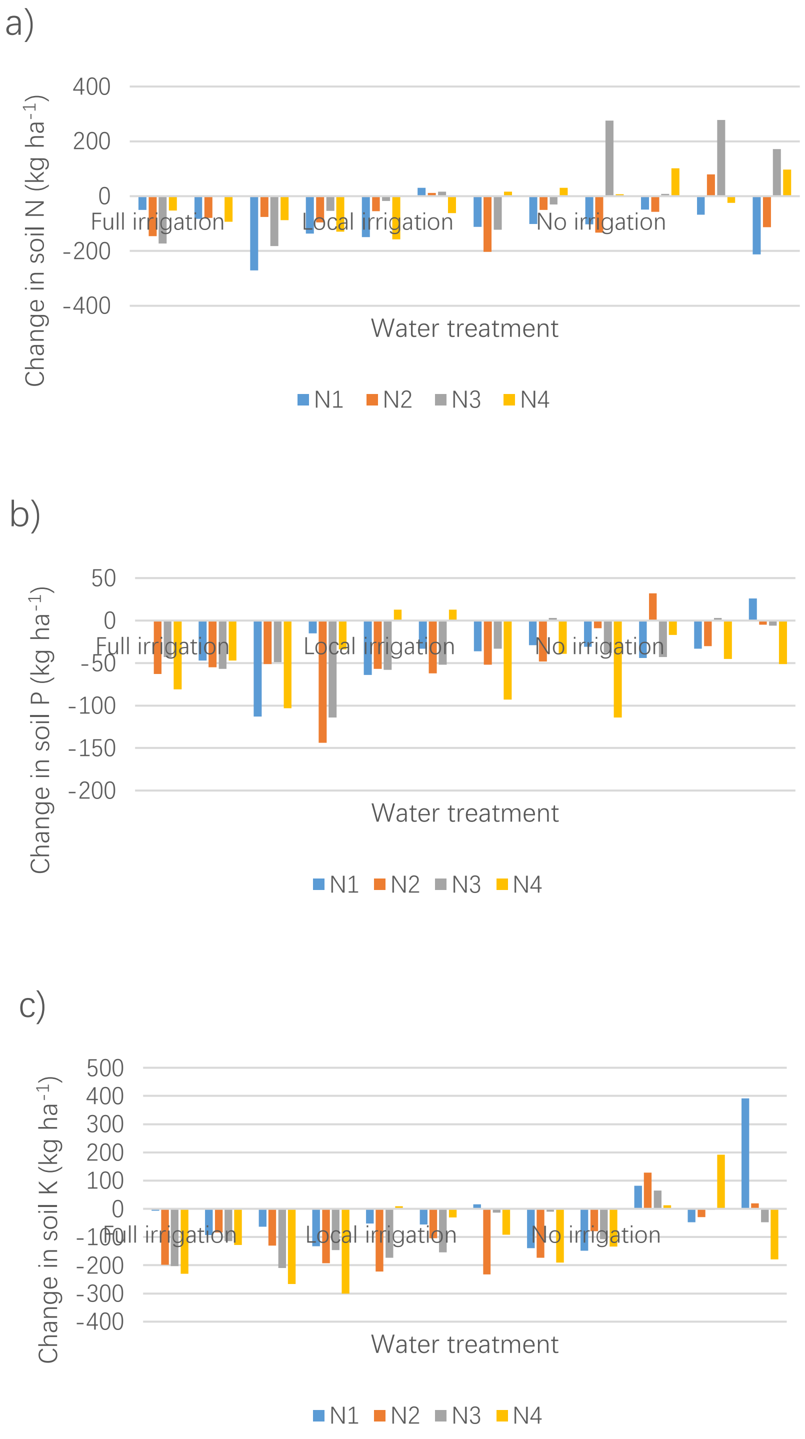
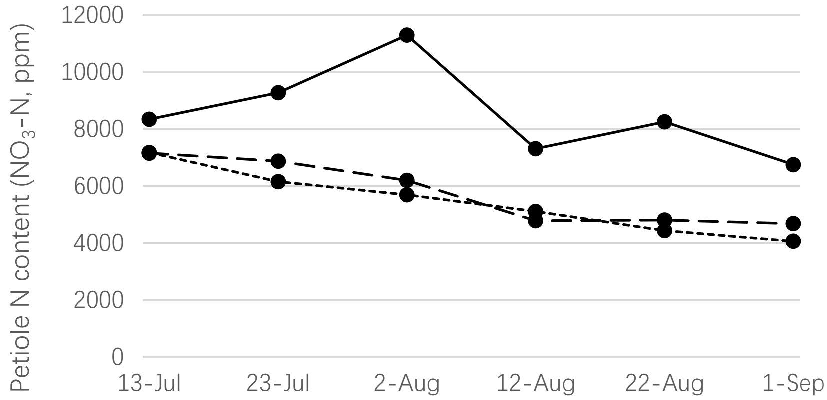


Figure A12: The changes in soil NPK (kg ha^{-1}, after harvest minus before planting) of each subplot seeded with entire tubers. 'N1', 'N2', 'N3' and 'N4' means the nitrogen treatment 0, 184, 267 and 225 kg ha^{-1} respectively; 'Full irrigation', 'Local irrigation' and 'No irrigation' represent the water treatment of 280, 235 and 0 mm irrigation respectively. The effects of blocks are not considered in this figure. (a) The changes in soil N; (b) the changes in soil P; (c) the changes in soil K. The data is recorded in Xiaohan Zhou's Internship Report Section 3.2, Table 10.

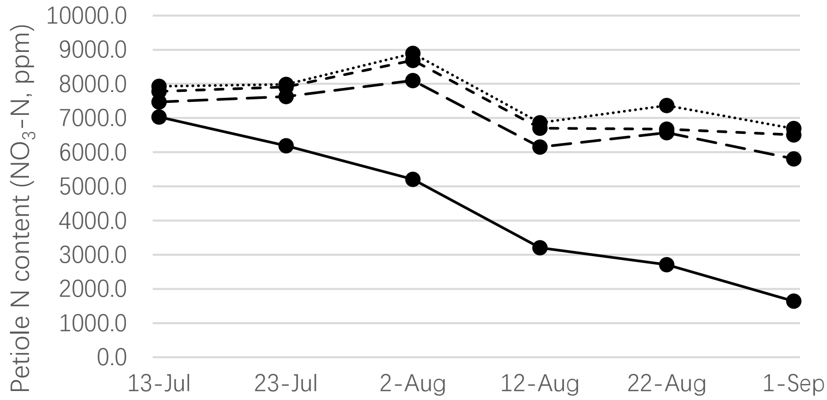
Appendix 13: Fluctuations in petiole N contents

(a)



	13-Jul	23-Jul	2-Aug	12-Aug	22-Aug	1-Sep
Full	7175	6150	5687.5	5106.3	4437.5	4058.1
Local	7153.3	6868.8	6193.8	4782.5	4804.5	4677.5
No	8337.5	9268.8	11287.5	7300	8250	6750

(b)



	13-Jul	23-Jul	2-Aug	12-Aug	22-Aug	1-Sep
N4	7783.3	7908.3	8691.7	6708.3	6675.0	6508.3
N3	7929.3	7983.3	8891.7	6858.3	7366.7	6691.7
N2	7475.0	7633.3	8100.0	6150.0	6575.0	5808.3
N1	7033.3	6191.7	5208.3	3201.7	2706.0	1639.2

Figure A13: The fluctuations of petiole N contents (NO_3-N, ppm). The petiole N contents were measured every 10 days between July 13th and September 1st, 2017. 'N1', 'N2', 'N3' and 'N4' means the nitrogen treatment 0, 184, 267 and 225 kg ha^{-1} respectively; 'Full', 'Local' and 'No' represent the water treatment of 280, 235 and 0 mm irrigation respectively. Urea was applied between July 2nd and 5th, and between July 28th and 30th. On August 13th, Cyazofamid (C13H13ClN4O2S) was applied for potato late blight. Cyazofamid contains nitrogen (only 10.37 g N ha^{-1}). The data is from Xiaohan Zhou's Internship Report Section 3.3, Table 15.