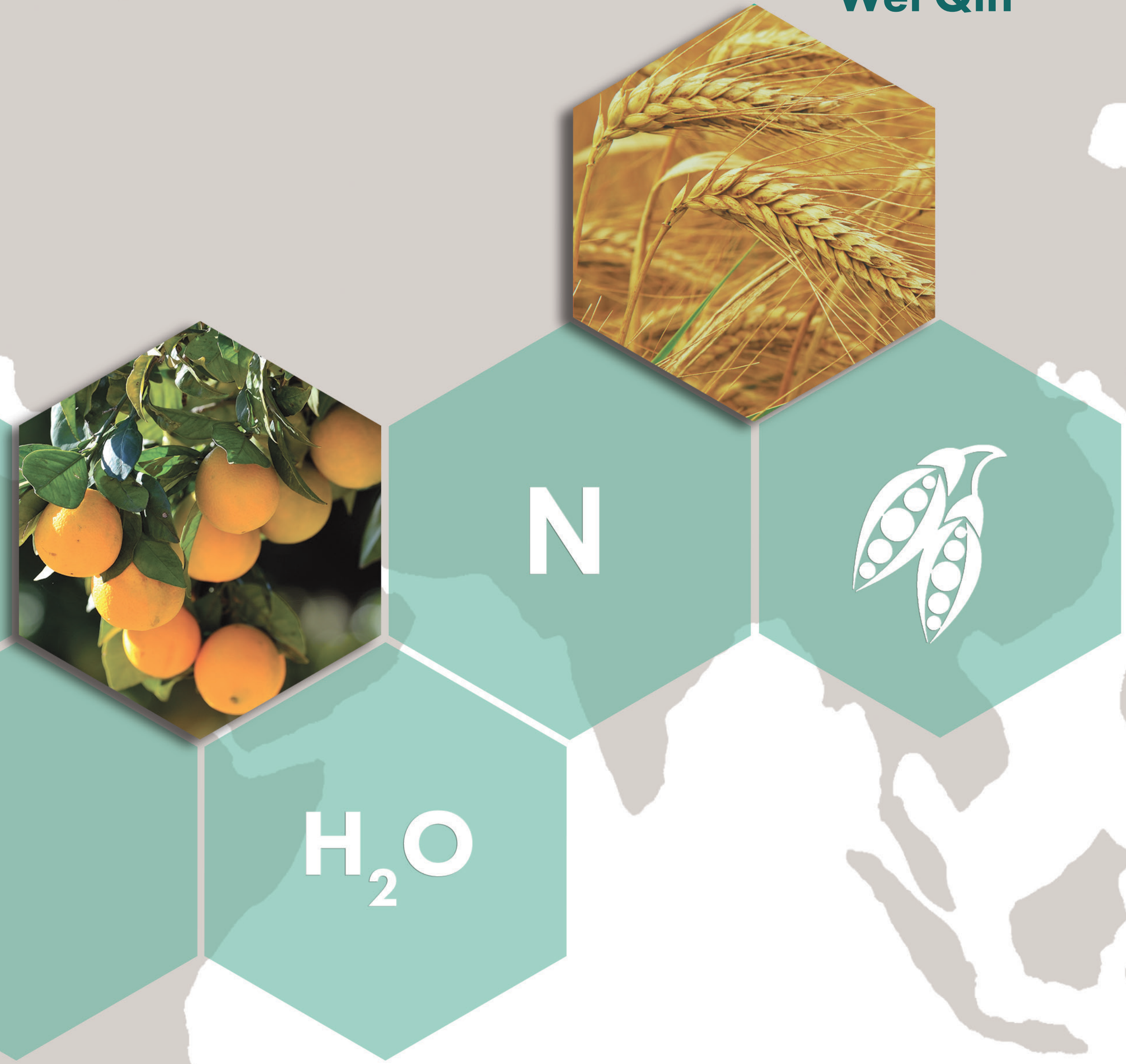


Wei Qin

Exploring options for improving **water & nitrogen use efficiency** in crop production systems

Exploring options for improving water and nitrogen use efficiency in crop production systems

Wei Qin

2015

Exploring options for improving water and nitrogen use efficiency in crop production systems

Wei Qin

Thesis committee

Promotor

Prof. Dr Oene Oenema
Special chair, Department of Soil Quality
Wageningen University

Co-promotors

Prof. Dr Chunsheng Hu
Professor, Centre for Agricultural Resources Research
Institute of Genetics and Developmental Biology
China Academy of Sciences

Dr Marius Heinen
Senior researcher, Alterra
Wageningen University and Research Centre

Other members

Prof. Dr Paul Struik, Wageningen University
Prof. Dr Coen Ritsema, Wageningen University
Prof. Dr Jan Willem Erisman, VU University Amsterdam
Prof. Dr Dirk Raes, KU Leuven, Belgium

This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology and Resource Conservation.

Exploring options for improving water and nitrogen use efficiency in crop production systems

Wei Qin

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Friday 6 November 2015
at 11 a.m. in the Aula.

Wei Qin
Exploring options for improving water and nitrogen use efficiency in crop production systems,
190 pages.

PhD thesis, Wageningen University, Wageningen, NL (2015)
With references, with summary in English

ISBN: 978-94-6257-503-5

Contents

Chapter 1

General introduction

1.1. Introduction

1.1.1. Water and nitrogen in crop production

Crop production provides food, feed, fuel and fibre for human and animal populations. Crop production systems require large amounts of water and nutrients, especially nitrogen (N). Currently, about 70% of the total fresh water withdrawal (2800 km^3) from surface waters and groundwater and more than 100 Tg fertilizer N are being used by global crop production systems (FAO, 2014b; Fowler et al., 2013; Molden, 2007). Yet, global crop production is significantly limited by water and N availability and inadequate management (Mueller et al., 2012; Rockstrom et al., 2010; Vitousek et al., 2009). The gap between currently observed crop yields and the attainable yields (when water and N are supplied in adequate amounts) is large in many regions of the world, especially in less developed countries. Mueller et al. (2012) estimated that global crop production may be increased by 45 to 70% for most crops (64% for maize, 71% for wheat and 47% for rice) following improvements in water and N management. Such yield increases can only be achieved by improving water and N availability simultaneously, and by understanding their interactions in crop yields, also because crop yields are often co-limited by both water and N. Achieving such increases requires a quantitative understanding of the water and N use requirements by the growing crops over time, and of the water and N supplies by soil, atmosphere, fertilizers, animal manures and crop residues over time.

Forecasts suggest that total food production may have to double in order to feed the increasing human population (up to 9-10 billion) in the world by 2050. Especially the need for cereals (mainly wheat, maize and rice), fruits and vegetables will increase (Alexandratos and Bruinsma, 2012; FAO, 2009; Ray et al., 2013). Further, human diets are changing due to the effects of urbanization, globalization and the increases in prosperity of a part of the global population. Diets are shifting towards the intake of more animal products (dairy, meat and egg), fruits and vegetables (Bai et al., 2014; Foley et al., 2011; Ma et al., 2013). Animal-derived food products often require larger amount of water and N inputs, compared to crop-derived food products. Producing 1 unit of meat requires 3 to 10 times more water and N inputs than 1 unit of cereals (Hoekstra and Mekonnen, 2012; Tilman et al., 2002). Changing diets have become a main driver for global crop production systems, and at the same time have significant environmental impacts (Bai et al., 2014; Ma et al., 2013; Westhoek et al., 2014).

Evidently, there is a need to produce more food, feed, fuel and fiber on the limited area of global crop land. Also, there is need to lower food losses and wastes (Godfray et al., 2011). Massive increases in crop yields per unit of land area require that the yield gap will have to be minimized in many regions of the world, through improved (precision) water and nitrogen management and improved crop husbandry practices. Some have raised questions and concerns about the environmental sustainability of such intensification over the long term (Garnett et al., 2013; Godfray and Garnett, 2014; Tilman et al., 2011). They argue that consumption patterns and food wastes have to be considered, together with a fairer distribution of the available food among populations, given the fact that currently around a billion people are chronically malnourished, mostly in the poor regions (Foley et al., 2011). Beside cereals and animal proteins, fruits like oranges and vegetables can enrich the food basket diversity and ensure a more healthy diet (with vitamin C). However, orange production and vegetable production systems also require large inputs of water and N, and these are often not well managed (Quiñones et al., 2007).

Poor nutrient management leads to low nutrient use efficiency and often to large nutrient losses. Poor water management leads to low water use efficiency and possibly also to low nutrient use efficiency due to high nutrient leaching losses. Currently, only about half of the applied fertilizer N is taken up by the crop, depending on crop type and management, while the remainder accumulates in the soil temporarily and/or is lost to the atmosphere via ammonia volatilization and (de)nitrification losses, and/or is lost to groundwater and surface water bodies via leaching, overland flow and erosion (Sutton et al., 2013; Sutton et al., 2011). In China, the recovery of fertilizer N in the harvested crop is even much less than half, while N losses are more than half of the applied fertilizer N (Ju et al., 2009). The N losses to air and water bodies create a range of human health and ecological impacts (Sutton et al., 2013; Sutton et al., 2011). Low water use efficiency is often synonymous with wasting of fresh water resources, which are scarce and become depleted in many dryland areas. This threatens future crop production (Chen et al., 2014; Foley et al., 2011; Hoekstra and Wiedmann, 2014). Hence, there is an urgent need to increase water and N use efficiencies and to decrease water and N losses.

1.1.2. Interactions between water and nitrogen in crop production

Water and N are involved in many fundamental processes in crop production, including photosynthesis, respiration, transpiration, plant development and yield formation (de Wit, 1958; Marschner, 1995). Water stress often leads to stomata closure, which inhibits photosynthesis and thus growth and N uptake by the plant (Chaves et al., 2002; Downton et al., 1988a, b). Shortage of N constrains shoot and root growth, which reduces plant water and nutrient uptake capacity (Salvagiotti et al., 2008; Setiyono et al., 2010). A limited supply of water and/or N leads to a distorted crop development and growth and to low crop yields. Effects can be large when the supply of both is limited. In such a case, it may result in a positive interaction between water and N use in crop yields (Figure 1A). When the limitation of one is relieved, the interactions may be small (Figure 1B). When one is over-supplied, the interactions may become negative because of small or no further increases in yield (Figure 1C). For example, negative interactions in crop yields can be expected with over-optimal water inputs, which may lead to increased N leaching losses and denitrification losses, and thereby to decreases in yield, WUE and

NUE. Fertilizer N applications all at once at planting may stimulate early growth but may also lead to early exhaustion of soil water in dryland areas and thereby to a relatively low grain yield compared to the grain yield obtained with moderate and split fertilizer N dressings. Hence, both positive and negative interactions may occur between water and N use in crop yields, and in water and N use efficiencies (WUE and NUE), depending on climate, soil fertility, crop species and also water and N input levels. Though interactions between water and N use in crop yields are known for long time, there are relatively few studies conducted that address the optimization of water and N use simultaneously, and have examined interactions between water and N use in for example crop yield, WUE, NUE, and N losses.

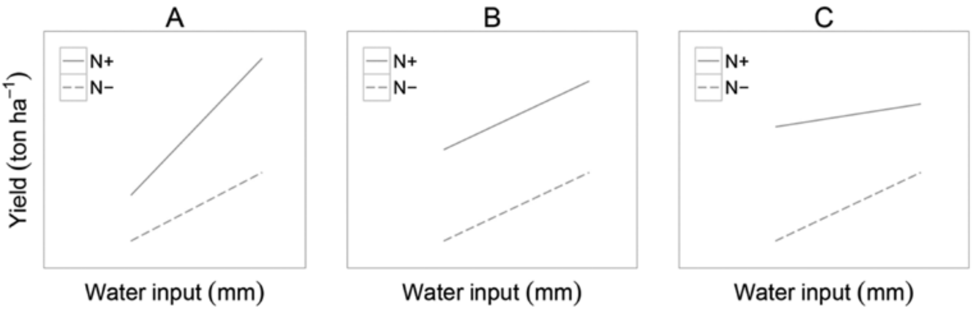


Figure 1. An illustration of possible interactions between water (irrigation) and N fertilization in crop yields. “N+” represents high N input, “N-” represents low N input. Panel A indicates a positive interaction, panel B indicates no interaction and panel C indicates a negative interaction.

1.1.3. Definitions of water and N use efficiencies

Water use efficiency (WUE) is commonly defined as crop yield over evapotranspiration (ET) (Bouman, 2007):

$$WUE = Y / ET \tag{1}$$

where WUE is often expressed in kg m^{-3}, *Y* is harvested crop yield (kg ha^{-1}) and *ET* is evapotranspiration (m^3 ha^{-1}). Evapotranspiration (*ET*) is the sum of soil evaporation (*E*) and crop transpiration (*T*) (Kang et al., 2002; Siahpoosh and Dehghanian, 2012; Zhang et al., 1999; Zhang et al., 2006). Actually, only T is a direct consequence of crop production, while *E* is ‘unproductive’ water loss. Soil evaporation (*E*) can be large, especially in arid and semi-arid regions with unpredictable rainfall. Hence, the central question for rainfed agriculture is ‘how to transform unproductive water loss (*E*) into productive water use (*T*)’. Unfortunately, the partitioning between *E* and *T* is often unknown, due to difficulties and high cost in distinguishing *E* and *T*. As a result, water use of crops is commonly reported as evapotranspiration (*ET*), instead of *E* and *T* separately (Kang et al., 2002; Zhang et al., 1999; Zhang et al., 2010). Lack of quantitative information on *E* and *T* partitioning also makes it difficult to assess how much of the evaporative water loss can be used for increasing yields by appropriate measures. Fertilization can enhance root growth and early development, which leads to larger and earlier plant canopy and thereby reduces *E*. Increasing planting density may also increase plant canopy and reduce *E*. However, there may be also trade-offs; consuming too much water at the early stage may lead to water stress at the later stage. Minimizing negative trade-offs requires a quantitative understanding of the water balance of the crop growing seasons.

Nitrogen use efficiency (NUE) can be defined in different ways (Dobermann, 2007). For example, NUE can be defined as the ratio of yield to total N inputs, also known as partial factor productivity (PFP) (Cassman et al., 1998):

$$NUE = Y \;/\; N \tag{2}$$

where NUE is often express as kg kg^{-1}, Y is harvested crop yield (kg ha^{-1}) and N is the sum of the N input via fertilizer, animal manure, atmospheric N deposition and biological N fixation (kg ha^{-1}). Some estimates of NUE only consider the N input via fertilizers and/or animal manures, and neglect the inputs via atmospheric N deposition and biological N fixation, because these latter are difficult to manage and the main interest is commonly in the efficiency of the used fertilizer (Cassman et al., 1998).

The NUE of fertilizer N applications can be increased through the so-called 4R strategy, i.e., applying the <u>right fertilizer</u>, at the <u>right amount</u>, the <u>right time</u> (synchronization), and at the <u>right place</u> (synlocalization) (IPNI, 2012). Fertigation, i.e., the combined application of water and N through precision drip irrigation is an advanced technology for increasing both WUE and NUE. Due to the relatively high cost of the investment and maintenance, fertigation is mainly used in high-value crops and not in cereal crops. However, even with fertigation, the optimization of water and N applications remain challenging because of the erratic rainfall and often unpredictable supply of N from soil (Phogat et al., 2013b).

1.1.4. Water and nitrogen use efficiency in crop production

Water and N use efficiencies (WUE and NUE) vary greatly between crop production systems, region and managements. In many arid and semi-arid regions of less-developed countries, WUE and NUE are often low due to low crop yields, degraded soil fertility and low and erratic water and N inputs (Rockstrom and Falkenmark, 2015; Rockstrom et al., 2010; Sanchez, 2010). In many developed and rapidly developing countries, WUE and NUE are also rather low because of over-application and poor management (Sutton et al., 2013; Zwart and Bastiaanssen, 2004; Zwart et al., 2010).

Recently, Zwart et al. (2010) reported that WUE of wheat varied from 0.2 to 1.8 kg m^{-3} (Table 1). Therefore, mean WUE of wheat is around 1 kg m^{-3}, i.e., producing 1 kg of wheat requires about 1 m^3 of water. The reported WUE of wheat also largely varied between regions, likely due to differences in climate, soil fertility, crops and field management. Among the world top 10 wheat producers, France and Germany scored the highest country average WUE of 1.42 and 1.35 kg m^{-3}, respectively. The WUE of wheat in other regions were significantly lower than these levels. The reported WUE also varied between studies, likely due to different methods used for the estimation of WUE. For example, Zwart et al. (2010) used remote sensing data, Liu et al. (2007) used the GEPIC model and Chapagain and Hoekstra (2004) used FAO statistics.

Table 1. Summary of water use efficiency (in kg m^{-3}) of the ten major wheat producing countries in the world, as estimated by Zwart et al. (2010), Liu et al. (2007) and Chapagain and Hoekstra (2004). The table was modified based on Zwart et al. (2010).

Country	WUE (kg m-3)		
	(Zwart et al., 2010)	(Liu et al., 2007)	(Chapagain and Hoekstra, 2004)
Australia	1.12	0.65	0.63
Canada	0.64	0.86	0.67
China	0.82	0.79	1.45
France	1.42	1.45	1.12
Germany	1.35	1.47	1.33
India	1.06	0.89	0.61
Pakistan	0.8	0.91	0.3
Russia	0.69	0.62	0.42
Turkey	0.64	0.65	0.65
USA	0.79	0.81	1.18
Average	**0.93**	**0.91**	**0.83**

Globally, NUE of crop systems showed decreasing trends for many continents over the last 50 years, mainly because of increasing N applications, poor N management, and the effect of the law of diminishing returns (Figure 2). The implication of decreasing trends of NUE suggest that N losses increase (Ju et al., 2009; Liu et al., 2013). Recently, Lassaletta et al. (2014) reported only 47% of the fertilizer N input is converted into harvested products, compared to 68% in the early 1960s, while total fertilizer N input increased by a factor of 9 over the same period, suggesting that more than half of the N input is currently lost to the environment. In Europe, however, there has been a slight upward trend of NUE in recent years, due to strict environmental regulations and improved N management, but further efforts are needed to significantly reduce N losses to the environment (Lassaletta et al., 2014; Sutton et al., 2013; Sutton et al., 2011). Note that the differences between countries are related to differences in cropping systems, environmental conditions and N management strategies.

Overall, these studies provided good overviews at the regional and global scales. However, there are also large uncertainties in such large scale studies because detailed information on field management, such as actual water and N input, cannot be taken into accounts. Improving crop yields, WUE and NUE requires site-specific knowledge at the field level.

1

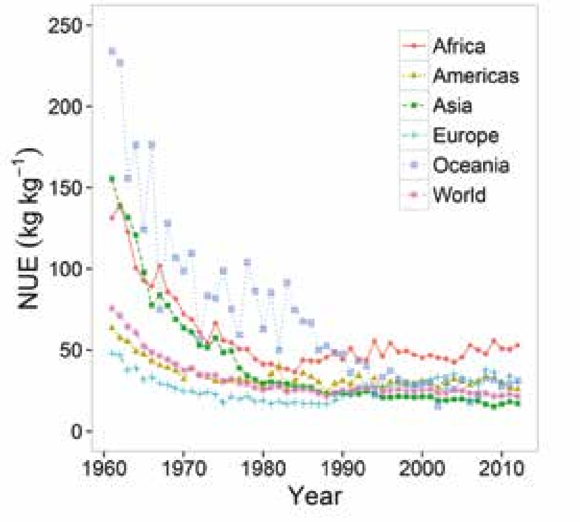


Figure 2. Fifty years' trends in nitrogen use efficiency (NUE) of five continents and the world. NUE was defined as the ratio between cereal grain production and fertilizer N input to cereal crop land per region. Data were derived from FAO database (FAO, 2014b). Note that the exceptionally high NUE in especially Africa reflect low N inputs, soil mining and/or errors in the statistical databases.

1.1.5. Water and nitrogen saving techniques

There are various techniques and management strategies available that allow more 'crop per drop and bag'. These techniques and strategies are often based on a combination of (i) increasing yield through improved breeds and crop husbandry practices, (ii) improved water and N application strategies, and (iii) water and N saving techniques, which reduce 'unproductive' water and N losses. Examples of the latter include soil mulching techniques. Soil mulching via straw and/or plastic covers can effectively reduce soil evaporation and save water, and thereby increase crop yield, WUE and NUE, especially for rainfed systems in arid and semi-arid regions (Gan et al., 2013; Li et al., 2013b).

Fertigation allows the proper (precision) management of water and nutrient supply so as to meet crop demand, and at the same time, minimize water and nutrient losses. To achieve these goals, deficit irrigation (or deficit fertigation) is often practiced, and sometimes done to achieve better quality products (Castellanos et al., 2013; Phogat et al., 2013c; Quemada et al., 2013).

So far, water-saving and N-saving techniques and management strategies are often studied separately, in part because of different research interests, and in part also because the simultaneous optimization of water and N use in cropping system is complicated. The water and N demand by the crop and the effective water and N supply by soil and atmosphere both depend on the seasonal and regional variations in climate, soils, cropping systems and managements. As a consequence, the full potential of positive interactions between water and N use in crop yields (e.g. Figure 1A) are likely not realized in practice.

1.1.6. Role of long-term field monitoring studies

Long-term field experiments are needed for examining interactions between water and N use in crop production, because of the large annual variations in water and N demands by the crop and water and N supply by soil and atmosphere (Zhang et al., 2012; Zhang et al., 2006). Most studies on water and N use optimization though were relatively short-term, ranging from 2-5 years (Belder et al., 2004; Kang et al., 2002; Liu et al., 2003). It remains unclear therefore whether the proposed management strategies (e.g., water and N saving techniques, soil mulching, soil organic amendments) in these studies will be sustainable over the long-term. Long-term experimental data provide the opportunity to better understand and unravel the effects of fluctuations in uncontrollable climate factors such as rainfall and temperature. Thereby, long-term field experimental data can increase the robustness of the analysis and avoid misinterpretations. Effects of some field practises, e.g., the effects of soil organic amendments with crop residue and/or animal manure on soil fertility and crop yields can only be identified accurately in long-term experiments (Hua et al., 2014). Furthermore, data from long-term experiment allows better calibration and validation of simulation models.

1.1.7. Role of soil-crop modelling

Soil-crop modelling can also be used as tool for exploring new and improved management strategies. Over the last five decades, there have been significant developments and improvements in soil-crop modelling (Sinclair and Seligman, 1996; Steduto et al., 2012). Soil-crop modelling has been used in many studies, and has proven to be useful, provided that the models are well calibrated and validated (Heinen et al., 2012; Hu et al., 2008b; Hu et al., 2010).

Among many crop models, AquaCrop is a relatively new crop water productivity model developed by the Land and Water Division of FAO (Steduto et al., 2009). It is meant to be applied in practice to increase water productivity (more crop per drop). One of the important aspects is that AquaCrop uses a normalized water productivity so that the application of AquaCrop is less sensitive to the variations in locations. Compared to other crop models, AquaCrop requires a relatively small number of parameters and input variables, and has a good balance of accuracy, simplicity and robustness (Steduto et al., 2012; Steduto et al., 2009). AquaCrop can separately calculate evaporation (E) from soil and transpiration (T) by plants, and can simulate the crop yields as a function of water use under pre-defined soil fertility levels (Steduto et al., 2012; Steduto et al., 2009). The model is particularly suited to address conditions where water is a key limiting factor in homogeneously cropped fields.

AquaCrop simulates soil water dynamics in a simple one-dimensional manner and is therefore unable to simulate drip irrigated crop production appropriately. In drip irrigated crop production systems, such as in orange orchards, water moves into the soil in three dimensions from the point of application, leaving significant areas of the soil dry in between the drippers. Drip irrigation thereby reduces ‘unproductive’ water loss through evaporation. Such situations require models that are able to simulate water and solute transport in soil in three dimensions, such as in FUSSIM (Heinen, 2001). However, FUSSIM is unable to simulate crop growth and development. Coupling AquaCrop to FUSSIM may possibly result in a tool that allows exploring fertigation strategies of for example orange orchards in a proper way.

1.1.8. Objectives

Water and nitrogen are key limiting factors in global crop production. The optimization of water and N use is often studied separately and interactions between water and N use in crop yields are often neglected. The main objective of this thesis research was ‘to increase the understanding of interactions between water and N use in crop production’. The specific objectives were (i) to analyse water and N use and their interactions in crop yields and in water and N use efficiencies, and (ii) to explore options for increasing crop yields and water and N use efficiencies simultaneously.

Two main and contrasting crop production systems were chosen, i.e., annual cereal-based production system and perennial orange production system. Cereal production systems were chosen because of their importance in ensuring global food and feed supply. Special attention were given to rainfed wheat and maize systems because their yields are significantly limited by water and N availability, especially in arid and semi-arid regions (Mueller et al., 2012; Rockstrom et al., 2010; Sutton and Bleeker, 2013; Vitousek et al., 2009). Fertigated orange production systems were considered because of their increasing importance in the global fruit market and in human diets. Rapid development in orange production is also because of the improvements in technologies and facilities, such as drip irrigation/fertigation, logistics and food processing.

The main research questions were:

- What are the effects of soil mulching on yields, WUE and NUE?
- What are the options for increasing yield, WUE and NUE in rainfed dryland system?
- What are the effects of long-term applications of soil organic amendments and mineral fertilizers on crop yields, WUE and NUE in rain fed dryland system?
- What are the potentials of increasing WUE and NUE in orange production?
- What are the possible fertigation strategies for improving WUE and NUE in orange production?

1.1.9. Outline of this thesis

In Chapter 2, I conducted a meta-analysis on the effects of soil mulching on wheat and maize yields, WUE and NUE, using 1310 yield observations from 74 studies conducted in 19 countries. Soil mulching (with plastic film cover and/or straw mulching) reduces evaporation, modifies soil temperature and thereby affects crop yields. The effects of soil mulching on crop yields, WUE and NUE were quantified and possible trade-offs were discussed.

In Chapter 3, I analysed the relationships between water input and yields, WUE and NUE of a rainfed winter wheat system in the Loess Plateau, using data of a long-term (>30 years) monitoring field experiment in Shanxi province, China. The loess Plateau is an arid and semi-arid region with limited annual rainfall (<500 mm), which is often the main limiting factor for crop yields. Water losses via soil evaporation (E) can be large, which may lead to shortage of water for plant transpiration (T). The partitioning of E and T can provide a better understanding of the water balance of the system. Therefore, in this chapter, I calibrated and validated the FAO AquaCrop model, using data of the long-term experiment. Further, the potentials for improving yield, WUE and NUE were explored, via model simulations.

In chapter 4, I analysed the productivity of a rainfed wheat-soybean system in the North China Plain, using data of a long-term (> 30 years) field experiment conducted in Anhui province. In this chapter, I investigated the effects of a series of field management practices (i.e., recommended fertilization, and the same fertilization with additions of straw and animal manure as soil organic amendments) on crop yield, WUE and NUE over time. I used the FAO AquaCrop model to explore the potentials for improving yield, WUE and NUE via model simulations.

In chapter 5, I conducted a meta-analysis on orange production systems in the world, using 1009 yield observations from 55 studies conducted in 11 countries. Orange trees mainly grow in subtropical and tropical regions, and require relatively large amounts of water and N. In this chapter, relationships between water input and orange yield, WUE and NUE, and between N input and yield, WUE and NUE were analyzed. Also, effects of sub- and over-optimal water and N supply on yield, WUE and NUE were quantified and water and N saving potential of each regions were estimated.

In chapter 6, I explored the simultaneous optimization of water and N use for orange production in the Mediterranean region, using two models, i.e., the soil hydrological model FUSSIM-3D and the water-driven crop model AquaCrop, which were coupled. In total, 47 fertigation strategies were investigated, which included 27 main scenarios (3x3x3 factorial design): 3 irrigation levels (80,100 and 120% ET), 3 N supply levels (100, 200 and 300 kg N ha^{-1}) and 3 split applications. 20 additional scenarios were investigated, which included the effects of rainfall, soil type and fine-tuning fertigation strategies.

Chapter 7 provides the general discussion and overall synthesis of my thesis research.

Wei Qin
Chunsheng Hu
Oene Oenema

Chapter 2

Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis

This chapter has been submitted for publication

2

Abstract

Global crop yields are limited by water and nutrient availability. Soil mulching (with plastic or straw) reduces evaporation, modifies soil temperature and thereby affects crop yields. Reported effects of mulching are sometimes contradictory, likely due to differences in climatic conditions, soil characteristics, crop species, and also water and nitrogen (N) input levels. Here we report on a meta-analysis of the effects of mulching on wheat and maize, using 1310 yield observations from 74 studies conducted in 19 countries. Our results indicate that mulching significantly increased yields, WUE (yield per unit water) and NUE (yield per unit N) by up to 60%, compared with no-mulching. Effects were larger for maize than wheat, and larger for plastic mulching than straw mulching. Interestingly, plastic mulching performed better at relatively low temperature while straw mulching showed the opposite trend. Effects of mulching also tended to decrease with increasing water input. Mulching effects were not related to soil organic matter content. In conclusion, soil mulching can significantly increase maize and wheat yields, WUE and NUE, and thereby may contribute to closing the yield gap between attainable and actual yields, especially in dryland and low nutrients input agriculture. The management of soil mulching requires site-specific knowledge.

Keywords: meta-analysis, mulching, plastic, wheat, maize, yield, nitrogen, water

2.1. Introduction

Wheat and maize account for ~70% of the world cereal production but their yields are significantly limited by the availability of water and nutrient, especially in arid and semi-arid regions(FAO, 2015b; Mueller et al., 2012; Rockstrom et al., 2010; Rockstrom et al., 2007). In regions with sufficient water and nutrients input, the water and nutrient use efficiencies of wheat and maize are often low due to suboptimal management(Dobermann and Cassman, 2005; Vitousek et al., 2009; Zwart and Bastiaanssen, 2004), which leads to large losses(Ju et al., 2009; Liu et al., 2013; Sutton et al., 2013). Forecasts project that food production, including wheat and maize, will have to double in order to feed the growing world population, now 7 billion but expected to be 9 to 10 billion in 2050(FAO, 2009). This will increase the pressure on the use of our limited natural resources, such as land, water and nutrients. There is an urgent need to increase water and nutrients use efficiencies in the major cropping systems, especially in rainfed agricultural systems(Green et al., 2010).

Rainfed agriculture covers 80% of the world's cultivated land, and contributes about 60% to the total crop production(UNESCO, 2009). Low productivity in many arid and semi-arid rainfed agricultural systems is often due to degraded soil ferity and limited water and nutrients input. There are various options for increasing 'crop yield per drop and bag', such as straw mulching and plastic mulching(Gan et al., 2013; Li et al., 2013b). These soil mulching management techniques can reduce evaporation and erosion, modify soil temperature, and reduce weed infestation, and thereby may lead to increases in yield, and possibly water use efficiency (WUE) and nitrogen (N) use efficiency (NUE)(Gan et al., 2013; Li et al., 2013a; Li et al., 2013b; Qin et al., 2013). The effects of mulching were partially reported before in some previous studies along with other main objectives, such as the comparison between tillage and no or reduced tillage. For example, Rusinamhodzi et al. (2011) assessed the effect of long-term no tillage, crop rotation and straw mulching on maize grain yield. They found that mean maize yield was ~1 ton ha^{-1} higher with conservation agriculture practices (with straw mulching) when mean annual precipitation was below 600 mm. However, when mean annual precipitation was above 1000 mm, these conservation agriculture practices may have lower yields (~1 ton ha^{-1}). Recently, Pittelkow et al. (2014) reported that crop yields increased by 7.3% under rainfed agriculture in dry climates when no-tillage, straw mulching and crop rotation are implemented together. No-till applied alone (without straw mulching and crop rotation) reduced yields by 11.9%. Also, effects of no-tillage with or without mulching were larger in dry conditions than humid conditions(Pittelkow et al., 2014). Others found that straw mulching may retard seed germination and early growth of crops, especially in relatively cold climatic conditions(Chen et al., 2007). Currently, plastic films are widely used in some regions such as China and India, mainly because of governmental subsidies. Plastic films are more effective in reducing soil evaporation compared to straw mulching, but large amounts of plastic film residual may have negative effects on soil structure, water and nutrient transport and crop growth, thereby reducing crop production(Liu et al., 2014a). Therefore, the reported effects of mulching often differ and sometimes contradict between studies, likely due to differences in the climatic conditions (rainfall and temperature), soil characteristics, crop species, and also water and N input levels. As yet, a systematic and quantitative assessment of the effects of soil mulching on crop yields, WUE and NUE as function of environmental conditions has not been carried out.

Here, we examine the effects of straw and plastic mulching on yield, WUE and NUE of wheat and maize, as function of environmental conditions using a meta-analysis of published results. We selected wheat and maize as test crops because of their global importance, and their contrasting responses to environmental conditions. A comprehensive and quantitative understanding of the effects of mulching may contribute to closing yield gaps between attainable and actual crop yields, and to guiding practitioners better. The objectives of our study were (1) to examine the effects of mulching on wheat and maize yield, WUE and NUE on the basis of results of published studies; (2) to relate variations in the effects of mulching to variations in inputs of water and N, temperature, and to soil organic matter; and (3) to quantify possible interactions between water and N use in yield, WUE and NUE.

2.2. Methods

2.2.1. Data collection

We searched in peer-reviewed literature for publications investigating the effects of mulching on yield of maize and wheat using Scopus (Elsevier). Search terms included ‘mulch’ and/or ‘mulching’, ‘maize’ and/or ‘wheat’, ‘yield’, ‘water’ or ‘nitrogen’ in the article title, abstract, and keywords. Conference proceedings and non-English language publications were excluded. This search produced a total of ~600 publications, which were screened on the basis of the following criteria: (1) studies must contain both no-mulching and mulching treatments (either straw or plastic mulching); (2) crop yields, water input and N input were all reported so that the interactions between water and N can be quantified; (3) location, year and soil information of the experiment was stated. The final analysis was based on 1310 yield observations from 74 studies conducted in 19 countries.

2.2.2. Definitions and data analysis

Water use efficiency (WUE, in kg m^{-3}) was defined as:

$$WUE = Y / ET \tag{1}$$

where Y is yield (in kg ha^{-1}), ET is evapotranspiration (mm, m^3 ha^{-1}) reported in the study. Because most of the studies were conducted in water-limited environment where ET is closely related to total water (rainfall + irrigation) input, when ET was not reported in the studies, we considered ET is equal to total water (rainfall + irrigation) input (mm, m^3 ha^{-1}) during the crop growing season.

Nitrogen (N) use efficiency (NUE, dimensionless, or kg kg^{-1}) was defined as:

$$NUE = Y / N \tag{2}$$

where N is the total N input from fertilizer and/or manure, all converted to N content (kg ha^{-1}). The N content of the straw for soil mulching was too small (<20 kg N ha^{-1}) therefore neglected. A few observations (75) with zero (0) N input were excluded from the final dataset to avoid errors (non-values) in the calculation of NUE.

The magnitude of the mulching effects on yield in each study was calculated as the natural logarithm of the response ratio (R)(Hedges et al., 1999):

$$\ln R = \ln(Y_{obs} / Y_{ref}) \tag{3}$$

where Y_{obs} is each observed yield of the study, including yields from both mulching and no-mulching treatments, Y_{ref} is the mean yield of no-mulching treatment(s) in a specific year (and also in a specific experimental site if there are multiple sites) of a study, set as the reference to be compared with. Hence, the comparisons were side-by-side and equal weight was given to each calculated effect size.

In meta-analysis studies, the observations can be weighted by many ways. When studies did not report standard deviation or standard error, which is often the case in agronomic studies, the observations can be weighted equally (or unweighted), weighted with sample size of the study or weighted with number of replicates of control and treatment group(Hedges et al., 1999; Hungate et al., 2009; van Groenigen et al., 2014). We tested and compared three different weighting methods for each observation. In the end, we chose the equal weight method for each observation because this method produced the smallest AIC (Akaike information criterion) value, among all three weighting methods.

We used the mean yield of no-mulching treatment(s) as the reference because of the following reasons: Although most of studies included in our dataset match the criteria of side-by-side comparison between mulching and no-mulching, there were still some studies which were not specifically designed for testing the effects of mulching. For example, there can be multiple observations with no-mulching treatments, mostly with different tillage (no tillage, reduced tillage or conventional tillage) and/or land preparation (flattening the field or making ridges and furrows). This then led to multiple observations with no-mulching treatments (instead of one value) in some studies. In such case, if each observed yield was compared to the minimum yield from no-mulching treatments, the effects of mulching would be overestimated; the opposite is also true, i.e., if each observed yield was compared to the maximum yield from no-mulching, the effects of mulching would be underestimated. To avoid either over- or under-estimate of the mulching effects, we decided to use the mean yield from no-mulching treatments as reference, and then compare each observed yield to the reference to derive the response ratio. The same approach was applied to the calculation of the effect size of WUE and NUE.

The effect size (ln R) was statistically analyzed with a mixed-effect model via the R package “nlme” (Pinheiro et al., 2013; R Core Team, 2013):

$$\ln R = \alpha + \beta_1 * M + error \quad (4)$$

where α is the intercept with the same dimension as *ln R*, b_1 represent the response due to the mulching treatment (M) and *error* represents the residual that was not explained by the mulching variable. In this mixed-effect model, mulching treatments (i.e., no-mulching, straw mulching, and plastic mulching) were set as fixed effects and studies were set as random effects.

To investigate how the effects of mulching varied due to the levels of water input, N input and temperature, the whole dataset was separated into two sub-datasets according to the 50^{th} percentile value of the water input, N input, temperature and soil organic matter (SOM) content, respectively. Mean effects of mulching were considered significant if confidence intervals did not overlap with 0 (P values = 0.05). Mean effects for different subgroups were considered to be significantly different from one another if their 95% confidence intervals did not overlap. For ease of interpretation, all results were back-transformed and reported as percentage change in yield (and in WUE and NUE) for each mulching treatment. The analysis was conducted for wheat and maize separately. Similar procedure has been used in some recent meta-analysis studies(Hou et al., 2014; Pittelkow et al., 2014; van Groenigen et al., 2014).

Also, the overall mean effects of multiple variables and possible interactions between variables, including mulching, soil organic matter, temperature, water and N input on yield (and on WUE and NUE) were analysed, using the whole dataset with the following formula:

$$Y = \alpha + \beta_1 * M + \beta_2 * SOM + \beta_3 * T + \beta_4 * W + \beta_5 * N + \beta_6 * W * N + error \quad (5)$$

where Y is yield (in ton ha^{-1}), $b_{1\text{-}6}$ represent the response due to changes in each variable, M is mulching treatment, T is mean air temperature during the growing season (°C), W is mean water input (rainfall + irrigation) during the growing season (m^{-3} ha^{-1}), and N is fertilizer and/or manure N input (kg ha^{-1}), among which only M is a discrete variable and all others are continuous variables. Note that there are differences in the interpretation of β related to discrete and continuous variables. For the mulching treatment (*M*), b_1 is interpreted as the change in yield in absolute terms, compared to the intercept (α) with no-mulching (the reference). For the continuous variables, b_{2-6} is interpreted as the response in yield due to per unit change in the variable. Note also that the response variable in Eq 5 is actual yield (and in Eq 4 is *ln* R).

2

2.3. Results

2.3.1. Overview of the dataset

Our dataset consists of 1310 yield observations from 74 studies conducted in 19 countries. There are 569 observations for wheat (CK: 208, Straw: 289, Plastic: 72) and 741 observations for maize (CK: 270, Straw: 328, Plastic: 143). There are more observations for maize and wheat, and more observations for straw mulching and plastic mulching. Wheat received relatively less water compared to maize. The water input of wheat ranged from 25 to 1000mm, and that of maize ranged from 150-2000mm. However, most of the observations were concentrated below 800mm. Wheat also received relatively less N input, compared to maize. The N input of wheat ranged from 20-200 kg N ha^{-1}, that of maize ranged from 30-400 kg N ha^{-1}. The 25th and 75th percentile values indicate that wheat yields ranged from 2.5 to 7.0 ton ha^{-1} and maize yields ranged from 2.5 to 10 ton ha^{-1}; WUE of wheat ranged from 0.5 to 1.5 kg m^{-3} and WUE of maize ranged from 0.5 to 2.5 kg m^{-3}; NUE of wheat ranged from 20 to 50 kg kg^{-1} and NUE of maize from 20 to 80 kg kg^{-1}.

2.3.2. Overall effects of mulching on yields, WUE and NUE

Yields, WUE and NUE of wheat and maize were significantly increased by both straw mulching and plastic cover, compared to the reference value with no-mulching (Figure 1). The mulching effects on yield, WUE and NUE were highly similar because WUE and NUE were calculated as yield per water/N input. On average, straw mulching and plastic mulching increased yield, WUE and NUE of wheat by 20%. The mean effect of straw mulching on maize were similar to that of wheat, but plastic mulching increased yield, WUE and NUE of maize by ~60%.

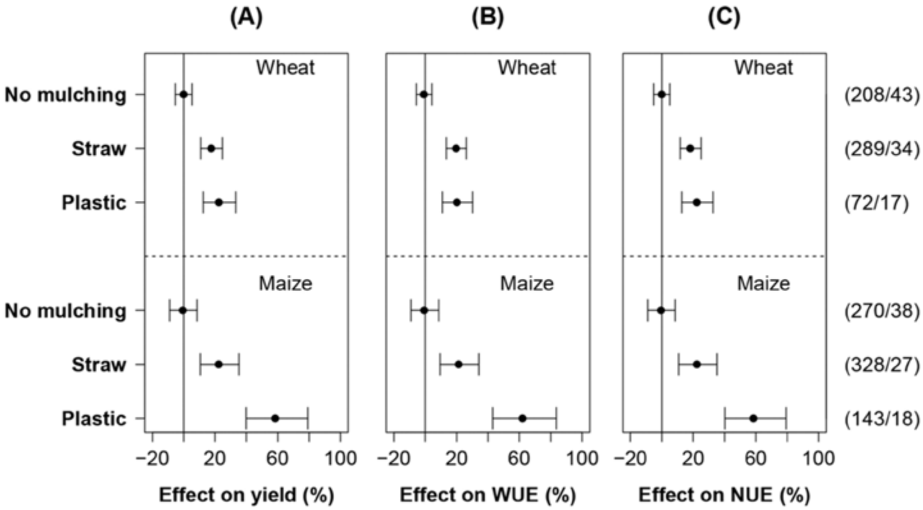


Figure 1. Effect of mulching on crop yield (A), water use efficiency (B) and nitrogen use efficiency (C) of wheat (upper panels) and maize (lower panels). Dots show means, error bars represent 95% confidence intervals. The number of observations and total number of studies for each treatment are displayed in parentheses on the right-hand side of the figure, respectively.

2.3.3. Effects of mulching on yields, WUE and NUE at different water input levels

The effects of mulching were affected by water input. Here the dataset was separated into two sub-datasets according to the 50th percentile value of the water input of each crop with plastic mulching treatments (because of relatively small number of observations), in order to have reasonable comparisons. The mean effect of straw mulching on wheat yields was 20% at low water input level (<250mm), which decreased to 15% at high water input (>250 mm). In contrast, the mean effect of plastic mulching on wheat yields was 15% at low water input and 35% at high water input (Figure 2A). For maize the mean effect of straw mulching on maize yield was 20%, independent of water input level. The mean effect of plastic mulching on maize yield was 60% at low water input (<370mm) and 40% at high water input (Figure 2B). Interestingly, the confidence intervals (CI) of the mulching effects on maize yields also decreased with increased water input. For example, the CIs of straw mulching were ±18% at low water input and decreased to ±8% at high water input.

The mean effect (20%) of straw mulching on WUE of wheat was not affected by water input, but the mean effect of plastic mulching was 15% at low water input and 28% at high water input (Figure 3A). For maize, the mean effect (20%) of straw mulching on WUE was also independent of water input level, the mean effect of plastic was 70% at low water input and 40% at high water input (Figure 3B). The CIs of the mulching effects on WUE of maize also decreased with increased water input.

The mean effects of straw mulching on NUE of wheat were slightly higher at low water input than at high water input. Mean effects of plastic mulching on NUE were lower at low water input than at high water input (Figure 4A). For maize, the mean effect of straw mulching on NUE was around 20%, independent of water input level, whereas that of plastic mulching decreased from 60% at low water input level to 40% at high water input level (Figure 4B).

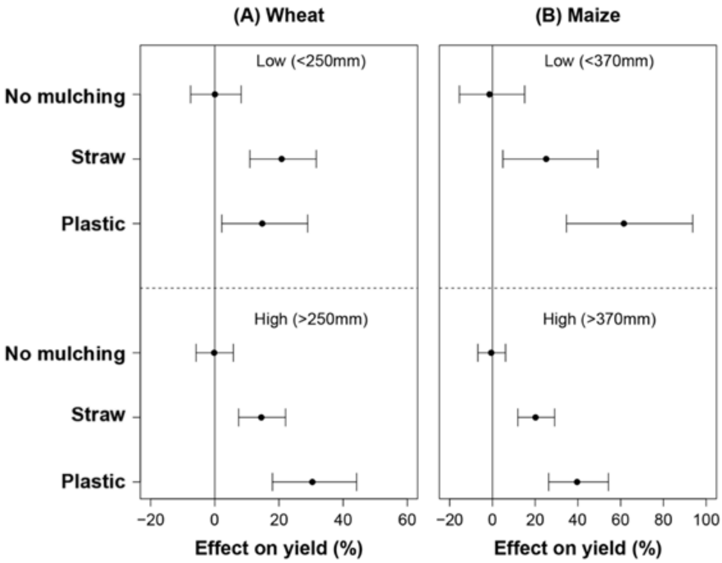


Figure 2. The effect of mulching on wheat (A) and maize (B) yields at different water input levels. Data were sub-grouped according to the 0.5 quantile value of the water input of each crop with plastic mulching treatments and displayed as low and high (from top to the bottom).

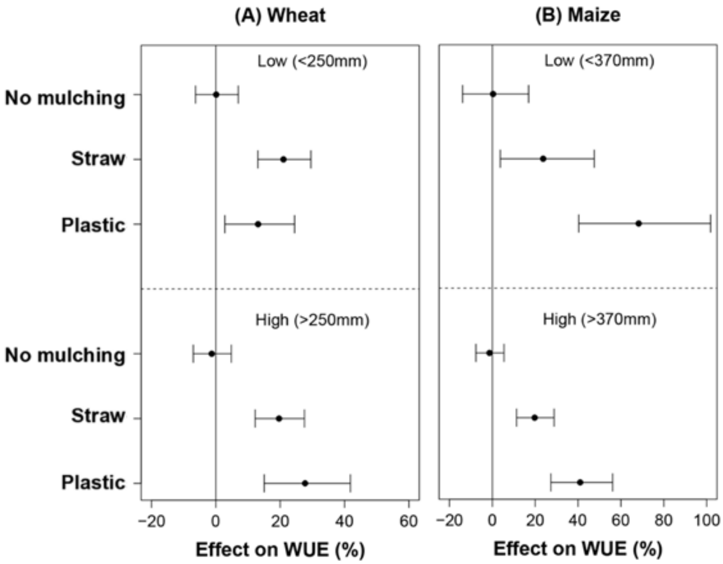


Figure 3. The effect of mulching on WUE of wheat (A) and maize (B) at different water input levels. Data were sub-grouped according to the 0.5 quantile value of the water input of each crop with plastic mulching treatments and displayed as low and high (from top to the bottom).

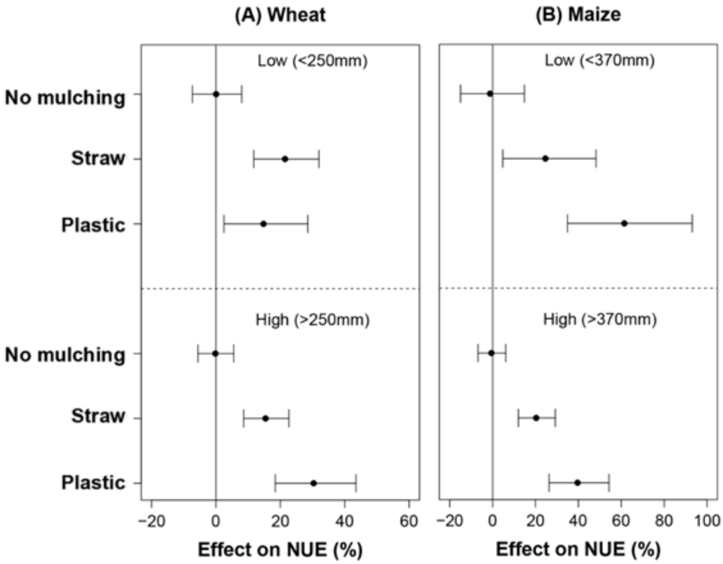


Figure 4. The effect of mulching on NUE of wheat (A) and maize (B) at different water input levels. Data were sub-grouped according to the 0.5 quantile value of the water input of each crop with plastic mulching treatments and displayed as low and high (from top to the bottom).

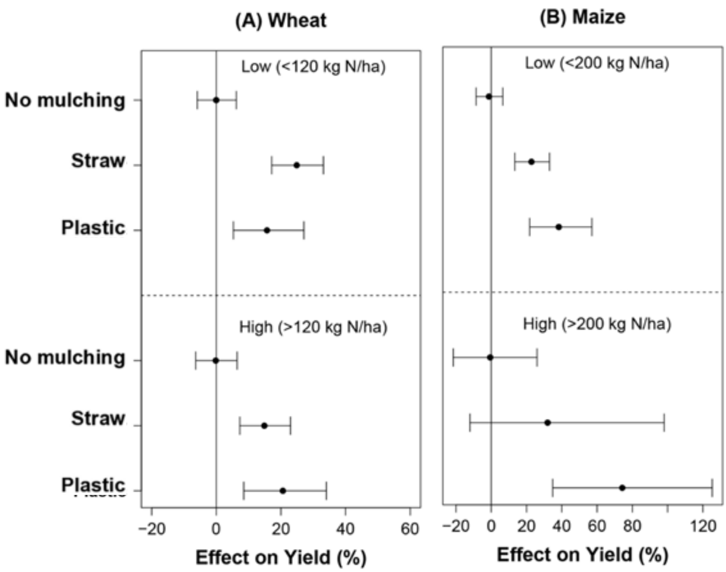


Figure 5. The effect of mulching on wheat (A) and maize (B) yields at different N input levels. Data were sub-grouped according to the 0.5 quantile value of the N input of each crop with plastic mulching treatments and displayed as low and high (from top to the bottom).

2.3.4. Effects of mulching on yields, WUE and NUE at different N input levels

The mulching effects were also affected by N input level. Again, the dataset was separated into two sub-datasets according to the 50th percentile value of the N input of each crop with plastic mulching treatments. The mean effect of straw mulching on wheat yield was 25% at low N input (<120 kg N ha^{-1}) and 15% at high N input level. For plastic mulching we observed opposite trends (Figure 5A). For maize, the effects of mulching was larger at high input level (>200 kg N ha^{-1}), but CIs were also larger at high N input. The mean effect of plastic mulching was 75% at high N input and was 40% at low N input (Figure 5B).

The mean effect of straw mulching on WUE of wheat was slightly larger at low N input (<120 kg N ha^{-1}). In contrast, the mean effect of plastic mulching on WUE of wheat was slightly larger at the high N input level, but the differences between low and high N input were rather small (Figure 6A). For maize, the mean effect of plastic mulching on WUE was 80% at high N input and halved at low N input (Figure6B).

The mean effects of mulching (~20%) on NUE of wheat did not largely differ between low and high N input (Figure 7A). For maize, the mean effect of plastic mulching on NUE was 78% at high N input level and also halved at low N input. The CIs of the mulching effects were larger at high N input level (Figure 7B).

2.3.5. Effects of mulching at different temperature

The effects of mulching were also affected by temperature. The mean seasonal temperature of maize growing season was higher than that of wheat. Interestingly, at low temperature (4.9 - 16.3 °C), the effects of plastic mulching in wheat yields were larger than that of straw mulching; whereas the opposite trend was found at high temperature (16.3 - 25.5 °C) (Figure 8A). In maize, the effect of straw mulching were much larger (60%) at low temperature (12.7 - 19.1 °C), and decreased to 18% at high temperature (19.1-30.4 °C). The mean effects of plastic mulching in maize yield remained around 60% at both low and high temperature (Figure 8B).

2.3.6. Effects of mulching at different soil organic matter content

The effects of mulching seemed not significantly affected by soil organic matter content (SOM). The mean effect of both straw and plastic mulching in wheat yield was ~18% (Figure 9A). For maize, the mean effect of straw and plastic mulching on yield was ~20 and 58%, respectively (Fig 9B). Soil organic matter content was mostly lower than 2% in our dataset, indicating relatively dry environment where water availability and temperature may be dominant factors. Furthermore, fertilization may also dilute the effects of SOM.

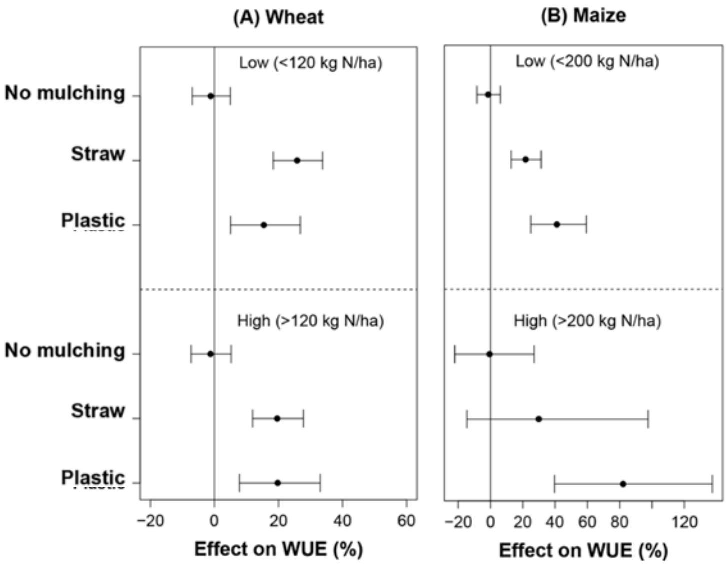


Figure 6. The effect of mulching on WUE of wheat (A) and maize (B) at different N input levels. Data were sub-grouped according to the 0.5 quantile value of the water input of each crop with plastic mulching treatments and displayed as low and high (from top to the bottom).

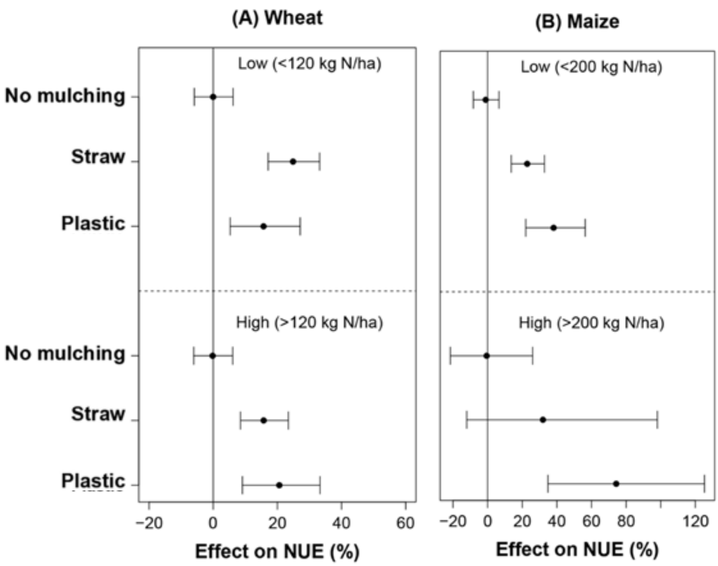


Figure 7. The effect of mulching on NUE of wheat (A) and maize (B) at different N input levels. Data were sub-grouped according to the 0.5 quantile value of the water input of each crop with plastic mulching treatments and displayed as low and high (from top to the bottom).

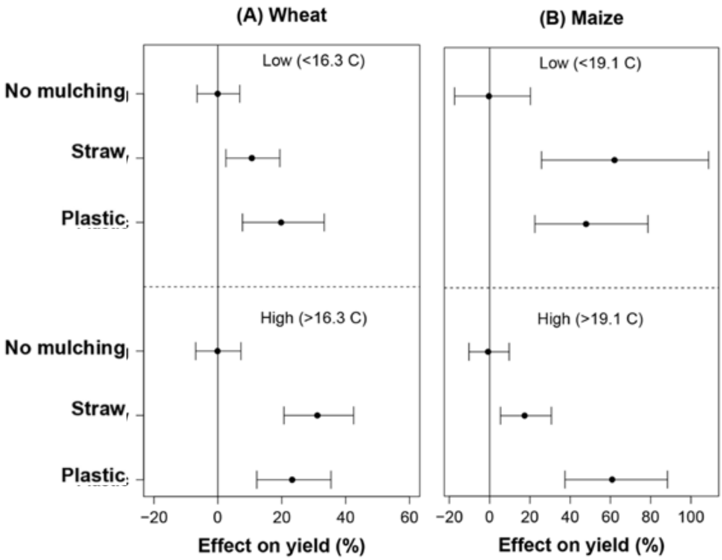


Figure 8. The effect of mulching on wheat (A) and maize (B) yields at different temperature. Data were sub-grouped according to the 0.5 quantile value of the seasonal mean temperature of each crop with plastic mulching treatments and displayed as low and high.

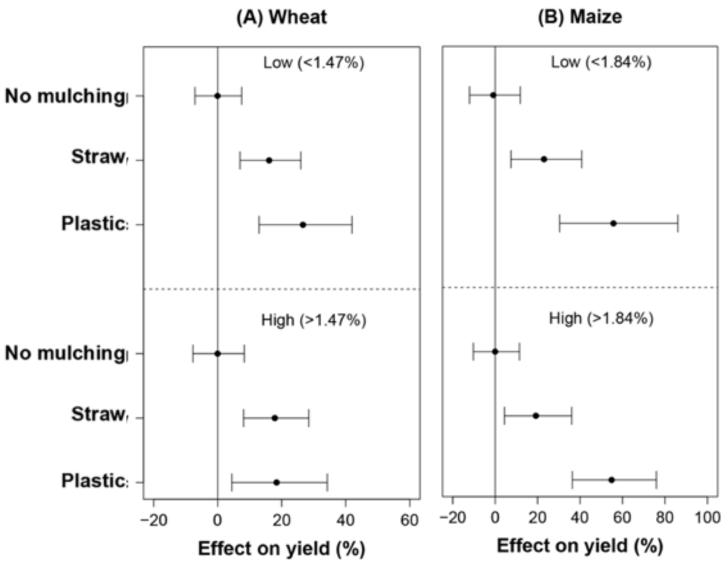


Figure 9. The effect of mulching on wheat (A) and maize (B) yields at different soil organic matter contents. Data were sub-grouped according to the 0.5 quantile value of the SOM of each crop with plastic mulching treatments and displayed as low and high.

2.3.7. Interactions between water and N inputs in yield, WUE and NUE

Results of the statistical analysis of the effects of mulching, water and N inputs and their interactions, as well as those of soil organic matter (SOM) and mean air temperature during the growing season, on yield, WUE and NUE are summarized in Tables 1, 2 and 3. Both straw mulching and plastic mulching had significant and positive effects on wheat and maize yields (Table 1). There were significant positive interactions between water and N inputs in wheat yield, indicating that the effect of N input increased with increased water input, and vice versa. However, the interactions between water and N inputs were not significant in maize yield, likely due to relatively high water availability for the maize growing season. Both wheat and maize yield significantly and positively responded to N input. Wheat yields were not significantly affected by SOM content and temperature; whereas maize yields were both positively related to SOM content and temperature.

WUE of wheat was negatively related to water input and positively to N input (Table 2). There were positive interactions between water and N inputs in WUE of wheat. WUE of maize was also negatively related to water (but not significantly) and positively to N inputs, but there was a negative interaction between water and N inputs, indicating that increases in water input reduced the positive effect of N on WUE. WUE of wheat and maize was not significantly related to SOM content and temperature.

NUE of wheat and maize were positively related to water input and negatively to N input (Table 3). There were negative interaction between water and N inputs in NUE of wheat and maize; however the interactive effects were not significant. The NUE of wheat and maize was significantly and positively related to SOM.

Table 1. The effects of multiple variables on wheat and maize yields.

Crop	Item†	Estimate	SD	DF	*t* value	*p* value	Sign.‡
Wheat	α (Intercept)	1.71	0.81	513.00	2.11	0.035	*
	β_1 (Plastic)	0.56	0.15	49.00	3.73	0.001	**
	β_1 (Straw)	0.46	0.10	49.00	4.61	0.000	***
	β_2 (SOM)	0.03	0.19	513.00	0.18	0.857	NS
	β_3 (Temperature)	0.01	0.04	513.00	0.12	0.905	NS
	β_4 (Water)	5E-04	0.00	513.00	0.77	0.445	NS
	β_5 (N)	6E-03	0.00	513.00	3.10	0.002	**
	β_6 (W*N)	2E-05	0.00	513.00	4.27	0.000	***
Maize	α (Intercept)	-10.45	3.40	725.00	-3.07	0.002	**
	β_1 (Plastic)	2.19	0.25	44.00	8.62	0.000	***
	β_1 (Straw)	0.80	0.19	44.00	4.09	0.000	***
	β_2 (SOM)	2.13	0.65	37.00	3.28	0.002	**
	β_3 (Temperature)	0.47	0.12	725.00	3.77	0.000	***
	β_4 (Water)	9E-04	0.00	725.00	1.14	0.256	NS
	β_5 (N)	9E-03	0.00	725.00	3.51	0.001	**
	β_6 (W*N)	-1E-06	0.00	725.00	-0.23	0.816	NS

†See formula (5) for explanation of the items. ‡ "***" means $p \le 0.001$, "**" means $0.001 \le p < 0.01$, "*" means $0.01 \le p < 0.05$ and "NS" means $p \ge 0.05$.

Table 2. The effects of multiple variables on WUE of wheat and maize.

Crop	Item†	Estimate	SD	DF	*t* value	*p* value	Sign.‡
Wheat	α (Intercept)	1.01	0.24	513.00	4.23	0.000	***
	$β_1$ (Plastic)	0.15	0.05	49.00	3.16	0.003	**
	$β_1$ (Straw)	0.15	0.03	49.00	4.66	0.000	***
	$β_2$ (SOM)	-0.01	0.06	513.00	-0.25	0.806	NS
	$β_3$ (Temperature)	-5E-03	0.01	513.00	-0.37	0.715	NS
	$β_4$ (Water)	-1E-03	0.00	513.00	-4.63	0.000	***
	$β_5$ (N)	2E-03	0.00	513.00	3.62	0.000	***
	$β_6$ (W*N)	4E-06	0.00	513.00	2.06	0.040	*
Maize	α (Intercept)	-0.85	0.82	725.00	-1.03	0.302	NS
	$β_1$ (Plastic)	0.61	0.06	44.00	9.86	0.000	***
	$β_1$ (Straw)	0.19	0.05	44.00	4.07	0.000	***
	$β_2$ (SOM)	0.31	0.16	37.00	1.97	0.056	NS
	$β_3$ (Temperature)	0.06	0.03	725.00	1.94	0.053	NS
	$β_4$ (Water)	-8E-05	0.00	725.00	-0.40	0.693	NS
	$β_5$ (N)	4E-03	0.00	725.00	6.36	0.000	***
	$β_6$ (W*N)	-4E-06	0.00	725.00	-3.96	0.000	***

†See formula (5) for explanation of the items. ‡ “***” means $p \leq 0.001$, “**” means $0.001 \leq p < 0.01$, “*” means $0.01 \leq p < 0.05$ and “NS” means $p \geq 0.05$.

Table 3. The effects of multiple variables on NUE of wheat and maize.

Crop	Item†	Estimate	SD	DF	*t* value	*p* value	Sign.‡
Wheat	α (Intercept)	59.41	10.51	470.00	5.65	0.000	**
	$β_1$ (Plastic)	5.53	1.72	49.00	3.22	0.002	**
	$β_1$ (Straw)	5.47	1.09	49.00	5.01	0.000	***
	$β_2$ (SOM)	7.99	2.44	470.00	3.27	0.001	**
	$β_3$ (Temperature)	-8E-01	0.53	470.00	-1.60	0.110	NS
	$β_4$ (Water)	5E-02	0.01	470.00	4.55	0.000	***
	$β_5$ (N)	-3E-01	0.03	470.00	-9.40	0.000	***
	$β_6$ (W*N)	-1E-04	0.00	470.00	-1.34	0.182	NS
Maize	α (Intercept)	-1.18	25.97	654.00	-0.05	0.964	NS
	$β_1$ (Plastic)	18.35	3.30	43.00	5.55	0.000	***
	$β_1$ (Straw)	6.20	2.67	43.00	2.32	0.025	*
	$β_2$ (SOM)	10.22	4.43	36.00	2.31	0.027	*
	$β_3$ (Temperature)	1.59	0.97	654.00	1.64	0.102	NS
	$β_4$ (Water)	0.01	0.01	654.00	1.53	0.128	NS
	$β_5$ (N)	-1E-01	0.03	654.00	-3.59	0.000	***
	$β_6$ (W*N)	-5E-05	0.00	654.00	-1.01	0.312	NS

†See formula (5) for explanation of the items. ‡ “***” means $p \leq 0.001$, “**” means $0.001 \leq p < 0.01$, “*” means $0.01 \leq p < 0.05$ and “NS” means $p \geq 0.05$.

2.4. Discussion

Our study provides a systematic and quantitative analysis of the mulching effects on yields, WUE and NUE of wheat and maize as observed in published experimental studies across the world. We focused on wheat and maize because of their importance in the global food production and food security, in total these two crops accounts for 70% of the world cereal production(FAO, 2015b). We excluded rice because rice is mainly grown as paddy rice with flood irrigation, and mulching on rice has not been extensively studied and reported as wheat and maize.

We found that straw mulching significantly increased wheat and maize yields (as well as WUE and NUE) by 20%, and plastic mulching by up to 60% (Figure 1). The effects of plastic mulching were larger than straw mulching, and the effects were larger in maize than in wheat. Moreover, although the patterns of the mulching effects remain complicated, a significant fraction of the variations in the mulching effects can be related to water and N input levels (Figure 2-6), and to mean air temperature during the growing season of wheat and maize (Figure 7). The effects of mulching tended to decrease with increasing water input but increased with increasing N input (Figure 2-6). The mulching effect was largest for plastic films at relatively low water input levels.

Straw mulching commonly reduces soil temperature and plastic mulching commonly increases soil temperature. A decrease of soil temperature by straw mulching may delay the germination and development of winter wheat, especially in temperate regions, which may reduce grain yield by 5-7%(Chen et al., 2007). Plastic mulching are more effective than straw mulching in terms of reducing evaporation and increasing soil temperature, which may favour early seed generation and root growth, especially in the case of winter wheat(Gan et al., 2013; Li et al., 2013b). This may explain why plastic mulching performs better for wheat at relatively low temperature. However, in tropical regions, straw mulching may modulate soil temperature in such a way that crop yield increases(Chakraborty et al., 2010; Chakraboyty et al., 2008). This pattern was also shown in Figure 7A. However, for maize, the effects of plastic mulching were significantly larger that straw mulching at high temperature (Figure 7B), likely related to more effective reduction in soil evaporation by plastic mulching, compared to straw mulching.

Overall, the mulching effects were larger in maize, likely because maize is a C4 crop and more efficient in photosynthesis than wheat (C3 crop)(Long et al., 2006). Maize yields were often higher than wheat yields; maximum maize yield were 15 ton ha^{-1} and maximum wheat yields were only 8 ton ha^{-1} in our dataset. Large effects of mulching in maize could be related to the larger yield potential of maize. Furthermore, maize often has a much lower planting density (65,000 to 85,000 plants ha^{-1}) than wheat (>100,000 plants (tillers) ha^{-1}). Maize often grows during the summer period when the evaporative demand is high, whereas wheat grows during winter and early summer. As a consequence, mulching may reduce evaporation more in maize than in wheat.

Furthermore, the positive effect of SOM in maize yields likely reflects either an increased availability of N and/or other nutrients through the mineralization of SOM, especially at high temperature, because SOM is often positively related to N mineralization rate and also soil water holding capacity(Carter, 2002; Haynes and Naidu, 1998; Hudson, 1994; Li et al., 2004; Schmidt et al., 2011). Wheat often grows at relative low temperature and has much longer growing season. Therefore, the effects of SOM and temperature may have less influence in wheat yields.

Our results suggest that soil mulching may contribute to closing yield gaps between attainable and actual yields, and to increasing water and N use efficiencies. Mueller et al. (2012) estimated that actual grain yields are often only 30 to 80% of the attainable yield, i.e., the yield obtained in well-managed field trials. These yield gaps may be narrowed down by increased inputs of water and nutrients and improved crop husbandry, but also by reducing the evaporative demand through mulching as indicated by this study. However, mulching may also have negative effects, depending on actual environmental conditions. Results of our study indicate that mulching effects depend on water and N input levels, mean air temperature during the growing season, and crop type. To be able to cash the full benefits of mulching, extension services, the plastic supplying industries and farmers must know the relationships between mulching effects, crop type and environmental conditions. Recently, progress has been made in the optimization of the time and methods (when and how) of mulching. For example, Bu et al. (2013) concluded that plastic film mulching was more effective than straw and/or gravel mulching in counteracting water limitations and low temperatures in the Loess Plateau in China. Liu et al. (2014b) reported that removing the film at the silking stage decreased the plant senescence rate and slightly increased the final kernel number and weight, thus increasing the grain yield of maize by 0.6 to 1.2 ton ha^{-1}. These results clearly indicate the importance of site-specific knowledge and management of mulching.

Thanks to governmental subsidies, plastic mulching and straw mulching have been widely adopted in many regions in the world, especially in China and India. For example, the Comprehensive Subsidy on Agricultural Inputs in China has increased from ¥12 billion in 2006 to ¥71.6 billion in 2010. As a result, the area of plastic film coverage reached ~20 million ha, and the amount of plastic film used reached 1.25 million tons in 2011(FAO, 2012). However, production of plastic films is energy demanding, and residues of plastic mulching may contribute to soil and environmental pollution; plastic residues have accumulated in soils, trees and ditches in some regions. The practice of plastic mulching may not be sustainable without proper collection and recycling of the residues of these plastic films. Alternatively, plastic mulching could be made from biodegradable plastic (Liu et al., 2014a).

Plastic mulching is also being tested in some regions in Africa. The potentials are relatively large, as the effects of covers on yield, WUE and NUE can be large in low water and N input areas. The question is whether plastic films have a future without subsidies, without site-specific and crop-specific guidelines, and without a proper mechanism for the collection and recycling of the residues. Use of plastic films in Africa is limited by the financial cost (and/or lack of governmental subsidies), but also by the cost of the distribution of the plastic films and the collection and recycling of the plastic residues. Straw mulching is limited by the availability of straw in the field, which is often being used also for feeding ruminants or as biofuel. This is often the case for small household farmers in Africa(Giller et al., 2011). Alternative sources of mulches may be provided by pruning from agroforestry trees(Coulibaly et al., 2014; Fagerstrom et al., 2002), which require extra labour costs.

Evidently, straw and plastic mulching is not without difficulties. Governmental subsidies and extension services have stimulated its use in practice, and the results of our study shows that these mulching practices can have significant yields advantages. However, labour costs are relatively high, straw mulches not always available and residues of plastic mulching not easily collected and recycled. These side-effects as well as the site-specificity of the mulching effects must be included in the guidelines for mulching practices.

2.5. Conclusions

Straw and plastic mulching can significantly increase wheat and maize yields, and also WUE and NUE by up to 60%. Mean effects were larger for plastic films than straw mulching, and larger for maize than wheat. The effects of mulching depended on water and N input levels, temperature and to some extent also SOM. The effects of mulching on crop yields tended to increase with a decrease in the availability of water but increased with N input.

Results of the statistical analysis indicated that yields of maize and wheat were related to water and N inputs and/or their interactions, irrespective of mulching practices. Significant interactions between water and N in yields, WUE and NUE also suggest that many regions are still water and N limited where soil mulching may contribute to closing the yield gap between attainable and actual yields.

Though soil mulching has clear positive and rather consistent effects on yields, WUE and NUE of wheat and maize, there are also clear trade-offs. Straw mulching is limited by the availability of straw in the field, which is often being used also for feeding ruminants or as biofuel. Use of plastic films is limited by the financial cost, but also by the cost of the collection and recycling of the plastic residues. Therefore, guidelines for mulching practices should consider the effects of water and N input levels, crop type and the side-effects of mulching.

Acknowledgements

We thank Yang Yu and Yong Hou from Wageningen University and Research Centre for many useful discussions on the meta-analysis.

Wei Qin
Baoliang Chi
Oene Oenema

Chapter 3

Long-term monitoring of rainfed wheat yield and soil water at the Loess Plateau reveals low water use efficiency

This chapter has been published as:
Qin, W., Chi, B.L., Oenema, O., 2013. Long-Term Monitoring of Rainfed Wheat Yield and Soil Water at the Loess Plateau Reveals Low Water Use Efficiency. Plos One 8.

Abstract

Increasing crop yield and water use efficiency (WUE) in dryland farming requires a quantitative understanding of relationships between crop yield and the water balance over many years. Here, we report on a long-term dryland monitoring site at the Loess Plateau, Shanxi, China, where winter wheat was grown for 30 consecutive years and soil water content (0-200 cm) was measured every 10 days. The monitoring data were used to calibrate the AquaCrop model and then to analyse the components of the water balance. There was a strong positive relationship between total available water and mean cereal yield. However, only one-third of the available water was actually used by the winter wheat for crop transpiration. The remaining two-thirds were lost by soil evaporation, of which 40 and 60% was lost during the growing and fallow seasons, respectively. Wheat yields ranged from 0.6 to 3.9 ton/ha and WUE from 0.3 to 0.9 kg/m^3. Results of model experiments suggest that minimizing soil evaporation via straw mulch or plastic film covers could potentially double wheat yields and WUE. We conclude that the relatively low wheat yields and low WUE were mainly related to (i) limited rainfall, (ii) low soil water storage during fallow season due to large soil evaporation, and (iii) poor synchronisation of the wheat growing season to the rain season. The model experiments suggest significant potential for increased yields and WUE.

3.1. Introduction

Water scarcity is a growing global concern (de Wit, 1958; Hoekstra and Mekonnen, 2012; Marschner, 1995; Piao et al., 2010). For rainfed agriculture, this pressure may become more severe under climate change due to the expected more erratic rainfall and longer dry spells (Hanjra and Qureshi, 2010; IPCC, 2007; Marris, 2008; Milly et al., 2008). Currently, rainfed agriculture covers 80% of the world's cultivated land and accounts for 60% of crop production (UNESCO, 2009). However, crop yield and water use efficiency (WUE) are often low in rainfed agriculture, especially in arid and semi-arid areas due to, for example, degraded soils, erratic rainfall and poor water management (Rockstrom et al., 2010). Many of these areas in Africa and Asia face also rapid population growth. Hence, there is a pressing need to increase crop yields and WUE in rainfed agriculture (Godfray et al., 2010; Sachs, 2008; Smil, 2000; Tilman et al., 2002; Vitousek et al., 1997).

Water use efficiency is commonly defined as crop yield over evapotranspiration (ET), where ET is the sum of soil evaporation (E) and crop transpiration (T) (Kang et al., 2002; Siahpoosh and Dehghanian, 2012; Zhang et al., 1999; Zhang et al., 2006). The latter (T) is a direct consequence of crop production, while E is 'unproductive' water loss. The central question for rainfed agriculture in arid and semi-arid regions is 'how to transform unproductive water loss (E) into productive water use (T)'. Unfortunately, the partitioning between E and T is often not well-known, due to difficulties and high cost in distinguishing E and T in the field. As a result, water use of crops is commonly reported as evapotranspiration (ET) (Kang et al., 2002; Zhang et al., 1999; Zhang et al., 2010). This lack of information makes it difficult to assess how much of the evaporative water loss can be used for increasing yields by appropriate measures.

Crop growth simulation models have the potential of providing more comprehensive insights into the functioning of soil-crop systems, and can be helpful to explore options for increasing yield and WUE (de Wit and Vankeulen, 1987; Steduto et al., 2009; Whisler et al., 1986). These models though are simplified representations of parts of reality and therefore require testing in the real world. Fortunately, numerous field studies have examined the effect of water availability, with or without irrigation treatments, on crop yield and WUE (Kang et al., 2002; Siahpoosh and Dehghanian, 2012; Zhang et al., 1999; Zhang et al., 2010; Zhang et al., 2006). In principle, these results can be used to calibrate and test the crop growth simulation models. However, most of these field studies are short-term (2-5 years) and focus on the growing season only, largely ignoring the water balance during the fallow season. Furthermore, crop yields and WUE show large variations due to differences in soils, climate conditions and crop husbandry practices. For example, in the North China Plain, annual precipitation ranges from 400 to 650 mm and wheat grain yields roughly range from

1 to 3 ton/ha/year under rainfed conditions. With 200 to 300 mm of irrigation, grain yield can be increased by 60 to 100% and WUE can be increased by 20 to 40% (Zhang et al., 1999). Globally, WUE of wheat shows even larger variation ranging from approximately 0.2 to 1.8 kg/m^3 (Zwart et al., 2010). Evidently, this wide range suggests considerable scope for improvement, but the underlying causes of WUE is not always well-known and irrigation water is not available on most places.

The study reported here has the objectives (i) to calibrate a water-driven crop growth model on the basis of monitoring data from a long-term field experiment with rainfed winter wheat, (ii) to analyse the components of the water balance of this field, and (iii) to explore the potential for increasing crop yield and WUE through model experiments. The field experiment was situated in the dryland of the Loess Plateau, Shanxi, China. Winter wheat was grown for 30 consecutive years and soil water content (0-200 cm) was measured every 10 days. The FAO AquaCrop model was chosen as simulation model because it is a water-driven crop growth model that can separately calculate E and T, and simulates the final crop yield as function of water use (Steduto et al., 2012; Steduto et al., 2009). The AquaCrop model uses canopy ground cover as the basis to calculate T and to separate E and T. Crop yield is then calculated as the product of biomass and harvest index (HI). The principles and modules of the AquaCrop model are well-documented in a series of AquaCrop publications (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2012; Steduto et al., 2009; Todorovic et al., 2009). Compared to some other crop growth models, AquaCrop requires relatively few input parameters (Steduto et al., 2009; Todorovic et al., 2009). Such a limited number of input parameters facilitates model calibration and utilization for different crops and under different management strategies (Abedinpour et al., 2012; Andarzian et al., 2011; Araya et al., 2010b; Dominguez et al., 2011; Farahani et al., 2009; Geerts et al., 2009a; Geerts et al., 2009b; Hsiao et al., 2009; Raes et al., 2009; Salemi et al., 2011; Steduto et al., 2009).

3.2. Materials and methods

3.2.1. Site information

The long-term monitoring site is located in Beizhang, Linyi county in Shanxi province on the Loess Plateau (35° 9’ 3.83” N, 110° 34’ 25.40” E, Altitude: 491 m) in China. The authority is Dryland Agriculture Research Centre, Shanxi Academy of Agricultural Sciences. We have the permission to conduct the study on this site. We confirm that the field studies did not involve endangered or protected species.

The site has a semi-arid climate with extensive monsoonal influence, which is dry and cold in winter, rainy and hot in summer. Rainfall in June to September accounts for more than 70% of annual rainfall. Average annual rainfall was 517 mm in the period of 1980 – 2010 with large annual variations, from a minimum of 331 mm to a maximum of 832 mm. Mean annual sunshine duration is 2270 h, annual average temperature 13.5 °C and mean annual potential evaporation is 1340 mm. The soil is a typical Loessial soils (Calcic Luvisols) of the Loess Plateau (ISS-CAS, 2012; IUSS, 2006; Wang et al., 2007; Wang et al., 2012b). Soil slope is <1% and soil texture is silt loam, with a small proportion of clay. The soil was rather homogeneous in texture and key physical properties (Table 1). Maximum soil water holding capacity was a significant fraction of the total annual rainfall (Table 2).

The top soil (30 cm) contained 5.8 g/kg of organic C and 0.55 g/kg of total N. Mean available N, P and K were 63 mg/kg, 14 mg/kg and 142 mg/kg, respectively, in 2007. Since 1983, mean available P and K have been increased by 7 mg/kg and 10 mg/kg, respectively (Xie et al., 2011). Total soil organic C was measured by dry combustion combined with elemental C analysis. Total N was measured by Kjeldahl method. Soil mineral N was extracted with 1 M KCl and analysed by the cadmium reduction method. Available P was extracted with 0.5 M $NaHCO_3$. Available K was extracted with 1.0 M NH4OAc.

3

3.2.2. Experimental design and measurements

The long-term crop yield and soil moisture monitoring experiment started in 1980. There were no experimental treatments. The size of the field is 0.5 ha. Winter wheat was planted each year between 25 September and 5 October, depending on the actual climate and soil water conditions. Sowing rate was 150 kg seed/ha. The growing period of the winter wheat is approximately 245 days (from 1 October to 1 June of the next year). The fallow season is about 120 days (from 2nd June to 30th September) (Figure 1). Local bred cultivars (Jinmai) were used for all years. Information about crop parameters is listed in Table 3. Fertilizers were applied at planting at a rate of 127.5 kg/ha of N as urea and 90 kg/ha of P_2O_5 as superphosphate, for all years. At harvest, grain yields were measured in 5 random plots (2 m^2 per plot) selected from two diagonal lines of the field. Dry matter content of grain and straw was measured at the laboratory after drying at 70 °C. Soil water contents were measured in 16 different layers up to 2 m depth every 10 days by using the gravity method. The top 10 cm was sampled in 5 cm intervals. From 0.1 to 1 m, samples were taken at 10 cm intervals, and from 1 to 2 m at 20 cm intervals (Figure 2). Each sample consisted of 5 subsamples, taken randomly on two diagonal lines across the field. Observations during soil sampling over years revealed that spatial variations in soil profile were small.

Table 1. Soil physical properties for different layers up to 200 cm.

Soil layer	Bulk density	Field Capacity	Wilting point	Texture, (particle size, µm in %)			
cm	g/cm3	v/v in %	v/v in %	>63µm	63 - 20µm	20 - 2µm	<2µm
5	1.34	31.4	6.8	7.5	41.0	32.4	19.2
10	1.34	31.4	6.8	7.5	41.0	32.4	19.2
20	1.39	32.9	8.5	8.3	41.8	31.2	18.8
30	1.43	34.5	8.4	6.9	44.3	30.1	18.7
40	1.39	33.6	7.0	6.9	44.3	30.1	18.7
50	1.43	33.6	7.3	6.9	44.3	30.1	18.7
60	1.39	32.8	7.0	4.5	40.5	31.4	23.6
70	1.36	30.9	7.2	4.5	40.5	31.4	23.6
80	1.25	27.6	6.9	4.5	40.5	31.4	23.6
90	1.28	27.9	8.3	4.5	40.5	31.4	23.6
100	1.32	28.3	8.2	4.5	40.5	31.4	23.6
120	1.30	29.3	7.8	3.0	43.4	34.4	19.2
140	1.32	29.7	7.9	3.0	43.4	34.4	19.2
160	1.31	29.5	7.9	2.4	40.4	38.7	18.5
180	1.32	29.7	7.9	2.4	40.4	38.7	18.5
200	1.32	29.7	7.9	2.4	40.4	38.7	18.5

Table 2. Soil moisture holding capacity of the soil profile (0-200 cm).

	Total water, mm (mm)	Available water, mm (mm)	In volume, % (v/v)
Saturation	860	711	43
Field capacity	596	447	30
70% FC	462	312	23
50% FC	373	223	19
Wilting point	149	0	8

Water balance and WUE estimations

Mean monthly rainfall data were collected at a near-by meteorological station (Linyi station, 35° 10’ 7.02” N, 110° 46’ 44.59” E, Altitude: 441 m), which is 25 km away from the experimental field. The water balance for both fallow and crop growing seasons reads as follows:

$$R + I \pm \Delta S = E + T + R_r + P_e \quad (1)$$

where R is rainfall, I is irrigation, ΔS is the change of soil water content, E is soil evaporation, T is crop transpiration, R_r is runoff and P_e is percolation. All units are presented in mm or in m^3/ha.

Irrigation was not applied in this study. Furthermore, runoff and percolation (leaching) were small and disregarded. Hence, the water balance of the fallow seasons was simplified to:

$$R \pm \Delta S = E \tag{2}$$

The water balance of the growing season was simplified to:

$$R \pm \Delta S = E + T \tag{3}$$

We used formula (2) and the recorded rainfall and soil water content data to calculate evaporation during the fallow season and formula (3) to calculate ET during the growing season. The partitioning of E and T was done by the AquaCrop model.

Water use efficiency (WUE, kg/m^3) was calculated as:

$$WUE = grain\ yield\ /\ ET \tag{4}$$

where ET is evapotranspiration (mm), the sum of E and T during the growing season.

3.2.3. Calibration and validation of the AquaCrop model

The FAO AquaCrop model is a water-driven crop growth model for the simulation of crop biomass and yield as function of water availability (Steduto et al., 2012; Steduto et al., 2009). AquaCrop requires 4 main sets of input data, i.e. climate data (rainfall, minimum and maximum temperature and reference evapotranspiration (ETo)), crop parameters, soil data and field management data. Climate data were collected from a near-by meteorological station (Linyi station, 35° 10’ 7.02” N, 110° 46’ 44.59” E, Altitude: 441 m), which is 25 km away from the experimental field. ETo was calculated by FAO Penman-Monteith equation as described in Allen et al. (1998a). Soil data (Tables 1 and 2) and field management data were derived from measurements and from recordings at the monitoring site. Crop data and parameters were derived from measurements, literature (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2012; Steduto et al., 2009) and by calibration (Table 3).

The objective of calibration and validation was to achieve the best match between simulated outputs and monitoring data (soil moisture and crop yield) for all 30 years, using a common procedure (Abedinpour et al., 2012; Andarzian et al., 2011; Araya et al., 2010b; Dominguez et al., 2011; Farahani et al., 2009; Geerts et al., 2009a; Geerts et al., 2009b; Hsiao et al., 2009; Salemi et al., 2011). We randomly selected 15 years’ data from the monitoring field for calibration and used the other 15 years’ data for validation of the calibrated model. In the calibration step, we used the year-specific climate, soil and initial soil water data as fixed input data. Then we adjusted some of the crop parameters (see Table 3), based on our understanding of crop growth, development and crop responses to water deficits, until the differences between simulated output and monitoring data were minimal. We repeated this process for all selected 15 years and ultimately obtained a satisfactorily index of agreement (d=0.92). Then, the calibrated model was validated with the other 15 years' data, and again obtained an acceptable index of agreement (d=0.93).

3.2.4. Data analysis

The root mean square error (RMSE) (Willmott, 1982) has been widely used to evaluate the performance of a model (Dominguez et al., 2011; Hu et al., 2008a; Hu et al., 2010; Mkhabela and Bullock, 2012; 2005). However, Willmott and Matsuura (2005) pointed out that, compared to RMSE, the mean absolute error (MAE) is a better indicator and therefore the evaluation of model performance should be based on the MAE. In this study, we used the MAE, the mean bias error (MBE) and the Willmott index of agreement (d) to evaluate the model performance.

The MAE measures the weighted average magnitude of the absolute errors and was calculated as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |\,\mathrm{Mi} - \mathrm{Oi}\,| \tag{5}$$

where n is the number of observations, Mi is the modelled yield or soil water content and Oi is the observed yield or soil water content.

The MBE indicates whether the model is under or over predicting the observed values and also indicates the uniformity of error distribution. Positive MBE values indicate over prediction, negative values indicate under prediction and a value of zero indicates equal distribution between negative and positive values. The MBE was calculated as follows:

$$MBE = \frac{1}{n}\sum_{i=1}^{n} (\mathrm{Mi} - \mathrm{Oi}) \tag{6}$$

The Willmott index of agreement (d) (Willmott, 1982) has values ranging from 0 to 1. A value close to 1 suggests a good model performance. The agreement index d was calculated as follows:

$$d = 1 - \frac{\sum_{i=1}^{n} \left(\mathrm{Mi} - \mathrm{Oi}\right)^2}{\sum_{i=1}^{n} \left(\left|\mathrm{Mi} - \bar{\mathrm{O}}\right| + \left|\mathrm{Oi} - \bar{\mathrm{O}}\right|\right)^2} \tag{7}$$

where $\bar{\mathrm{O}}$ is the average value of the observed yield or soil water content.

3.2.5. Model experiments

To investigate the potentials of minimizing soil evaporation so as to increase crop yield and WUE, we set up six model experiments as follows:

Experiment 1 (E1): Reference A; winter wheat was planted at 50% of field capacity (FC) (low soil water content)

Experiment 2 (E2): E1 + organic mulch (straw)

Experiment 3 (E3): E1 + plastic film cover

Experiment 4 (E4): Reference B; winter wheat was planted at 70% of FC (high soil water content)

Experiment 5 (E5): E4 + organic mulch (straw)

Experiment 6 (E6): E4 + plastic film cover

In the model experiments, we used E1 and E4 as references to simulate crop growth under relatively low (with 50% FC) and high (with 70% FC) soil water content at winter wheat seeding (Table 2). The range from 50 to 70% FC largely represented the initial soil water content for the planting period. The low value is representative for no water harvesting, and the high values is representative for water harvesting during the fallow period via mulching and/or covers. Model experiments E2 and E5 aimed at testing the effects of organic mulch during the growing season, and experiments E3 and E6 aimed at testing the effects of plastic film during the growing season on crop yield and water balance. The effectiveness of the soil evaporation reduction by organic mulch and plastic film cover during the growing season were estimated at 50 and 90%, respectively, which are default values of the AquaCrop model (Steduto et al., 2012). However, since plastic film will cover only about 80% of the wheat planted field, the overall soil evaporation reduction by plastic film was set at 72%. In practice, the plastic film covers are used for the growing season only and destroyed or removed after harvesting the crops. We ran these six experiments for the period of 1980-2010.

3.3. Results

3.3.1. Patterns of monthly rainfall and soil water content

Most of the rainfall occurs in the summer from June to September, accounting for more than 70% of the total annual rainfall while winter wheat was seeded in the end of September or beginning of October, and harvested in the end of May or beginning of June. Hence, most of the rain fell when wheat had matured already, i.e., during the fallow period. Therefore, the growing season of winter wheat was poorly synchronized to the rain season. On the other hand, due to concentrated rainfall in

June to September, mean soil water content in the upper two metre was highest in October when winter wheat was seeded. Thereafter, the soil water content gradually decreased, due to soil evaporation and crop transpiration. Mean soil water content was lowest in June, at the beginning of the rain season when the winter wheat was harvested (Figure 1).

The changes of the soil water content (for 16 layers in the upper 2 meter of the soil) during the fallow and growing seasons are shown in Figure 2. The changes in water content in the fallow season mirror the changes during the growing season, i.e. water stored in the soil during the fallow season largely equalled to soil water depletion during the growing season. The soil water changes for fallow season were calculated as the soil water content of October deducted by that of June. Similarly, the soil water changes for growing season were calculated as the soil water content of June deducted by that of October in the previous year. Soil water content mostly changed in the top 1 m, accounting for 70% of total soil water change (±120mm) (Figure 2). We cannot exclude that some of the seasonal variations are caused by slight spatial variations in soil characteristics.

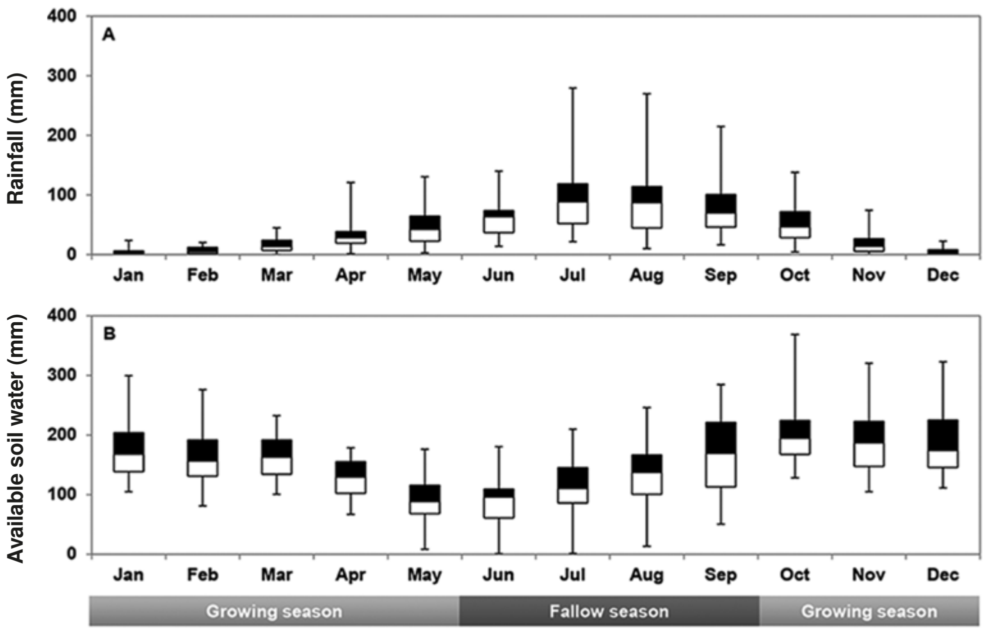


Figure 1. Monthly rainfall and available soil water during the period of 1980 - 2010. (A: monthly rainfall distribution; B: monthly available water content) Black and white boxes show 75 and 25% percentile values. Whiskers show maximum and minimum values (the same applies to other figures). The growing season of winter wheat was 245 days from 1st Oct. to 1st Jun. of the next year, highlighted in green bar. Fallow season was 120 days from 2nd Jun. to 30th Sep., highlighted in red bar.

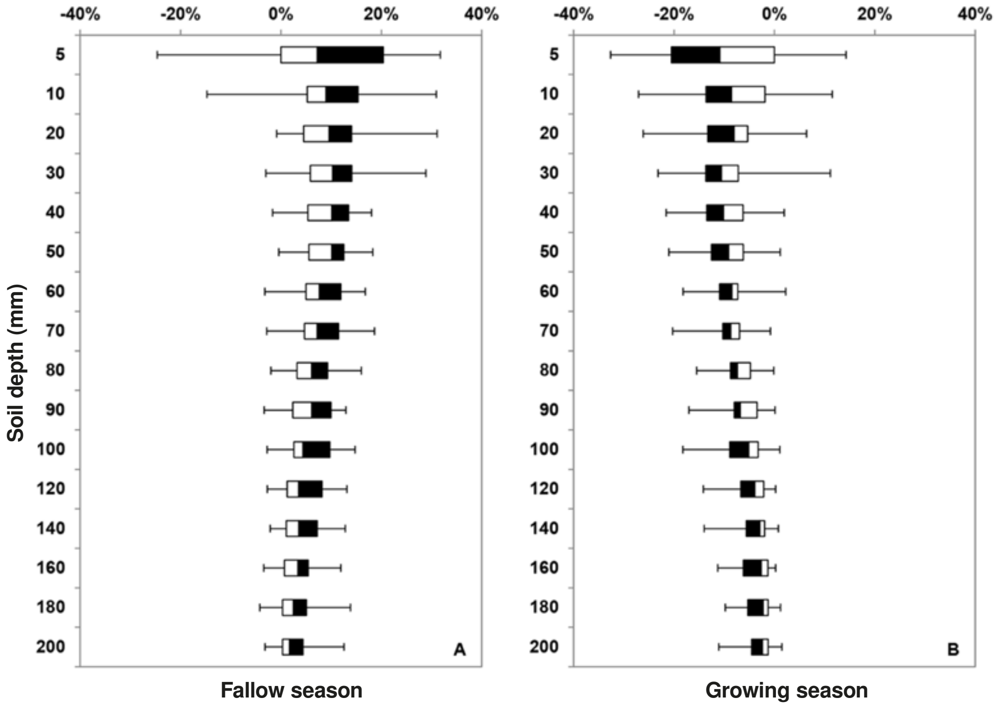


Figure 2. Changes in soil water content in the upper 2 meter of the soil during the period of 1980 - 2010. A: water stored in the upper 2 meter during the fallow season, presented in positive percentage (in volume, v/v); B: water depletion in the upper 2 m during the growing season, presented in negative percentage (in volume, v/v).

3.3.2. Model calibration and performance

The AquaCrop model was calibrated using the climate data, soil data, field management data and monitoring data. The full set of crop parameters is listed in Table 3. The performance of the model on the simulated crop yield and soil water balance is shown in Figure 3. The relationship between observed and modelled grain yield of the calibrated model for the second set of 15-years data (validation step) was almost as good as for the whole set of data (not shown). For the 30 years' data, the relationship between observed and modelled grain yield had a correlation coefficient of (R^2) of 0.77, and the index of agreement (d) was 0.93 (Figure 3A). Similarly, the relationship between observed and modelled soil water content showed a R^2 of 0.78 and an index of agreement (d) of 0.93 (Figure 3B). Mean absolute errors (MAE) were 311 kg/ha and 25 mm, respectively. Mean bias errors (MBE) were -168 kg/ha and -12 mm in simulating yields and soil water balance, respectively, suggesting that the model slightly underestimated grain yields and soil water contents by 8 and 9%, respectively. We conclude that the performance of the AquaCrop model was acceptable for doing further simulations.

Table 3. Full set of crop parameters used in this study.

Parameters	Contents and values	Source
Crop development	in calendar days	
From sowing to emergence	7 days	Field observation
From sowing to max. canopy	200 days	Field observation
From sowing to flowering	200 days	Field observation
From sowing to senescence	210 days	Field observation
From sowing to maturity	245 days	Field observation
Length for building up Harvest Index (HI)	44 days	Field observation
Duration of flowering	5 days	Field observation
Plant density	300 plants/m^2	Field observation
Sowing rate	150 kg seed/ha	Field observation
1000 seed mass	40 g	Field observation
Germination rate	80%	Field observation
Max. root depth	2 m	Field observation
Reference HI	42%	Field observation
Max HI	48%	Field observation
Crop water productivity	15g/m^2	Calibrated
Canopy development		
Initial canopy cover	4.5%	Field observation
Canopy expansion	2.9%/day	Calculated by AquaCrop
Max. canopy cover	90%	Field observation
Canopy decline	7.2%/day (39 days)	Calculated by AquaCrop
Thresholds temperatures		
Base temperature for biomass production	0 °C	Calibrated
Upper temperature for biomass production	26 °C	Calibrated
Range of cold stress for biomass production	0 - 14 °C	Calibrated
Range of cold stress for pollination	4-9 °C	Calibrated
Range of heat stress for pollination	32 - 37 °C	Calibrated
Water extraction pattern throughout the root zone		
Upper 1/4 (0-0.5m)	40%	Calibrated
Second 1/4 (0.5-1m)	30%	Calibrated
Third 1/4 (1-1.5m)	20%	Calibrated
bottom 1/4 (1.5-2m)	10%	Calibrated
Water stresses		
Canopy expansion	Moderately tolerant (upper = 0.25, lower = 0.65, shape factor = 5)	Calibrated
Stomatal closure	Extremely sensitive (upper=0.25, shape factor = 2.5)	Calibrated
Early canopy senescence	Tolerant (upper = 0.75, shape factor =2.5)	Calibrated
Aeration stress	Moderately tolerant (5 vol%)	Calibrated
Evapotranspiration		
Soil evaporation coefficient	Effect of canopy shelter in late season = 50%	AquaCrop default value
Crop transpiration coefficient	1.1 (reduction with age = 0.15%/day)	AquaCrop default value
Fertilities stresses	Not considered	AquaCrop default value

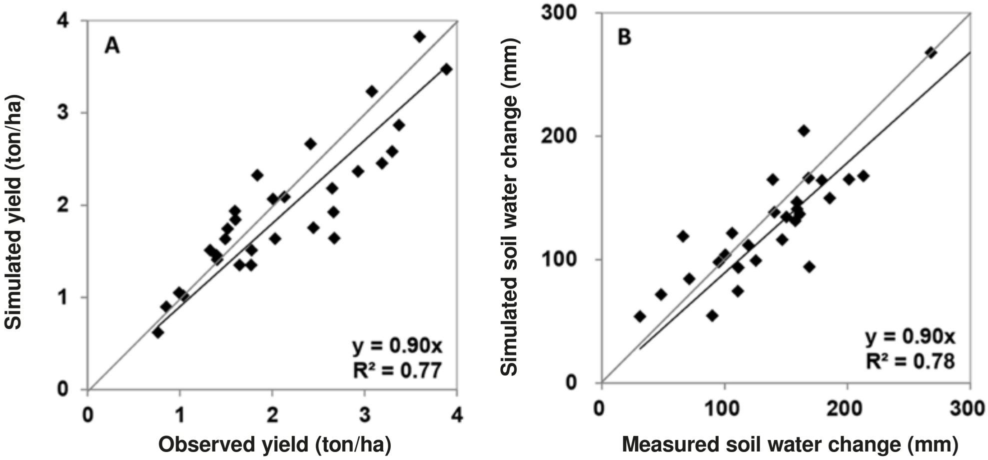


Figure 3. The AquaCrop Model simulations on yield (A) and soil water change (B). Diagonal lines represent 1:1 lines.

3.3.3. Water balance and partitioning of E and T

AquaCrop was used to estimate soil evaporation and crop transpiration, and the water balance for both fallow and growing seasons during the period 1980 – 2010 (Figure 4). There was only a very marginal change in soil water content when considering the water balance of the total season (fallow + growing season) over the 30 years' period; total rainfall was nearly equal to the sum of soil evaporation and crop transpiration. Crop transpiration accounted for approximately one-third of total seasonal rainfall. The remaining two-thirds were assumed to be lost by soil evaporation (Figure 4A), but we cannot exclude that a small fraction of this evaporative loss was actually lost by leaching and/or runoff. Mean rainfall in the fallow season was 323 mm, of which 207 mm (64%) was lost by soil evaporation and 116 mm (36%) was stored in the soil (Figure 4B). During the growing season, mean crop transpiration was 185 mm (57%) and soil evaporation was 137 mm (43%), of which rainfall and soil moisture contributed 194 (60%) and 128 mm (40%), respectively (Figure 4C). Mean rainfall of the growing season was slightly larger than mean crop transpiration.

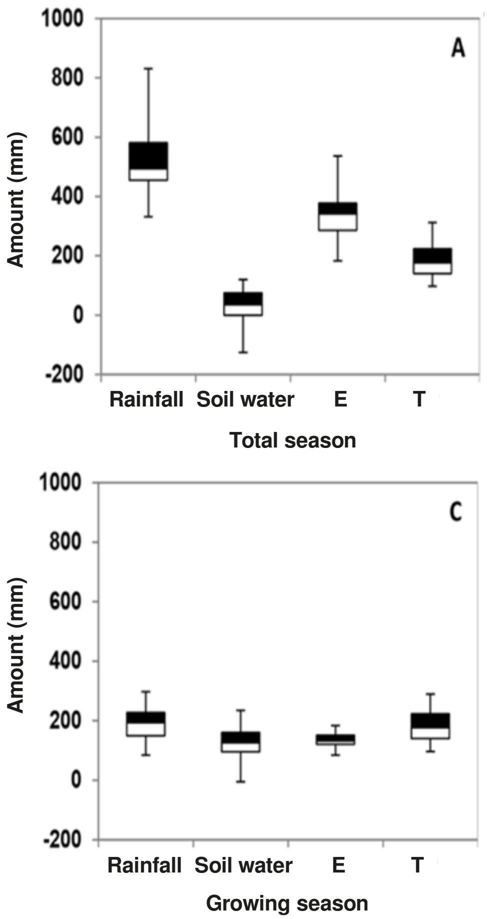


Figure 4. Water balance (rainfall, change in soil water, E, T) of the total season (A), fallow season (B) and growing season (C) during the period of 1980 - 2010. Total season means the sum of fallow season and growing season.

3.3.4. Wheat yield and WUE

Due to limited amounts of available water and the irregular rainfall pattern, wheat yield and WUE were rather low, ranging from 0.6 to 3.9 ton/ha/year and from 0.3 to 0.9 kg/m^3, respectively. Relationships between yield and annual rainfall (p=0.028), and between yield and growing season rainfall (p=0.027) were highly significant (Figures 5). The relationship between yield and rainfall during the fallow season was not significant (p=0.167). Furthermore, there were significant linear relationships between wheat grain yield and ET, T, and WUE, with coefficients of determination (R^2) of 0.61, 0.68 and 0.72, respectively (Figure 5). Given the slope (0.01) between yield and T, an increase of 1 mm available water can produce 10 kg grain per hectare.

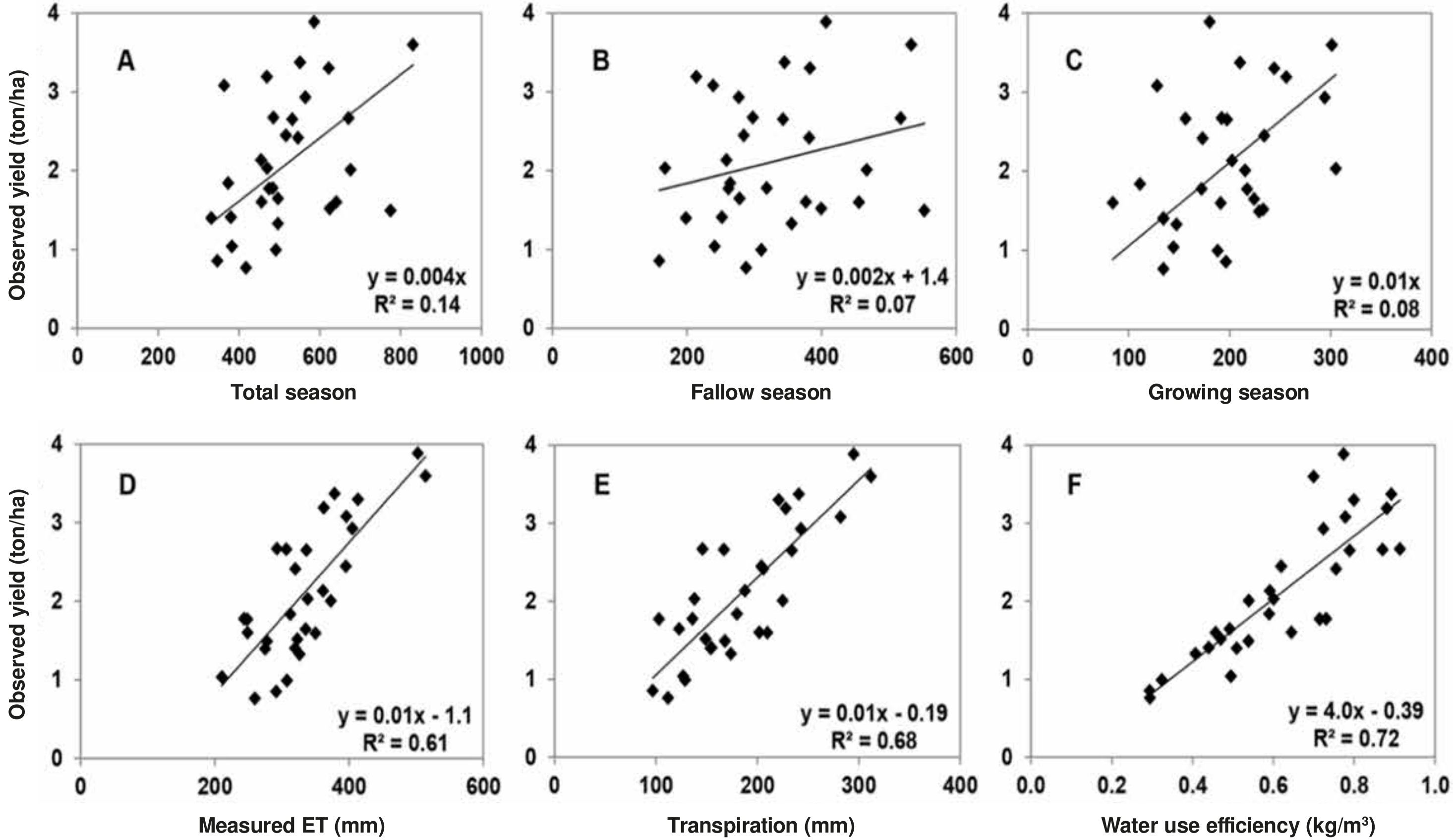


Figure 5. Relationships between observed yield and total rainfall (A), rainfall in fallow season (B), rainfall in growing season (C), measured ET (D), Transpiration (E) and WUE (F). The significant level is 0.028 for (A), 0.167 for (B), 0.027 for (C). For D, E and F, the significant level is all smaller than 0.01.

3.3.5. Model experiments

In model experiment E1 (winter wheat planted at 50% of FC), mean wheat yield and WUE were 2 ton/ha and 0.6 kg/m^3, respectively (Figure 6). In model experiment E2, with organic mulch during the growing season, mean yield increased to 2.3 ton/ha and WUE increased to 0.8 kg/m^3. In model experiment E3, with plastic film during the growing season, mean yield increased further to 2.5 ton/ha and WUE to 1.0 kg/m^3.

Similarly, in model experiment E4 (winter wheat planted at 70% of FC), mean yield and WUE were 2.9 ton/ha and 0.8 kg/m^3, respectively. With organic mulch (E5), mean yield and WUE increased to 3.2 ton/ha and 0.9 kg/m^3, and with plastic film cover (E6), mean yield and WUE increased further to 3.5 ton/ha and 1.1 kg/m^3. Our model experiments show that both organic mulch and plastic film cover could significantly improve yield and WUE, but the impact of plastic cover was bigger than the organic mulch mainly due to high effectiveness in reducing soil evaporation. Moreover, increasing water storage in the soil during the fallow season, so that available soil water content increases from 50 to 70% of FC in autumn at the time of winter wheat seeding, is at least as effective as a plastic cover during the growing season.

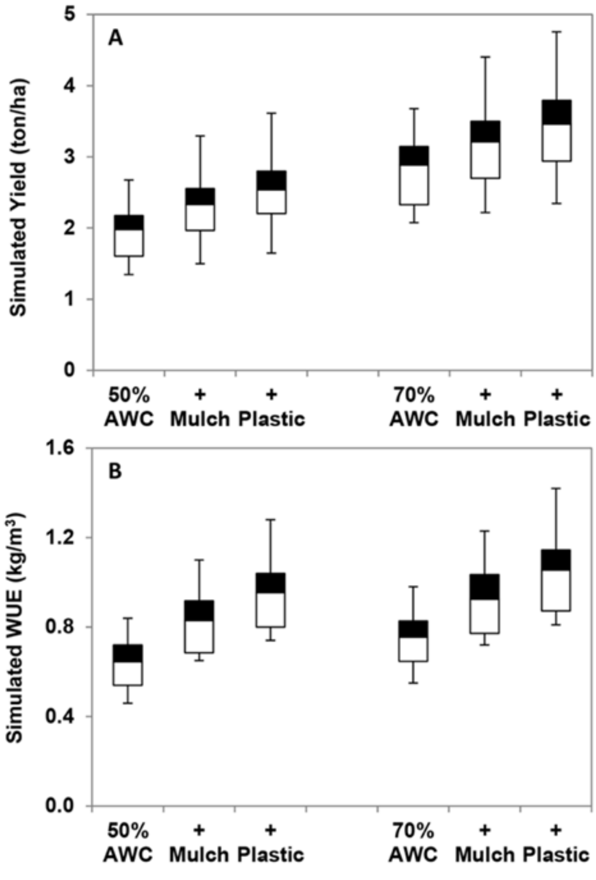


Figure 6. Results of six model experiments; effects of straw mulch and plastic film on wheat yield (A) and water use efficiency (B). Experiment E1: Planting at 50% of field capacity; Experiment E2: E1 + organic mulch; Experiment E3: E1 + plastic cover; Experiment E4: Planting at 70% of field capacity; Experiment E5: E4 + organic mulch; Experiment E6: E4 + plastic cover.

3.4. Discussion

We successfully calibrated and validated the AquaCrop model on the basis of the long-term monitoring data (30 years) of rainfed winter wheat on the Loess Plateau of northern China. The full set of crop parameters (Table 3) may provide also guidance to future studies and further model calibrations and validations. We also quantified four key components of the water balance, i.e., rainfall, changes in soil water, soil evaporation and crop transpiration, for both fallow and growing seasons by combining empirical data from a long-term wheat monitoring site with calculated results using the AquaCrop model. In the end, we also explored the potential for increasing wheat yield and WUE through model experiments.

The relationship between observed and modelled wheat yield had a R^2 of 0.77, slope of 0.9 and an index of agreement (d) of 0.93 (Figure 3). Mkhabela and Bullock (2012) reported a R^2 of 0.66, slope of 0.96, index of agreement (d) of 0.99 between observed and modelled wheat yields. Araya et al. (2010a) reported a R^2 > 0.80 when simulating barley biomass and grain yield. Stricevic et al. (2011) reported a R^2 > 0.84 when simulating yields of maize, sunflower and sugar beet. Similarly for simulating soil water content, we found a R^2 of 0.78, slope of 0.9 and an index of agreement (d) of 0.93 (Figure 3). Mkhabela and Bullock (2012) reported a R^2 of 0.9 and a slope of 0.9 for simulating soil water content. Hence, the performance of AquaCrop for our dryland wheat field is largely comparable with that of other modelling studies.

Water stress limited the crop yield at this site. According to our model simulations, water stress has led to suboptimal yields in essentially all years, for both low and relatively high wheat yields. For example, a very low grain yield (0.6 ton/ha) was recorded in the year 2000, when water stress for leaf expansion and stomatal closure started already at the 54th day after planting. In contrast, water stress for leaf expansion and stomatal closure started to occur only from day 156 after planting in 2003, when grain yield was 3.8 ton/ha. In both cases, water stress occurred before flowering stage (~200 days after planting). Water stress leads to low grain yield and low WUE, but depending on the stage and duration of the water stress (Kang et al., 2002; Zhang and Oweis, 1999).

We found significant linear relationships between wheat yield and ET, and between wheat yield and T (Figure 5), in line with some other studies (Huang et al., 2004; Kang et al., 2003b; Kang et al., 2002). Mean T/ET ratio in our study was only 58% during the growing season, which was 8-12% lower than that reported by Liu et al. (2002) and Kang et al. (2003a) but highly in line with that reported by Wang et al. (2012a). The higher T/ET ratio in the studies of Liu et al. (2002) and Kang et al. (2003a) was probably due to the irrigation treatments where the crop had more water for transpiration. It is well-known that crop yield and WUE are often lower in rainfed agriculture than in irrigated agriculture (Kang et al., 2002; Zhang and Oweis, 1999; Zhang et al., 2010), but depending also on possible nutrient, weed, and disease stresses and irrigation management.

Advanced technologies, such as precision irrigation, are for a long time available but unfortunately not affordable and applicable to the farmers of the Loess Plateau, mainly because of the high cost relative to the low value of cereals (Robert, 2002). Therefore, we focused on low-cost options, such as straw mulch and plastic film cover because those are the most accessible and low cost materials for farmers to implement in the field. Minimizing soil evaporation could save water for crop transpiration, and thereby increase wheat yield and WUE. Our model experiments suggest that wheat yield can be improved significantly by minimizing soil evaporation via organic mulch and plastic film cover, especially also during the fallow period. Mulching with crop residues can decrease soil evaporation and increase soil water retention. Plastic film cover can significantly increase crop yield and WUE, and promote crop growth during early growth when temperature is low. Our results show that crop yields can be increased by ~0.9 ton/ha through increasing soil water storage during the fallow period. Crop yields can be increased further by on average ~0.3 ton/ha through straw mulch and by ~ 0.5 ton/ha on through plastic film covers during the growing season. At the same time, WUE increases on average by 0.2 to 0.6 kg/m^3. These results are in line with results reported by Deng et al. (2006) and others (Chakraborty et al., 2010; Chakraboyty et al., 2008; Gao et al., 2009).

Evidently, increased rainwater harvesting during the fallow season is an effective option. Straw mulch significantly reduces the evaporative water losses during the fallow season and is conducive to the infiltration of rain water in the soil. Plastic film covers are less applicable during the fallow season, because they may limit the infiltration of rain water and thereby increase runoff. Reduced tillage can also improve soil water storage. According to a recent study of Hou et al. (2012), rotational tillage (rotation of no-tillage and subsoiling) could significantly increase soil water storage during the summer fallow and wheat growing season compared with conventional tillage. They found that rotational tillage increased wheat yields by 10 %, and WUE by 7.5%, respectively.

3.5. Conclusions

Low wheat yield at the monitoring site was largely due to (i) limited rainfall, (ii) low soil water storage during fallow season because of high water loss via soil evaporation, and (iii) the poor synchronisation of the wheat growing season to the rainfall distribution season. Although water was limited, on average only one-third of the total available water was actually used by the crop for transpiration. The remaining two-thirds was lost by soil evaporation, 60% during the fallow season and 40% during the growing season. Our model experiments suggest that minimizing soil evaporation via organic mulch or plastic film covers can significantly increase wheat yield and WUE. More importantly, these increases can be realized by the application of relatively low cost measures. Further studies are needed to test the effectiveness of these measures in the field.

Acknowledgements

We thank Xiaoguang Yang, from College of Resources and Environmental Sciences, China Agricultural University and Junqi Zhu, from Wageningen University and Research Centre, for providing the climate data for this study. We also thank Xinxin Wang, from Wageningen University and Research Centre, for helping us with statistics.

Wei Qin
Daozhong Wang
Xisheng Guo
Taiming Yang
Oene Oenema

Chapter 4

Yield response to water and nutrients in a rainfed wheat-soybean system in the North China Plain during a 30-years' period

This paper has been submitted for publication

Abstract

A quantitative understanding of yield response to water and nutrients is key for improving the productivity and sustainability of rainfed cropping systems. Here, we quantified the effects of rainfall, fertilization (NPK) and soil organic amendments (with straw and manure) on yields of a rainfed wheat-soybean system in the North China Plain (NCP), using 30-years' field experimental data (1982-2012) and the simulation model-AquaCrop. On average, wheat and soybean yields were 5 and 2.5 times higher in the fertilized treatments than in the unfertilized control (CK), respectively. Yields of fertilized treatments increased and yields of CK decreased over time. NPK + manure increased yields more than NPK alone or NPK + straw. The additional effect of manure is likely due to increased availability of K and micronutrients. Wheat yields were limited by rainfall and can be increased through soil mulching (15%) or irrigation (35%). In conclusion, combined applications of fertilizer NPK and manure were more effective in sustaining high crop yields than recommended fertilizer NPK applications. Manure applications led to strong accumulation of NPK and relatively low NPK use efficiencies. Water deficiency in wheat increased over time due to the steady increase in yields, suggesting that the need for soil mulching increases.

Keywords: double-cropping, evapotranspiration, irrigation, nutrients, soil quality, soybean, transpiration, water, wheat.

4.1. Introduction

Rainfed agriculture covers 80% of the world's cultivated land and produces 60% of total crop production (UNESCO, 2009). The relatively low productivity in rainfed agriculture is often due to limited water and nutrient availability, degraded soils, and poor water and nutrient management (Mueller et al., 2012; Rockstrom et al., 2010; Rockstrom et al., 2007). Forecasts suggest that food production must double in order to meet the demands of the expected 9-10 billion people in 2050(FAO, 2009). A large fraction of this increase has to come from rainfed agricultural systems. Achieving this production target will increase the pressure on land, fresh water and nutrient resources unless these resources are used much more efficiently(Green et al., 2010; Hoekstra and Mekonnen, 2012; Rosegrant and Cline, 2003). The pressure likely becomes more severe under climate change, when more extreme weather events may occur, such as droughts(Piao et al., 2010).

Water and nutrients are key factors for plant growth and development as they are involved in many processes in plants, including photosynthesis, respiration, transpiration, plant development, and yield formation(Bernacchi and VanLoocke, 2015; de Wit, 1958; Marschner, 1995). There are also possible interactions between water and nutrient use in crop yield; water stress may lead to stomata closure, which inhibits nutrient uptake by the plant(Chaves et al., 2002; Downton et al., 1988a, b). Plants with nitrogen (N) deficiency are often small and develop slowly, because of low efficiency in photosynthesis and plant development; as a consequence evaporative losses are relatively high and water use efficiency low. Adequate water and nutrient supply contribute to shoot and root growth, which increase plant water and nutrient uptake, and thereby yield(Salvagiotti et al., 2008; Setiyono et al., 2010).

Most of the water and nutrients are taken up by the crop from the soil, and soil quality or soil fertility is a major determinant of the productivity of the land(He et al., 2014). A combination of soil physical, chemical and biological characteristics defines how much water and nutrients can be stored in soil and how well these can be taken up by roots to meet the demands of the growing crop during the crop growing season. Farmers regularly apply fertilizers, manures, lime and crop residues to soils to improve the physical, chemical and biological quality and productivity of the soil. There has been a long standing debate whether chemical fertilizers alone can sustain soil quality and crop productivity over time(Rigby and Caceres, 2001; Seufert et al., 2012). Common view is now that chemical fertilizers can sustain crop productivity, provided all essential nutrients are supplied in adequate amounts and sufficient organic carbon is returned to the soil to replenish the decomposition losses. The remaining question is often how much nutrients have to be applied, and in which proportions, to sustain crop productivity and minimize environmental effects associated with nutrient losses.

This is also a key question in the North China Plain (NCP), which is a most important food production area in China, producing ~50% of the total national wheat and maize production (Jeong et al., 2014; Liu et al., 2010). Double cropping is common practice in NCP, i.e., winter wheat and summer maize or winter wheat and soybean(Gao et al., 2014; Yang et al., 2014). Double cropping systems often produce higher yields than mono cropping systems, provided there are sufficient water and nutrients(Meng et al., 2012). Approximately 70% of the winter wheat in the NCP is under irrigation, mostly via groundwater, which has led to severe groundwater depletion (decline by 1 m per year)(Aeschbach-Hertig and Gleeson, 2012; Liu et al., 2001). Though animal density is high and animal manure abundantly available, and despite China's long history of recycling of manures and wastes, almost no animal manure is being used in wheat and maize production during the last decades (but in vegetable and fruit production)(Wang et al., 2014). Instead, wheat and maize are heavily fertilized with mineral NPK fertilizers, and because of its liberal use, losses are relatively high(Ju et al., 2009). Questions were raised about the sustainability of these practices, which led to the initiation of long-term field experiments in NCP some 30 years ago. In these trials, combinations of chemical fertilizers with straw and animal manures were tested for underpinning fertilizer recommendations.

Here, we report on a comprehensive and quantitative analysis of data from a long-term (30-years) field trial, which was combined with a model simulation study. No results of this trial have been published before, apart from an analysis of soil organic matter changes as function of fertilizer and manure treatment(Hua et al., 2014). The objectives of our study are: (i) to quantify the effects of long-term fertilization and soil organic amendments on crop yield over time; (ii) to examine rainfall and treatment interactions in crop yield and (iii) to explore options to increase crop yield in rainfed wheat-soybean double cropping system in NCP.

4.2. Materials and methods

4.2.1. Site and soil description

The long-term field experiment is located at Madian Agro-Ecological Station in the North China Plain (N33°13′, E116°37′). The area has a sub-humid climate, with mean annual temperature of 16.5℃ (min. -7.4℃ and max. 36.5℃). Annual precipitation ranged from 400 to 1500 mm during the last 30 years, about 70% of which occurs from May to September (Figure 1).

The site is flat (slope <1%) and has been cultivated for many years. The predominant Vertisols have developed in fluvial and lacustrine deposits. They are classified as

Calcic Kastanozems, according to the soil classification system of the Food and Agriculture Organization (FAO). Soil pH ranges from 6.0 to 8.6 and soil organic carbon (SOC) content ranges from 5.8 to 7.5 g kg^{-1}. Main topsoil (0-20 cm) characteristics in the experimental field at the start in 1982 were as follows: soil bulk density: 1.45 g cm^{-3}, pH: 7.4, sand (0.2 to 0.02 mm): 280 g kg^{-1}, silt (0.02 to 0.002 mm): 306 g kg^{-1}, clay (<0.002 mm): 414 g kg^{-1}, SOC content: 5.8±0.08 g kg^{-1}, total N content: 0.96±0.04 g kg^{-1}, total P content: 0.28±0.02 g kg^{-1}. Information on soil bulk density, field capacity and wilting point for different layers up to 200 cm are shown in Table 1.

Table 1. Soil bulk density, field capacity and wilting point for different soil layers.

Soil layer cm	Bulk density g cm^{-3}	Field capacity v v^{-1} in %	Wilting point v v^{-1} in %
10	1.26	36.8	12.3
20	1.42	42.6	13.8
30	1.47	36.0	14.7
40	1.46	39.3	16.4
50	1.37	36.4	15.3
60	1.33	32.6	13.4
80	1.40	31.1	14.8
100	1.41	31.0	15.9
200	1.41	31.0	15.9

4.2.2. Cropping practice and experimental design

A winter wheat-soybean rotation is common practice in the region. At Madian Agro-Ecological Station, winter wheat (*Triticum aestivum L.*), variety Yedan 13, was grown from late October to May, and soybean (*Glycine max*), variety Zhonghuang 13, from June to September.

The long-term field experiment was initiated in 1982, and had six treatments (Table 2): no fertilization (CK), mineral NPK fertilizer alone (T1), mineral fertilizer combined with 2.5 ton ha^{-1} yr^{-1} of wheat straw (T2), mineral fertilizer combined with 5 ton ha^{-1} yr^{-1} of wheat straw (T3), mineral fertilizer combined with 7.8 ton ha^{-1} yr^{-1} of pig manure (T4), and mineral fertilizer combined with 12.5 ton ha^{-1} yr^{-1} of cattle manure (T5). The treatments were laid out in a randomized block design with four replications.

The plot size was 70 m^2 (14.9 m × 4.7 m). All plots were plowed (0-20 cm) after each harvest. Mineral N, P and K fertilization was applied as urea, calcium superphosphate and potassium chloride, respectively. The amounts of fertilizers applied were similar to the recommended amounts for this cropping system, i.e., 180 kg N, 90 kg P_2O_5, and 135 kg K_2O per ha per year. All fertilizers were applied as base fertilizer at once at the start of the wheat growing season in October. No fertilizers were applied to soybean.

Herbicides and pesticides were applied when necessary. Wheat and soybean were harvested manually and all above-ground biomass were removed from the experimental plots, except for the stubble. Grains yields were air dried, threshed and then weighted.

Table 2. Application rates of mineral fertilizers, wheat straw and pig and cattle manure as function of treatment (kg $ha^{-1}yr^{-1}$).

	Mineral fertilizers			Organic soil amendments		
Treatment	N	P_2O_5	K_2O	Wheat straw	Pig manure	Cattle manure
CK	0	0	0	0	0	0
T1	180	90	135	0	0	0
T2	180	90	135	2500	0	0
T3	180	90	135	5000	0	0
T4	180	90	135	0	7800	0
T5	180	90	135	0	0	12500

4.2.3. Soil sampling and analyses

4

Soil samples were collected from the top 20 cm after the soybean harvest in October of each year. Soil samples were randomly taken from three locations in each plot with a soil core sampler (inner diameter 7 cm) and analyzed per plot. The samples were air dried and passed through an 8 mm sieve. Visible pieces of crop residues and roots were removed. The dried and sieved soil was stored in glass jars until analysis. Soil bulk density was measured using the core method and soil pH was measured by the potentiometric method in a soil-water extract (2.5:1, w/v water)(Lu, 2000). Total N was determined by the method described by Walkley and Black (1934), and total P by Murphy and Riley (Black, 1965). Available N was measured by the alkali N-proliferation method, available P (Olsen-P) was extracted by 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) and then measured via Mo-Sb colorimetric method, available potassium was extracted by 1 mol L^{-1} NH_4-OAc (pH = 7) with 1:5 ratio of weight volume, and then measured via flame photometer method(Lu, 2000). Soil water contents were measured every 10 days by using the gravity method. The top 50 cm was sampled in 10 cm intervals, from 50 to 100 cm at 25 cm intervals and from 100 to 200 cm at 50 cm intervals. Each sample consisted of 5 subsamples, taken randomly on fertilized strips adjacent to the experimental field. Plant N, P and K contents were analysed at harvest once in every five years. Plant N content was measured by Kjeldahl method. Plant P content was measured by the Mo-Sb colorimetric method and plant K content was measured by flame photometer(Lu, 2000).

4.2.4. Definitions and calculations

The water balance for each crop growing seasons is defined as follows:

$$R + I = E + T + R_r + D \pm \Delta S \tag{1}$$

where R is rainfall, I is irrigation, E is soil evaporation, T is crop transpiration, R_r is runoff, D is drainage and ΔS is the change in soil moisture (or soil water content), all with the unit mm.

Irrigation was not applied in this study and runoff rarely occurred, and therefore was neglected. Hence, the water balance was simplified to:

$$R = E + T + D \pm \Delta S \tag{2}$$

Water use efficiency (WUE, in kg m^{-3}) is defined as:

$$WUE = Y / ET \tag{3}$$

where Y is grain yield (kg ha^{-1}), ET is evapotranspiration (mm), i.e. the sum of E and T during each crop growing season.

Nitrogen use efficiency (NUE, in kg kg^{-1}) is defined as agronomic efficiency of applied N (Dobermann, 2007):

$$NUE = Y_t - Y_{ck} \ / \ N\ input \tag{4}$$

where Y_t is yield of fertilization treatment (kg ha^{-1}), Y_{ck} is yield of CK treatment.

Similarly, PUE and KUE (in kg kg^{-1}) are defined as:

$$PUE = Y_t - Y_{ck} \ / \ P\ input \tag{5}$$

$$KUE = Y_t - Y_{ck} \ / \ K\ input \tag{6}$$

4.2.5. Descriptions of the AquaCrop model

The FAO AquaCrop model is a water-driven crop growth model, which can simulate crop biomass and yield as function of climate and water availability(Steduto et al., 2012; Steduto et al., 2009). AquaCrop requires 4 main sets of input data, i.e. (1) climate data (rainfall, minimum and maximum temperature and reference evapotranspiration (ET_0)), (2) crop parameters, (3) soil data and (4) field management data. Climate data were collected from a near-by meteorological station. ET_0 was calculated by the FAO Penman-Monteith equation as described in Allen et al. (1998a). Soil data and field management data were derived from measurements. The calibration and validation procedures for winter wheat, and evaluations of the model performance are documented in greater detail in Qin et al. (2013). A full list of crop parameters used in this study is summarized in Table S1.

4.2.6. Model experiments

We set up 4 model experiments (E1-E4) to investigate the effects of straw mulching, plastic cover and irrigation on crop yields as follows:

E1 (reference): common practice

E2: E1 + straw mulching

E3: E1 + plastic cover

E4: E1 + irrigation

We used E1 as references to simulate crop growth with two levels of initial soil water content at seeding, i.e. low with 60% FC and high with 75% FC. The range from 60 to 75% FC largely represented the initial soil water content during the experimental period. Model experiment E2 aimed at testing the effects of straw mulching, and model experiment E3 for the effects of plastic film cover. The effectiveness of straw mulching in reducing soil evaporation was estimated as 50% and that of plastic cover at 90%, which are the default values in the AquaCrop model(Steduto et al., 2012). However, plastic film covers around 80% of the field in practice. Hence, the overall soil evaporation reduction by plastic film was set at 72%. We assumed that the plastic film were used for the growing season only and removed after harvest. Model experiments E4 tested the effects of smart irrigation which allows 80% depletion of total available soil water (ASW). We ran these experiments for the period of 1982-2012.

4

4.2.7. Statistical analyses

Data were analyzed with a mixed-effect model via R package "Lme4"(Bates et al., 2014; R Core Team, 2013). A mixed-effect model is a statistical model containing both fixed effects and random effects. We quantify the effects of main variables, i.e. (1) rainfall, (2) treatments (CK, T1-T5), (3) rainfall and treatment interactions on crop yields as:

$$Y = \alpha + \beta_1 \times R + \beta_2 \times T + \beta_3 \times R \times T + error \quad (7)$$

where Y is yield (ton ha^{-1}), α is the intercept (ton ha^{-1}), R is rainfall (mm), b_1 is the effect of rainfall (fixed variable 1), b_2 is the effect of a specific treatment (fixed variable 2), b_3 is the effect of rainfall and treatment interactions, and *error* represents the residual effects that were not taken into consideration. Trial years are considered as random variable in the model.

An additional analysis considering the interactions between rainfall and N, P and K input on yields was conducted as follows:

$$Y = \alpha + \beta_1 \times R + \beta_2 \times N + \beta_3 \times P + \beta_4 \times K + \beta_5 \times R \times N + \beta_6 \times R \times P + \beta_7 \times R \times K + error \quad (8)$$

where $b_{2\text{-}4}$ represent the effect of N, P and K, and $\beta_{5\text{-}7}$ the effect of interactions between rainfall and N, P and K respectively. N, P and K input were the sum of that in fertilizer, manure and straw.

4.3. Results

4.3.1. Rainfall and soil water content

Long-term average annual rainfall (1981-2012) at the station was ~900 mm, and heavily influenced by the monsoon. Around two-third of the annual rain (~600 mm) fell in June to September, which is the growing season for soybean (Figure 1), and the other third (~300 mm) fell during the winter wheat growing season from October to May. High-yielding winter wheat and soybean crops normally require 450 to 650 mm of water, depending on climate, yield and length of the growing period and monthly distribution (FAO, 2015a). Evidently, winter wheat received relatively little rainwater, compared to soybean.

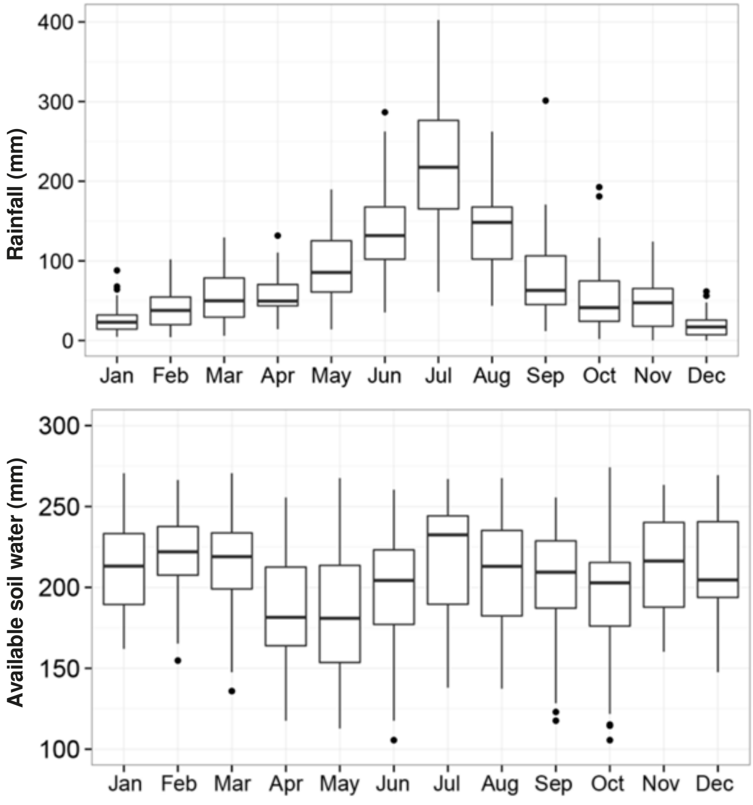


Figure 1. Distribution of monthly rainfall and available soil water in the top 2 meter during the period 1982-2012. Available soil water is defined as the total soil water content minus the water content at wilting point. Boxes show the range between 25th and 75th percentile values, i.e. interquartile between Q1 (25th percentile) and Q3 (75th percentile). Lines in the boxes show the median values. Whiskers show the range of Q1-1.5 interquartile at the bottom, and Q3+1.5 interquartile at the top. Dots are the outliers beyond the range of Q1-1.5 interquartile and Q3+1.5 interquartile.

Soil moisture contents decreased during the wheat growing season and increased during the soybean growing season. Available soil water (ASW) was defined as the measured soil moisture content minus the moisture content at wilting point in a 2 meter's profile. Mean ASW was lowest in May when wheat was harvested (Figure 1). From June, soil water content started to increase again. Winter wheat was planted in October, but soil water content did not change much till February because of relatively low temperature and slow development of wheat in the early stage. From March, soil water started to decrease, because evapotranspiration (ET) exceeded rainfall. On average, the upper 2 m of soil contained around 200 mm of available, ranging from 100 to 280 mm. The top 1 m of the soil profile accounted for ~70% of the changes in soil moisture content in the whole soil profile of 2 m.

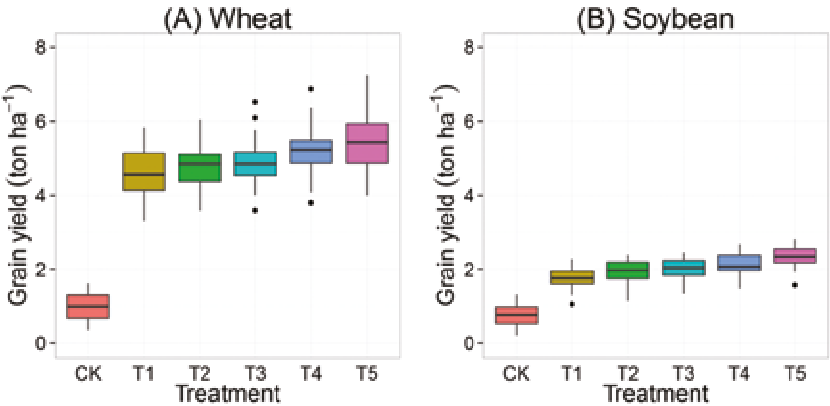


Figure 2. Wheat (A) and soybean (B) yields as function of fertilization treatments during the period 1982-2012. The treatments are noted as: no fertilization (CK), mineral NPK (T1), NPK + low rate of straw (T2), NPK + high rate of straw (T3), NPK + pig manure (T4) and NPK + cattle manure (T5). Details of experiments are provided in Table 1.

4.3.2. Crop yields

Figure 2 shows the ranges of wheat and soybean yields as function of fertilization treatments. Yields were low in the CK treatment. Fertilization and soil organic amendments significantly increased yields. The ranking of the treatments, from high to low yields, was T5 ≥ T4 > T3 ≥ T2 ≥ T1 >> CK. Mean wheat yield in CK was only 1 ton ha^{-1}, which is ~20% of the mean yields in the fertilized treatments (Figure 2A). Mean soybean yield in CK was 0.8 ton ha^{-1}, which is ~40% of the mean yields in the fertilized treatments (Figure 2B).

The NPK + manure treatments (T4 and T5) significantly increase wheat yields relative to NPK alone (T1). Treatments NPK + straw (T2 and T3) did not significantly increase wheat yields compared to NPK alone (Table 3). The results of soybean were rather similar to that of wheat, but NPK + high rate straw (T3) also significantly increased soybean yields relative to the NPK alone treatment.

Fertilization and soil organic amendments also increased yield stability over time (Table 4). The mean coefficient of variance (CV) in CK was 0.39 for both crops, while mean CV in the fertilization and soil organic amendment treatments ranged from 0.12-0.15 for wheat and from 0.12-0.18 for soybean.

There were increasing trends of wheat and soybean yields over time in fertilized treatments T1 to T5, whereas the opposite occurred in the CK treatment (Figure 3). Wheat yields in fertilized treatments T1-T5 increased on average by 50-70 kg $ha^{-1}yr^{-1}$ and soybean yields increased on average by 10-30 kg $ha^{-1}yr^{-1}$ (Table 4). Over the 30 years' time of the trial, wheat and soybean yield increased by 1.5-2.1 and 0.3-0.9 ton ha^{-1} in the fertilized treatments, whereas yields decreased on average by ~0.9 and ~0.6 ton ha^{-1} in the CK treatment for wheat and soybean, respectively.

Table 3. Results of the statistical analyses of wheat and soybean yields. The yield of treatment T1 was set as reference for the t-test. SD is standard deviation. CV is coefficient of variation, i.e. SD divided by mean.

Crop	Treatment†	Mean	SD	CV	p value	Sign.‡
Wheat	CK	1.0	0.38	0.39	0.00	***
	T1	4.6	0.70	0.15	1.00	NS
	T2	4.8	0.60	0.12	0.23	NS
	T3	4.9	0.64	0.13	0.09	NS
	T4	5.2	0.75	0.14	0.00	**
	T5	5.4	0.79	0.15	0.00	***
Soybean	CK	0.8	0.30	0.39	0.00	***
	T1	1.8	0.33	0.18	1.00	NS
	T2	1.9	0.32	0.16	0.10	NS
	T3	2.0	0.31	0.16	0.02	*
	T4	2.1	0.30	0.14	0.00	***
	T5	2.3	0.28	0.12	0.00	***

† Treatments are explained in Table 2.‡Significance were displayed with numbers of asterisk, '***' means p value ≤ 0.001, '**' means 0.001< p value ≤ 0.01, '*' means 0.01 <p value ≤ 0.05 and ' NS' means p value >0.05, i.e., not significant.

Table 4. Results of the statistical analysis of the trends in wheat and soybean yields over time.

Crop	Treatment	Intercept†	Slope	r^2	p value	Sign.‡
Wheat	CK	1.6	-0.03	0.51	0.00	***
	T1	3.7	0.05	0.36	0.00	**
	T2	4.0	0.05	0.44	0.00	***
	T3	3.8	0.06	0.59	0.00	***
	T4	4.1	0.07	0.53	0.00	***
	T5	4.5	0.05	0.30	0.00	**
Soybean	CK	1.1	-0.02	0.27	0.02	*
	T1	1.5	0.02	0.21	0.04	*
	T2	1.7	0.01	0.17	0.07	NS
	T3	1.6	0.02	0.30	0.01	*
	T4	1.7	0.02	0.48	0.00	***
	T5	1.8	0.03	0.69	0.00	***

†The unit of intercept is ton ha^{-1}. ‡ '***' means $p < 0.001$, '**' means $0.001 \leq p \leq 0.01$, '*' means $0.01 < p < 0.05$ and ' NS' means $p \geq 0.05$, i.e., not significant.

4

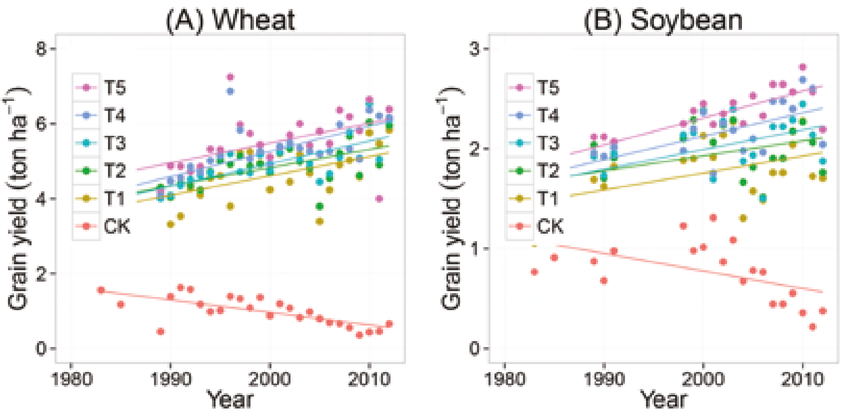


Figure 3. Trends of wheat (A) and soybean (B) yield over time during the period 1982 – 2012, as function of fertilization treatments. The treatments are noted as: no fertilization (CK), mineral NPK (T1), NPK + low rate of straw (T2), NPK + high rate of straw (T3), NPK + pig manure (T4) and NPK + cattle manure (T5). Statistics are summarized in Table 4.

4.3.3. Soil fertility

Long-term fertilization increased soil fertility characteristics and SOC content over time (Figure 4). Over the 30 years' period, NPK + cattle manure (T5) increased soil available N, P and K and SOC content most among all treatments. Soil available N at harvest time of soybean ranged from 125 to 175 mg kg^{-1} in the NPK + cattle manure treatment (T5), and from 100 to 125 mg kg^{-1} in the NPK + pig manure treatment (T4).

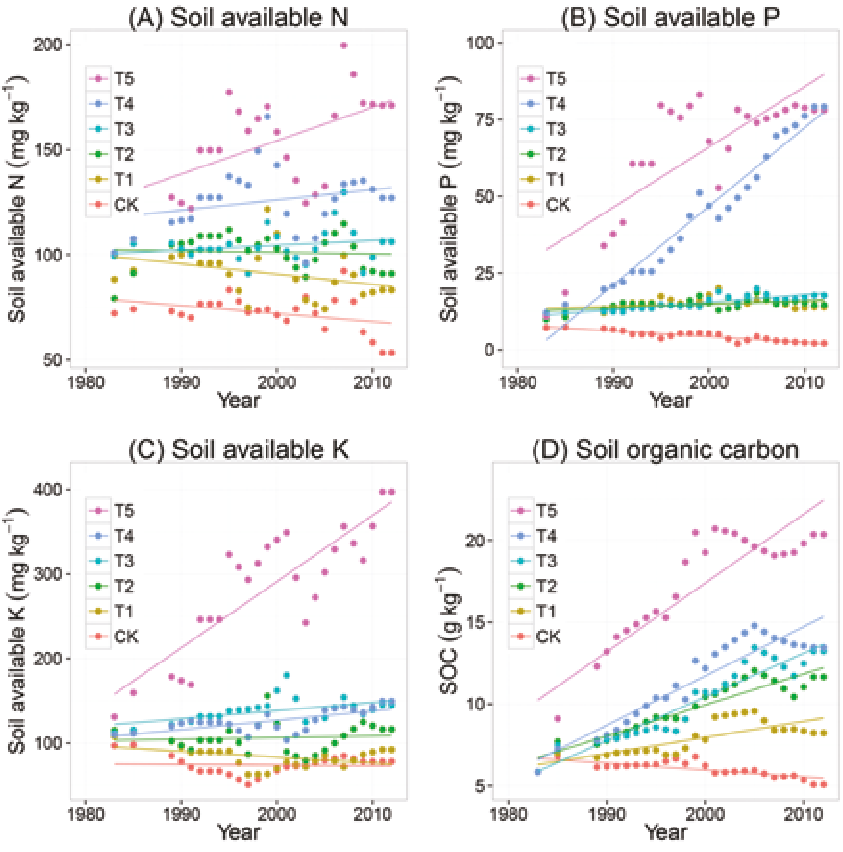


Figure 4. Trends of soil available (mineral) N (A), soil available (Olsen) P (B) soil available (Exchangeable) K (c) soil organic carbon (D) over time during the period 1982 – 2012, as function of fertilization treatments. The treatments are noted as: no fertilization (CK), mineral NPK (T1), NPK + low rate of straw (T2), NPK + high rate of straw (T3), NPK + pig manure (T4) and NPK + cattle manure (T5). Note that Olsen P leveled off at ~75 mg kg^{-1} and SOC leveled off at 20 g kg^{-1}.

Soil available N was around 75 to 125 mg kg^{-1} in the NPK alone (T1) and NPK + straw treatments (T2 and T3), and ranged from 50 to 75 mg kg^{-1} in the CK treatment. Olsen P increased from 12.5 to about 75 mg kg^{-1} in the NPK + manure treatments (T4 and T5), increased only very slightly in the NPK alone and NPK + straw treatments (T2, T3), and dropped to about 5 mg kg^{-1} in the CK treatment. Cattle manure application significantly increased soil available K much stronger than pig manure and straw return. Soil available K slightly decreased in the NPK alone and CK treatments, suggesting that the annual application of 135 kg K_2O ha^{-1} yr^{-1} was not sufficient to compensate for the annual K withdrawal in harvested crop and leaching losses. Soil organic carbon (SOC) content increased in all fertilized treatments but decrease in CK over time. SOC leveled off at ~20 g kg^{-1} in the treatment with cattle manure addition, and at 10-15 g kg^{-1} in the treatments with pig manure and straw. Fertilizer NPK alone slightly increased SOC content during the 30 years' period (Figure 4).

4.3.4. Interactions between rainfall and fertilization in yields

The effects of rainfall, fertilization (T1-T5) and their interactions in yields are shown in Table 5. The results of the treatments T2, T3, T4 and T5 were compared to the yields in the NPK alone treatment (T1), as reference. We excluded the results of the CK treatment for two reasons: first, to reduce the variance in the dataset caused by the CK treatment; and second, to examine the differences between the treatments with chemical NPK fertilizers alone and those with NPK fertilizers plus manure or straw. There were significant positive interactions between rainfall and NPK + manure treatments (T4 and T5) in wheat yields; the interactive effects were larger with cattle manure than with pig manure. These positive interactions suggest that years with relatively high rainfall increased wheat yields in treatments with NPK + manure, compared to treatments with NPK alone and NPK + straw (Table 5).

There were no significant interactions between rainfall and fertilization in soybean yields (Table 5), most likely because rainfall was abundant during the soybean growing season. Though soybean did not receive any fertilization, yields clearly benefited from the residual effects of the fertilizers, manure and straw applied to the wheat crop (Figure 2).

An additional analysis indicated that there were significant positive interactions between rainfall and K input in wheat yields, suggesting that the wheat benefited from the additional K inputs via straw and manure during years with relatively high rainfall (Table S2). Wheat yields in treatments T1-T5 were not related to total N and P inputs, suggesting that the N and P inputs via NPK fertilizers alone were sufficient, and the N and P inputs via straw and manure were largely redundant. In other words, the NPK inputs via manures can largely replace fertilizer N PK inputs.

Table 5. Results of the statistical analysis of the effects of rainfall (R), fertilization treatments (T1 to T5 and CK; see Table 2), and their interactions in yields of wheat and soybean.

Crop	Item†	Estimate	Std. Error	df	t value	p value	Sign.
Wheat	(Intercept)	5.31	0.54	42.14	9.89	0.00	***
	β_1 (R)	-2E-03	0.00	42.14	-1.42	0.16	NS
	β_2 (T2)	-0.43	0.40	103.97	-1.06	0.29	NS
	β_2 (T3)	-0.17	0.40	103.97	-0.42	0.67	NS
	β_2 (T4)	-0.25	0.40	103.97	-0.63	0.53	NS
	β_2 (T5)	-0.99	0.40	103.97	-2.47	0.02	*
	β_3 (R*T2)	2E-03	0.00	103.97	1.67	0.10	NS
	β_3 (R*T3)	1E-03	0.00	103.97	1.26	0.21	NS
	β_3 (R*T4)	3E-03	0.00	103.97	2.31	0.02	*
	β_3 (R*T5)	5E-03	0.00	103.97	4.80	0.00	***
Soybean	(Intercept)	1.51	0.25	96.48	5.92	0.00	***
	β_1 (R)	4E-04	0.00	95.13	0.92	0.36	NS
	β_2 (T2)	0.15	0.33	94.25	0.46	0.65	NS
	β_2 (T3)	0.14	0.33	94.25	0.41	0.68	NS
	β_2 (T4)	0.70	0.33	94.25	2.08	0.04	*
	β_2 (T5)	0.62	0.33	94.25	1.86	0.07	NS
	β_3 (R*T2)	3E-05	0.00	94.25	0.05	0.96	NS
	β_3 (R*T3)	2E-04	0.00	94.25	0.30	0.76	NS
	β_3 (R*T4)	-6E-04	0.00	94.25	-0.99	0.33	NS
	β_3 (R*T5)	-1E-04	0.00	94.25	-0.19	0.85	NS

† Yields of the NPK treatment (T1) are set as the reference.Intercepts show the mean yields of T1. ‡Significance were displayed with numbers of asterisk, '***' means p value $\leq$ 0.001, '**' means 0.001< p value $\leq$ 0.01, '*' means 0.01 <p value $\leq$ 0.05 and ' NS' means p value >0.05, i.e., not significant.

4.3.5. Water balance in wheat and soybean growing seasons

Figure 5 shows the water balance of the wheat and soybean growing seasons during the period 1982 - 2012, estimated by the AquaCrop model. The partitioning between soil evaporation (E) and crop transpiration (T) differed between treatments. Evaporation (E) was relatively high in the CK treatments, and transpiration (T) was relatively high in the fertilization treatments. During the wheat growing season, mean E was 280 mm and mean T was 60 mm in the CK treatment, i.e., T/ET ratio was 18%, while mean E was 120 and mean T 240 mm in the NPK + cattle manure treatment (T5), i.e., T/ET ratios was 67% (Figure 5A). In the soybean growing season, mean E was 310 mm and mean T 110 mm in the CK treatment, i.e., T/ET ratio was 26%, while mean E was 150 and mean T 300 mm in the NPK + cattle manure treatment (T5), i.e., T/ET ratios was 67%. Hence, the T/ET ratio greatly increased through fertilization.

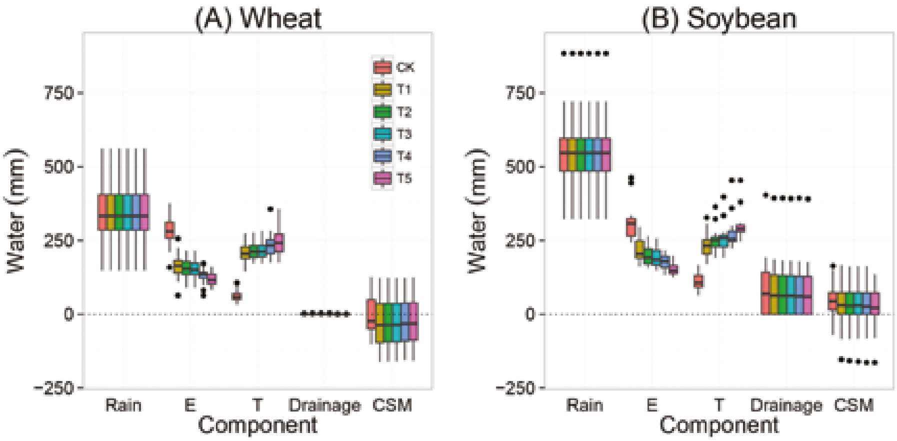


Figure 5. Water balance components for the wheat (A) and soybean (B) growing seasons during the period 1982 - 2012 as function of fertilization treatments: no fertilization (CK), mineral NPK (T1), NPK + low rate of straw (T2), NPK + high rate of straw (T3), NPK + pig manure (T4) and NPK + cattle manure (T5). Boxes show 25th and 75th percentiles (i.e. Q1 and Q3). Lines in the boxes show the median values. The components of water balance are shown on the x-axis, i.e., rainfall, soil evaporation (E), crop transpiration (T) , drainage and changes in soil moisture (CSM). See formula (2) and text for explanations.

4

4.3.6. Water and nutrient use efficiencies

Water use efficiency (WUE) was strongly related to yield (Figure 6). The ranking of treatments, from high to low WUE, was T5>T4>T3>T2>T1>CK. Mean WUE of wheat was 0.3 kg m^{-3} in CK, and ranged from 1.3 to 1.7 kg m^{-3} in the fertilized treatments. Mean WUE of soybean was 0.2 kg m^{-3} in CK, and ranged from 0.4 to 0.6 kg m^{-3} in the fertilized treatments.

Figure 7 presents the apparent nutrient use efficiencies of wheat. Note that the nutrient recovery by soybean was disregarded, although soybean benefitted from the residual effects of NPK fertilization and the soil organic amendments (Figs. 2 and 3). Also, N, P and K use efficiencies are confounded, because they were applied in combination as NPK fertilizers, straw and manures. As a result, the nutrient use efficiencies presented here for wheat are underestimates and therefore indicated as 'apparent efficiencies'. The mean apparent N use efficiency (aNUE) of wheat ranged from 13-20 kg kg^{-1}. There were no significant differences in aNUE between treatment NPK alone (T1) and NPK + straw (T2 and T3), but NPK + manure had significantly lower aNUE than treatment NPK alone. Mean aPUE ranged from 25-35 kg kg^{-1}; there were no significant differences between NPK fertilization alone (T1) and NPK fertilization + straw (T2 and T3) in aPUE. Animal manures provided extra P input (50-70 kg ha^{-1} yr^{-1}) and led to lower aPUE in treatment T4 and T5 compared to T1. Mean aKUE ranged from 20-26 kg kg^{-1}. NPK fertilization (T1) resulted in the highest aKUE. Adding straw and animal manures led to lower aKUE in T2-T5 relative to T1 because of the added K via straw and manures.

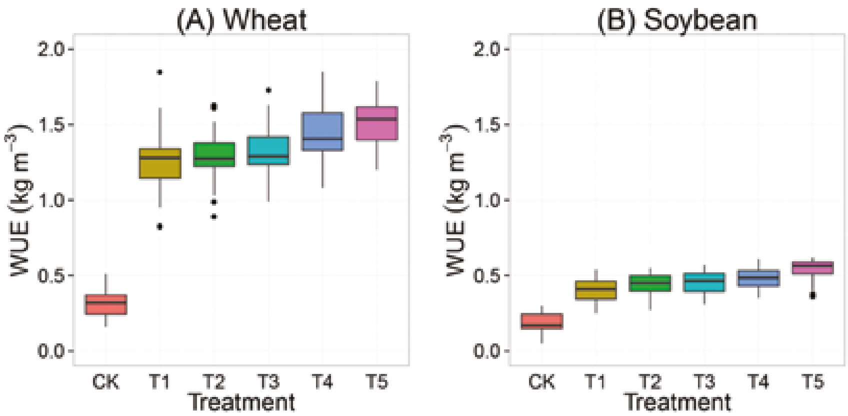
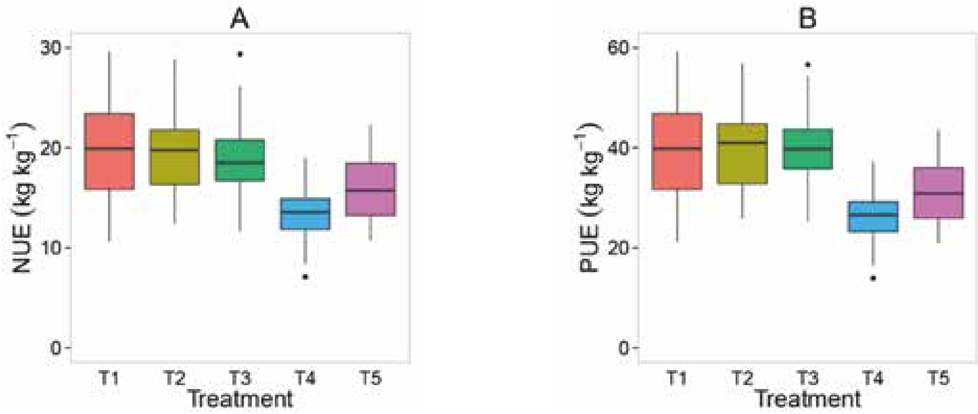


Figure 6. Water use efficiency (WUE) of wheat (A) and soybean (B) as function of fertilization treatments during the period 1982-2012. The treatments are noted as: no fertilization (CK), mineral NPK (T1), NPK + low rate of straw (T2), NPK + high rate of straw (T3), NPK + pig manure (T4) and NPK + cattle manure (T5). Boxes show 25th and 75th percentiles (i.e. Q1 and Q3). Lines in the boxes show the median values.



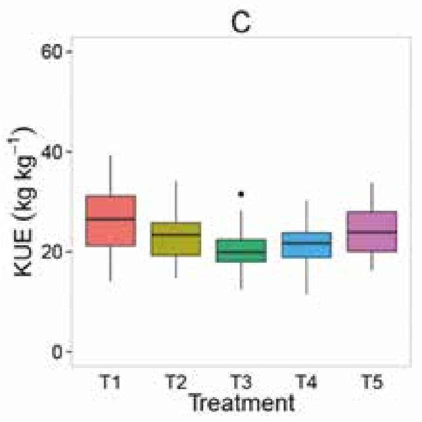


Figure 7. Effects of fertilization and soil conservation treatments on nitrogen use efficiency (A), phosphorus use efficiency (B) and potassium use efficiency (C) in wheat, as function of fertilization treatments during the period 1982-2012. The treatments are noted as: no fertilization (CK), mineral NPK (T1), NPK + low rate of straw (T2), NPK + high rate of straw (T3), NPK + pig manure (T4) and NPK + cattle manure (T5). Boxes show 25th and 75th percentiles (i.e. Q1 and Q3). Lines in the boxes show the median values.

4

4.3.7. Effects of straw mulching, plastic and irrigation

Figure 8 shows the calculated effects of straw mulching, plastic film cover and irrigation on wheat and soybean yields. Straw mulching and plastic cover may increase mean wheat yields by 10-15%, and irrigation by 35%, compared with the reference yields (Figure 8A). Straw mulching, plastic cover and irrigation had no effects on soybean yields, because soybean yields were not limited by water (Figure 8B). Mulching and plastic cover increased WUE of wheat by 15-25%, supplementary irrigation with 100 mm of water increased WUE by 5% (Figure 9A). Straw mulching, plastic film cover and irrigation decreased the variation in yield between years. Effects of mulching, covers and irrigation were larger in relatively dry years than in relatively wet years.

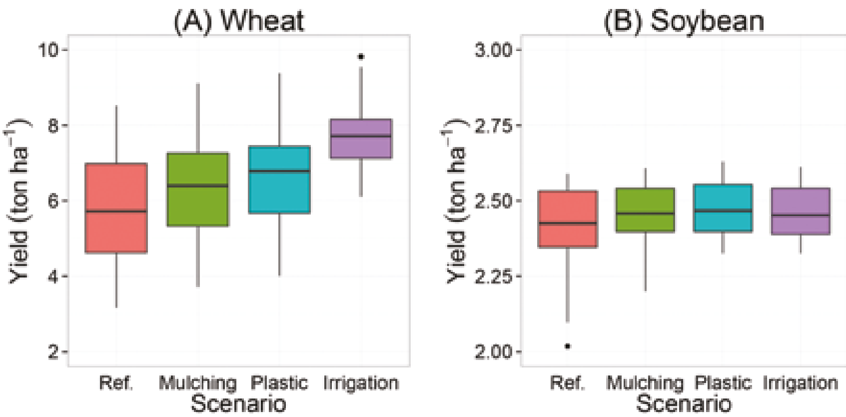


Figure 8. Simulated wheat (A) and soybean (B) yield with straw mulching, plastic film cover and irrigation for the period 1982 - 2012. The reference (Ref.) is the simulated yield with common range of initial soil water content of 60-75% field capacity.

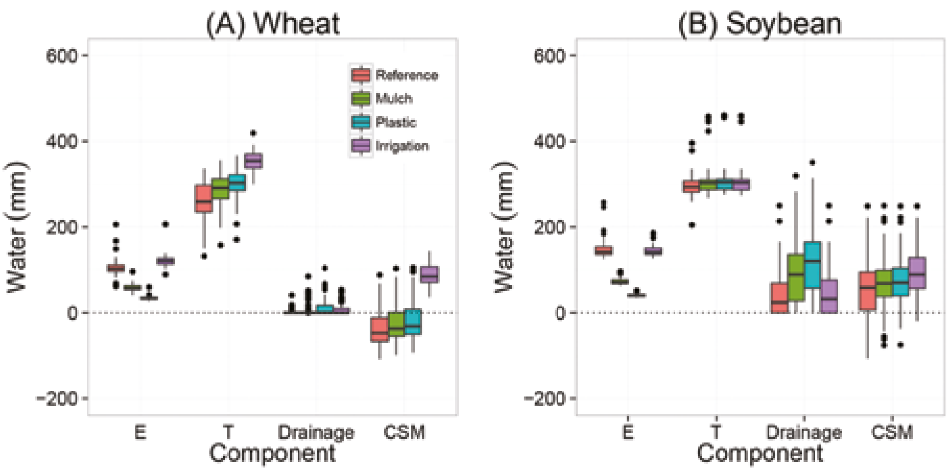


Figure 9. Simulated components of the water balances for wheat (A) and soybean (B) as function of straw mulching, plastic film cover and irrigation.

4.4. Discussion

4.4.1. Imbalances in fertilization

Wheat and soybean yields in the unfertilized control treatment (CK) of our long-term field experiment were strongly limited by nutrients. NPK fertilization increased yields of wheat and soybean on average by a factor of 5 and 2.5, respectively, compared to the CK treatment (Figure 2). NPK + manure increased yields more than NPK + straw and NPK alone. The additional effect of animal manure (compared to NPK alone) is likely due to the increased amounts of available K. Apparently, the recommended rate of 135 kg K_2O ha^{-1} yr^{-1} was insufficient to replenish the annual K withdrawal in harvested crop and K leaching losses. When assuming a mean K content of 5 g per kg in grain and 10 g per kg in straw (Figure S1), and a harvest index of 45%, the annual mean withdrawal with the harvested wheat crop is 85 kg K ha^{-1} yr^{-1}, equivalent to 100 kg K_2O ha^{-1} yr^{-1} (range 80-120 kg K_2O ha^{-1} yr^{-1}). Withdrawal of K with harvested soybean is estimated at 30-50 kg K_2O ha^{-1} yr^{-1} in the fertilized treatments. This simple balance calculation indicates that the total K withdrawal with harvested crops is equal to or exceeds the application rate with the chemical NPK fertilizers, and therefore is insufficient for sustaining high yields in the long term, especially when the soil has a relatively low K supplying capacity.

Potassium deficiency was identified as a constraint to increasing rice yields in Asia in 1990s. The low rates of K fertilization practiced at that time were insufficient to replenish the amount of K removed by intensive lowland rice production(Dobermann et al., 1998; Hoa et al., 2006). The occurrence of K deficiency is in part also related to the decreasing trend of using manures to cereal crops. China has a long history of using animal manures as nutrients input to crops. However, the application of organic manures to cereal crops dramatically decreased since the 1980s. As a result, K deficiency also became a limiting factor for rice, wheat and maize production in many regions in China(Darilek et al., 2009; Wang et al., 2014). In our study, manure application provided extra K input of some 50-60 kg ha^{-1}, which likely contributed to increased wheat yields.

Manure application contributed to P accumulation in the soil; Olsen P values in the treatment NPK fertilizer + manure (T4 and T5) rapidly increased to around 75 mg kg^{-1} and then remained at this level during the course of the experiment, suggesting soil P saturation and leaching of P from the top soil to the subsoil. The optimal P Olsen level for cereals in in the range of 10 to 20 mg kg^{-1} Bai et al. (2013). Olsen P remained within the recommended range of 10-20 mg kg^{-1} in the treatments T1-T3, suggesting that the P inputs via NPK fertilizers and straw were adequate. Manure application also provided extra N of 100-130 kg ha^{-1}. However, wheat yields in the fertilized

4

treatments were not related to N input (Table S2), suggesting that the N inputs via NPK fertilizers and biological N_2 fixation by soybean were adequate.

Soybean did not receive fertilization in the long-term experiment but clearly benefited from the residual effects of the chemical fertilizers, straw and manures applied to wheat in autumn (Figure 2 and 3). A meta-analysis of soybean N uptake and N fixation showed that, on average, ~55% of soybean N demand was met by biological N_2 fixation(Salvagiotti et al., 2008). In most cases, the amount of N fixed was not sufficient to produce high soybean yield (4-5 ton ha^{-1}). The partial N balance (fixed N in aboveground biomass - N in seeds) was negative in 80% of all data sets, with a mean net soil N mining of 40 kg N ha^{-1} (Salvagiotti et al., 2008). There was a slightly decreasing trend in soil available N in treatment T1 (NPK fertilizer alone) and a slightly increasing trend in SOC content (Figure 4) clearly indicating that the supply of N in this treatment was not excessive. When assuming a mean N content of 15 g per kg in grain and 5 g per kg in straw (Fig S5), and a harvest index of 45%, the annual mean withdrawal with the harvested wheat crop is 105 kg N ha^{-1} yr^{-1} (range 80-125 kg N ha^{-1} yr^{-1}). Withdrawal of N with harvested soybean is estimated at 55 kg N ha^{-1} yr^{-1} (range 25-75 kg N ha^{-1} yr^{-1}) in the fertilized treatments. This indicates that the total N withdrawal with harvested crops was close to but might exceed the N application rate of 180 kg ha^{-1} yr^{-1}, especially during the second half of the experimental period when N contents were slightly higher compared to the first half of the experimental period (Figure S1).

4

4.4.2. Water deficiency and fertilization effects

High-yielding wheat varieties require 450 to 650 mm of water, depending on climate, yield and length of the growing period(FAO, 2015a). In this study, the estimated ET of wheat ranged from 210 to 500 mm (mean=360 mm), and that of soybean from 370 to 630 (mean=440 mm). Likely, wheat yields in the fertilized treatments were limited by low seasonal rainfall (mean=300mm). The estimated mean ET was comparable with previous studies on wheat-soybean double cropping systems. For example, Daniels and Scott (1991) reported that mean ET of rainfed wheat was 328 mm. For irrigated and non-irrigated soybeans, the mean ET was 375 and 255 mm, respectively. Caviglia et al. (2004) reported that mean ET of wheat ranged from 313 to 334 mm, and that of soybean from 359 to 434 mm. Singh et al. (2014) reported that mean ET of wheat and soybean were around 350 and 400 mm, respectively.

Nutrient availability greatly affected crop transpiration and thereby yields; mean T/ET ratio was low in the CK treatments, i.e. 18% for wheat and 27% for soybean. Low T (and thereby low T/ET ratio) in the CK treatments was mainly due to severe soil nutrient deletion (Figure 5). Olsen P dropped to values of <5 mg kg^{-1}, and soil available N and K also had decreasing trends in CK (Figure 4). Nutrient deficiency in CK significantly limited crop growth and thereby led to low transpiration and relatively large soil evaporation. In the fertilized treatments, the T/ET ratio was 56-67% for wheat and 52-66% for soybean (Figure 5). Similar T/ET ratios (60-70%) have been reported for wheat by some previous studies(Kang et al., 2003a; Liu et al., 2002; Wang et al., 2012a). Despite of large differences in T/ET ratios between fertilized and unfertilized treatments, the total amount of water consumed as evapotranspiration (ET) was rather similar (differences<30mm), indicating that ET was not strongly affected by fertilization, as observed also by some previous studies(Corbeels et al., 1998; Jin et al., 2014; Lopez-Bellido et al., 2007). Therefore, yields were often more closely related to transpiration than to total available water (Figure S2).

Compared to semi-arid regions in Northwest China, Anhui has relatively high annual rainfall (900 mm), which provides the possibility to grow two crops per year. However, the annual yields of the rainfed wheat-soybean system highly depend on the amount of rain. Soil mulching with straw or plastic are common measures to reduce evaporation and thereby increase crop yields and WUE in Northwest China (Gan et al., 2013; Wang et al., 2012b), but not in Anhui. Our model simulations indicate that straw mulching and plastic cover could increase mean wheat yield by 10-15%, and supplementary irrigation of 100 mm could increase mean wheat yields by 35% (Figure 7A). Most of the straw is currently used as animal feed, burned or ploughed down in the soil. In treatments with chemical NPK fertilizers and straw (T2 and T3), the straw is ploughed into the soil after harvest of the wheat. Further field studies need to be conducted to evaluate the effectiveness, efficiency and feasibility of straw mulching and plastic covers in this region.

4.4.3. Increasing trend of crop yields

Over the 30 years' period, mean wheat and soybean yields increased by 1.5-2.1 and 0.3-0.9 ton ha^{-1} in the fertilization and soil organic amendment treatments. In contrast, yields decreased in the control treatments. Evenson and Gollin (2003) indicated that improvements in breeding accounted for around 50% of the yield increase in developing countries during the period 1981 to 2000, whereas improved management and inputs of fertilizers, irrigation, mechanization, and improved labor skill together accounted for the other 50%. We were not able to quantify the contributions of single factors to the steady yield increase during the period 1982 to 2012, but improved genetic varieties and improved crop husbandry (including weed and pest control) certainly have played a role. Inputs of fertilizers, straw and manure did not change over time (Table 2), although we cannot exclude the possibility that the quality of the straw and manure has changed over time, and that the indirect effects have contributed to the steady yield increases.

Long-term fertilization and addition of organic amendments led to increased soil organic matter contents over time(Hua et al., 2014), which may contribute indirectly to increased crop growth and development. Li et al. (2009) reported that long-term additions of animal manure increased soil moisture availability by 30 to 45 mm in a 2 meter deep soil profile. Contents of SOC increased significantly in the treatments with manure and straw (Figure 4), but we have no experimentally derived data that indicated how much soil moisture availability changed over time. Likely, some of the yield difference between the treatments with chemical fertilizer without and with manure has to be attributed to the increased SOC content and to the likely increased soil moisture availability in the treatments with animal manure. There were clear correlations between SOC content and crop yield (Figure S3), but the relationship between SOC and yield is highly nested to soil available N (soil N mineralization) and K. Further, manure provides also other essential nutrient elements than NPK (including sulphur, copper, zinc), which may have contributed to the yield difference between treatments T1 and T4/T5.

4.5. Conclusions

Long-term fertilization significantly improved soil fertility over time, which enhanced crop transpiration and thereby yields of wheat and soybean. On average, wheat yields were 5 times and soybean yields 2.5 times higher in fertilized treatments than in the unfertilized CK. Among the fertilized treatments, NPK + manure increased yields more than NPK + straw and NPK alone. The additional effect of animal manure (compared to NPK alone) is likely due to the increased amounts of available K, and possibly the supply of sulphur and micronutrients. Furthermore, long-term fertilization and soil organic amendments also significantly improved yield stability of wheat and soybean.

Wheat yields in the fertilized treatments (T1-T5) were not significantly related to N and P inputs. Manure application rapidly increased P-Olsen to ~75 mg kg^{-1}. Thereafter P-Olsen did not increase further, suggesting leaching of P from the top soil to the subsoil. Clearly, manure application had additional effects to mineral NPK fertilizers. However, manure application rates were far too high for optimal fertilization; manure could have largely replaced the chemical NPK fertilizer input.

Model simulations reveal that wheat yields were limited by water and may be increased by 15% through soil mulching or by 35% through irrigation. The effectiveness of these measures need to be tested further in the fields. Given the important role of the North China Plain in ensuring the national food security with limited land and water resources, increasing the productivity and the sustainability of the rainfed agricultural systems in China will rely on delicate field managements that can integrate soil improvement, and water and nutrient use in site and crop specific manner.

Acknowledgements

We thank the staff of Madian Agro-Ecological Station for conducting the long-term field experiments. We thank Zhanguo Bai from ISRIC and Igor Staritsky from Wageningen UR for helping us with data collection. We thank Walter Andriuzzi and Xinxin Wang from Wageningen UR for many useful discussions on statistical analysis.

Supplementary information

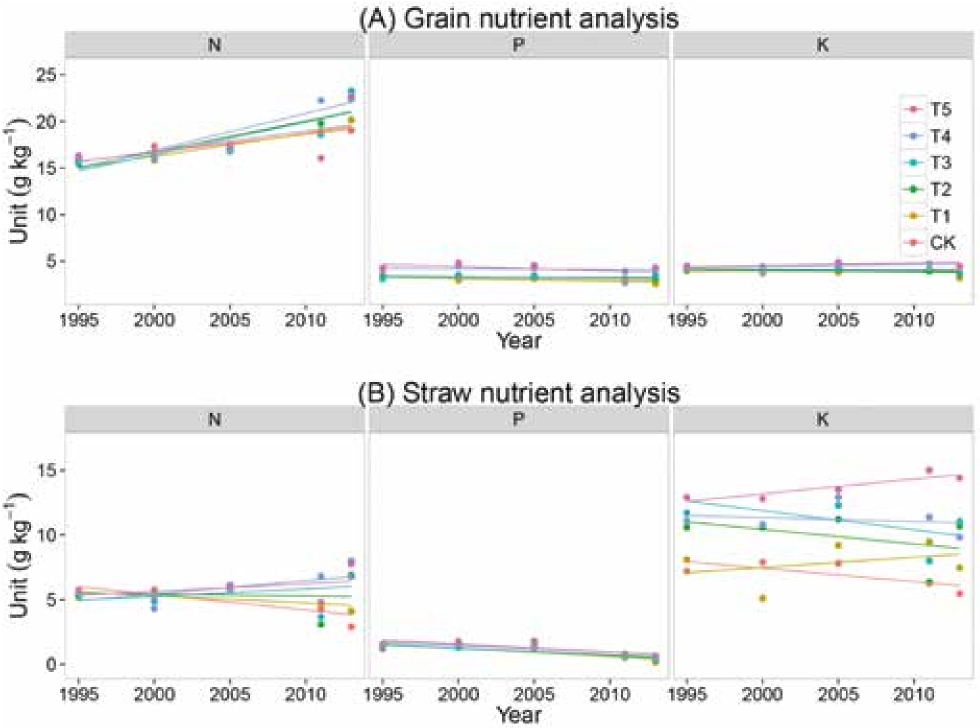


Figure S1. Nutrient content of grain (A) and straw (B) of wheat over time. N, P and K content were analysed at harvest. Grain N content slightly increase over time, ranging from 15 to 20 g/kg, whereas grain P and K contents mostly ranged from 2.5 to 5 g/kg. Grain P and K content in manure treatments were higher than that in other treatments. Straw N content ranged from 2.5 to 7.5 g/kg, straw P content ranged from 1 to 2 g/kg and had slightly decreasing trend. Variation in straw K content was relative large (range 5 to 15 g/kg), with higher contents in manure treatments. This suggest that K was perhaps a yield limiting factor; note also that K content in CK decreased.

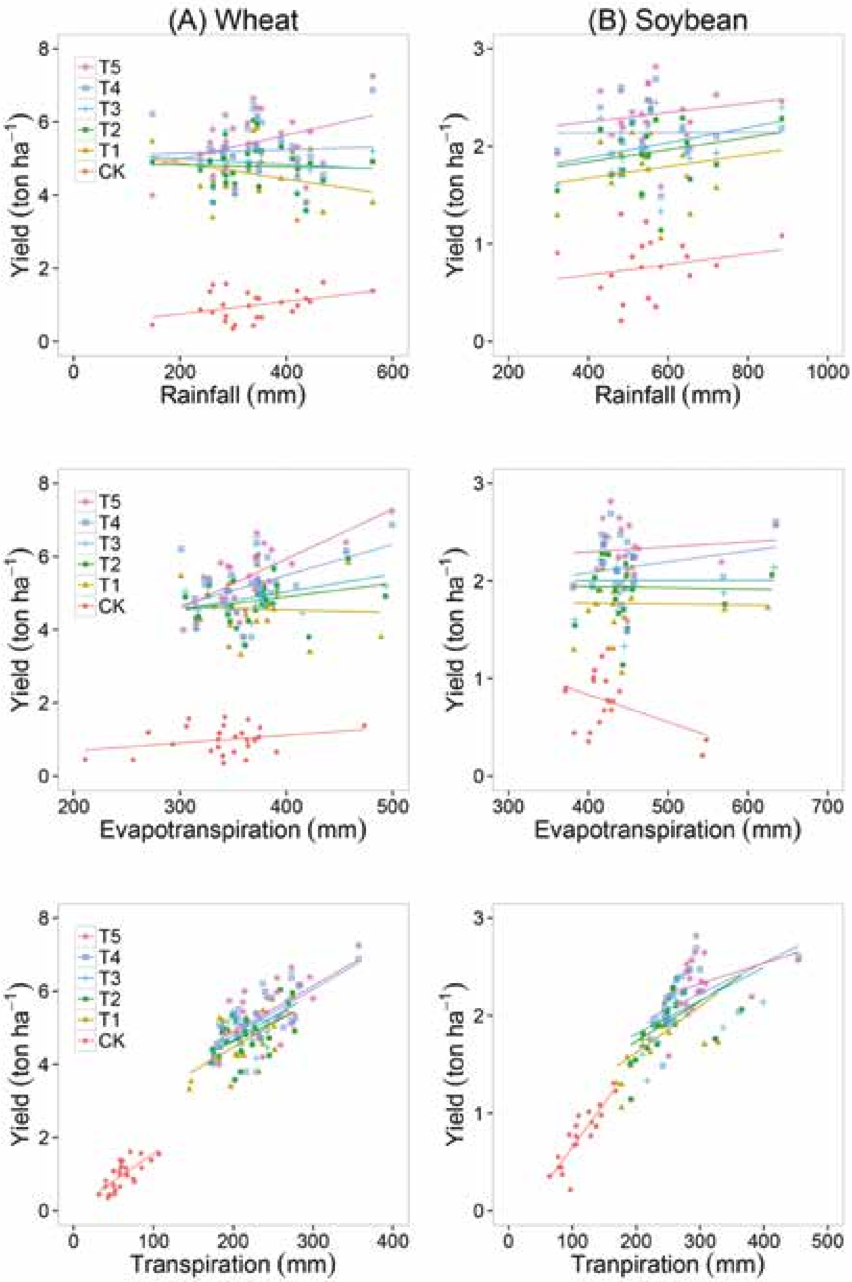


Figure S2. Relationships between rainfall, evapotranspiration (ET) and transpiration (T) and grain yields of wheat and soybean. Statistics are summarized in Table S3.

4

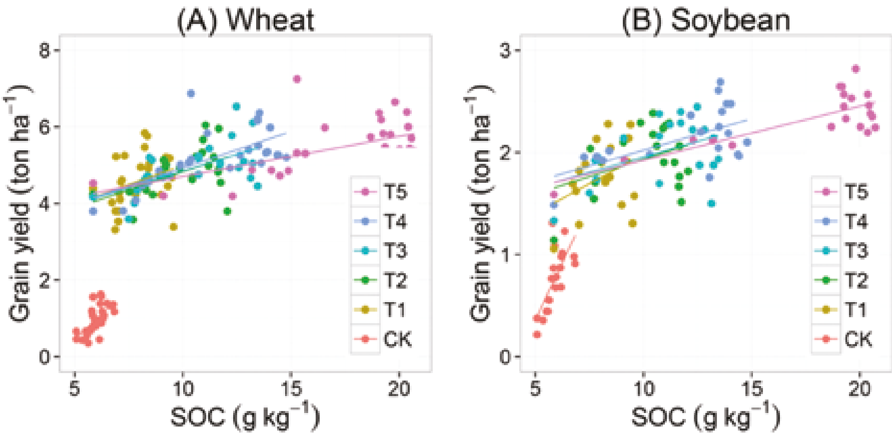


Figure S3. Correlations between grain yields of wheat and soybean to soil organic carbon.

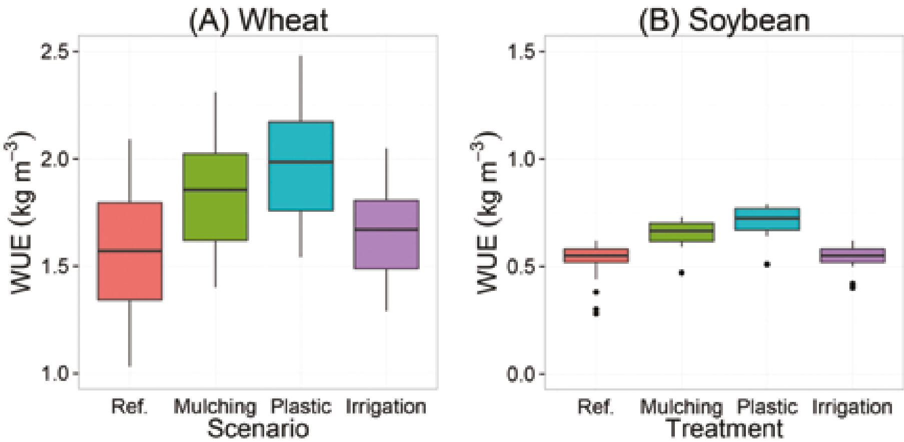


Figure S4. Simulated WUE of wheat (A) and soybean (B) with straw mulching, plastic film cover and irrigation for the period 1982 - 2012.

Table S1. List of crop parameters for wheat and soybean used in the AquaCrop model.

Parameters	Crops		Sources
	Wheat	Soybean	
Crop development (in calendar days)			
From sowing to emergence	10 days	10 days	Field observation
From sowing to max. canopy	150 days	60 days	Field observation
From sowing to flowering	160 days	75 days	Field observation
From sowing to senescence	190 days	100 days	Field observation
From sowing to maturity	220 days	110 days	Field observation
Building up Harvest Index (HI)	32 days	35 days	Field observation
Duration of flowering	15 days	10 days	Field observation
Plant density	300 plants m^{-2}	180 plants m^{-2}	Field observation
Sowing rate	150 kg seed ha^{-1}	405 kg seed ha^{-1}	Field observation
1000 seed mass	40 g	180	Field observation
Germination rate	80%	80%	Field observation
Max. root depth	2 m	2 m	Field observation
Reference HI	45%	42%	Field observation
Max HI	52%	46%	Field observation
Crop water productivity	20g m^{-2}	9 g m^{-2}	Calibrated
Canopy development			
Initial canopy cover	4.5%	9%	Field observation
Canopy expansion	4% day^{-1}	9.8% day^{-1}	Calculated by AquaCrop
Max. canopy cover	95%	95%	Field observation
Canopy decline	7.2% day^{-1} (41 days)	10.3% day^{-1} (28 days)	Calculated by AquaCrop
Thresholds temperatures			
Base temperature for biomass production	0 ^{o}C	0 ^{o}C	Calibrated
Upper temperature for biomass production	32 ^{o}C	35 ^{o}C	Calibrated
Range of cold stress for biomass production	0 - 14 ^{o}C	0-10 ^{o}C	Calibrated
Range of cold stress for pollination	4-9 ^{o}C	3-8 ^{o}C	Calibrated
Range of heat stress for pollination	32 - 37 ^{o}C	40-45 ^{o}C	Calibrated
Water extraction pattern in the root zone			
Upper 1/4 (0-0.5m)	40%	40%	Calibrated
Second 1/4 (0.5-1m)	30%	30%	Calibrated
Third 1/4 (1-1.5m)	20%	20%	Calibrated
bottom 1/4 (1.5-2m)	10%	10%	Calibrated

4

Water stresses			
Canopy expansion	Moderately tolerant (upper = 0.25, lower = 0.60, shape factor = 5)	Sensitive (upper = 0.15, lower = 0.65, shape factor = 3)	Calibrated
Stomatal closure	Extremely sensitive (upper=0.25, shape factor = 2.5)	Moderately sensitive (upper=0.5, shape factor = 3)	Calibrated
Early canopy senescence	Tolerant (upper = 0.75, shape factor =2.5)	Moderately tolerant (upper = 0.7, shape factor =3)	Calibrated
Aeration stress	Moderately tolerant (5 vol%)	Moderately tolerant (5 vol%)	Calibrated
Evapotranspiration			
Soil evaporation coefficient	Effect of canopy shelter in late season = 50%	Effect of canopy shelter in late season = 25%	Default in AquaCrop
Crop transpiration coefficient	1.1 (reduction with age = 0.15%/day)	1.1 (reduction with age = 0.3%/day)	Default in AquaCrop
Fertilities stresses	Considered	Considered	Calibrated

Table S2. Results of the statistical analysis of the effects of rainfall (R), N, P and K inputs, and the interactions between rainfall and N, P and K input in wheat yields.

Interactions	Item	Estimate	Std. Error	df	t value	p value	Sign.
Included	(Intercept)	7.23	1.13	128.1	6.399	0.00	***
	β_1(R)	-0.01	0.00	128.2	-3.23	0.00	**
	β_2(N)	-0.01	0.02	107.7	-0.589	0.56	NS
	β_3(P)	0.02	0.03	107.5	0.586	0.56	NS
	β_4(K)	-8E-03	0.01	105.2	-1.438	0.15	NS
	β_5(R*N)	4E-06	0.00	107.5	0.074	0.94	NS
	β_6(R*P)	8E-06	0.00	107.2	0.105	0.92	NS
	β_7(R*K)	4E-05	0.00	105.1	2.66	0.01	**

† Yields of the NPK treatment (T1) are set as the reference in the statistical analysis. Hence, the intercept shows the intercept of yields of T1. The following items show the effects (slopes), compared to the intercept.
‡Significance were displayed with numbers of asterisk, '***' means p value $\leq$ 0.001, '**' means 0.001< p value $\leq$ 0.01, '*' means 0.01 <p value $\leq$ 0.05 and ' NS' means p value >0.05, i.e., not significant.

Table S3. Yield response to seasonal rainfall, evapotranspiration and transpiration.

		Rainfall					Evapotranspiration					Transpiration				
Crop	Treatment	Intercept†	Slope	r^2	p_value	Sign.	Intercept†	Slope	r^2	p_value	Sign.	Intercept†	Slope	r^2	p_value	Sign.
Wheat	CK	0.4	0.002	0.15	0.05	NS	0.3	0.002	0.07	0.18	NS	0.1	0.015	0.48	0.00	***
	T1	5.3	-0.002	0.07	0.18	NS	4.8	-0.001	0.00	0.83	NS	1.9	0.013	0.34	0.00	**
	T2	4.9	0.000	0.00	0.84	NS	3.4	0.004	0.07	0.20	NS	2.6	0.010	0.29	0.00	**
	T3	5.1	-0.001	0.01	0.62	NS	3.1	0.005	0.10	0.12	NS	2.1	0.013	0.39	0.00	***
	T4	5.1	0.000	0.00	0.80	NS	2.2	0.008	0.22	0.01	*	2.3	0.013	0.45	0.00	***
	T5	4.3	0.003	0.13	0.07	NS	0.5	0.014	0.52	0.00	***	2.4	0.013	0.43	0.00	***
Soybean	CK	0.5	0.001	0.04	0.38	NS	1.9	-0.003	0.18	0.06	NS	-0.2	0.009	0.77	0.00	***
	T1	1.4	0.001	0.05	0.37	NS	1.8	0.000	0.00	0.94	NS	0.7	0.005	0.37	0.00	**
	T2	1.6	0.001	0.05	0.33	NS	2.0	0.000	0.00	0.92	NS	0.9	0.004	0.29	0.01	*
	T3	1.6	0.001	0.08	0.22	NS	2.0	0.000	0.00	0.99	NS	1.1	0.003	0.25	0.02	*
	T4	2.1	0.000	0.00	0.98	NS	1.6	0.001	0.04	0.37	NS	1.3	0.003	0.31	0.01	*
	T5	2.1	0.000	0.04	0.40	NS	2.1	0.001	0.01	0.68	NS	1.7	0.002	0.11	0.15	NS

† The unit of intercept is ton ha^{-1}.

Wei Qin
Falentijn B.T. Assinck
Marius Heinen
Oene Oenema

Chapter 5

Water and nitrogen use efficiencies in orange production: a meta-analysis

This paper has been submitted for publication

Abstract

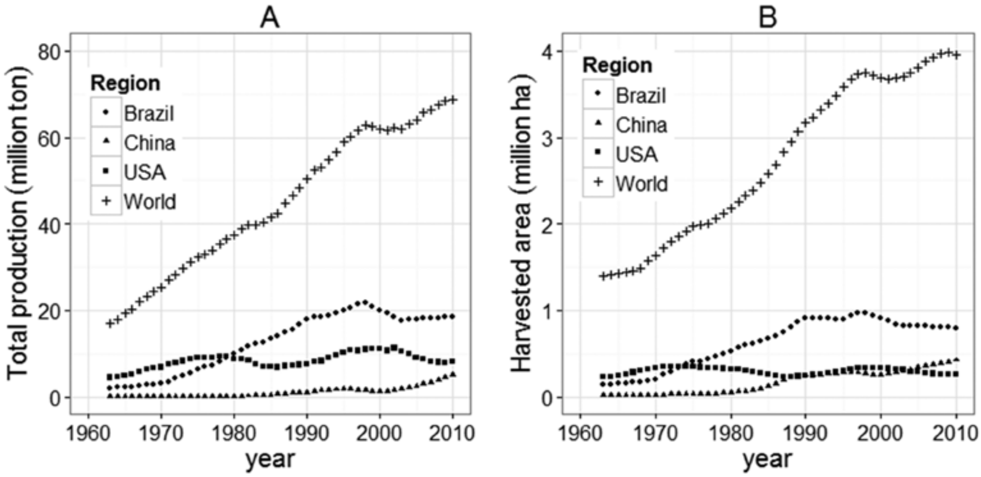
Water and nitrogen (N) are two key limiting factors for orange (*Citrus sinensis*) production. Reported effects of water and N inputs on orange yield, water use efficiency (WUE) and N use efficiency (NUE) vary greatly, mainly due to differences in cultivars, tree age, climate, soil types, and water and N input levels. So far, no systematic analysis has been performed, and as a result, the interactive effects of water and N inputs on yield, WUE and NUE of orange orchards are unknown. Also, gaps between attainable and actual yields, WUE and NUE have not been established yet. Here, we report on a global meta-analysis of yields, WUE and NUE of orange production systems, using 1009 observations from 55 studies, conducted in 11 countries. Median orange yields ranged from 30 to 60 ton ha^{-1}, which were in between average global yields (range 10-30 ton ha^{-1}) and attainable yields (range 60-90 ton ha^{-1}). Median WUE ranged from 2.5 to 5 kg m^{-3} and median NUE from 150 to 350 kg kg^{-1}. Orange yields were related to water and N inputs and tree age. Relationships between water and N inputs and yield, WUE and NUE were also analysed for sub-datasets and quantiles, to examine the relationships near the extremes. There were statistical significant interactions between water and N inputs in yield and NUE, but not in WUE. This indicates that studies aiming at the optimization of water and N inputs must consider interactions and must optimize water and N inputs simultaneously. Based on our analyses, we estimated that reducing over-optimal irrigation to optimal irrigation may increase orange yield by 20%, WUE by 30% and NUE by 15%. Similarly, reducing over-optimal N fertilization to optimal N fertilization may increase yield by 10%, WUE by 15% and NUE by 40%. We concluded that there is room for a significant increase in yield, WUE and NUE through the simultaneous optimization of water and fertilizer N inputs via precision fertigation.

5

Keywords: citrus, efficiency, fertilizer, irrigation, meta-analysis, nitrogen, orange, water.

5.1. Introduction

Oranges (*Citrus sinensis*) are one of the most important fruits in the global market. Global orange production has quadrupled from 16 million tons in the early 1960s to 68 million tons in 2012 (FAO, 2014b). This increase was the combined result of the increase in the area of orange orchards and the increase in fruit yield per unit area of land (Figure 1). The rapid development in orange production has been driven by the increasing demand of nutritious and healthy food (oranges have a high vitamin C content), and is facilitated by significant improvements in crop husbandry, logistics and processing (notably frozen concentrated orange juice) (Alva et al., 2008; FAO, 2014b; Steduto et al., 2012).



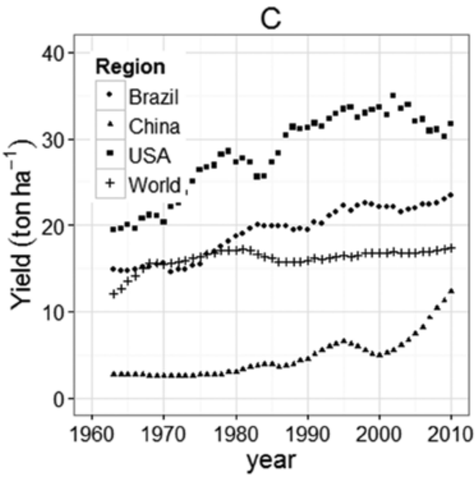


Figure 1. Historical trends of total orange fruit production (A), total harvested areas of orange orchards (B), and mean orange yields (C), for the world and for the three main orange producers USA, China and Brazil during the period 1961 to 2010. Results are presented as five-years moving averages. Data source: (FAO, 2014b).

5

Orange trees mainly grow in subtropical and tropical regions because of their sensitivity to low temperatures and differ between cultivars. Main cultivars are Valencia, Washington Navel, Salustiana and Shamouti. The trees produce oranges annually and continue to do so for many decades, when the trees are well-maintained. In the Northern Hemisphere, the main vegetative growth occurs in February and March. Most cultivars produce flowers in spring, and fruits may take 6 to 8 months to ripen, depending on the climatic conditions (Steduto et al., 2012). Because of the long growing season and warm climate, orange trees require relatively large amounts of water and nutrient elements.

Evapotranspiration (ET) by orange orchards ranges from 800-1500 mm yr^{-1}, depending on region and climate (Steduto et al., 2012). For important orange production regions, such as Spain, Brazil and Florida (USA), there is need for irrigation to supplement the deficit between ET and the supply via rainwater. The amount of irrigation typically ranges between 200 and 800 mm yr^{-1} (Ballester et al., 2011, 2013; Morgan et al., 2010; Romero et al., 2009). Soil evaporation may contribute significantly to ET, especially when the canopy of the orchard is small, the climate is hot and the whole field is irrigated. Because of shrinking freshwater resources, there is a pressing need to optimize the irrigation management and to reduce the amount of irrigation water where possible (Ballester et al., 2013; Steduto et al., 2012).

Fertilizer nitrogen (N) inputs in mature orange orchards typically range between 150 and 350 kg ha^{-1} yr^{-1}. Leaching losses of N can be high (50 – 150 kg ha^{-1} yr^{-1}), especially when N fertilizer supply is over-optimal (Alva et al., 2008; Alva et al., 2006a; Lidon et al., 2013; Quiñones et al., 2007). These N losses contribute to pollution of groundwater and surface water bodies and there is therefore a great need to reduce these losses (Sutton et al., 2013; Sutton et al., 2011).

5

Several studies have explored options to save water and fertilizer N in orange production systems, but these studies often focus on the optimization of the use of either water or N separately. The simultaneous optimization of water and N supply is complicated due to the many interacting factors, such as climate, crop variety, soil type and irrigation and fertilization technology, and also because of different disciplinary research interests (Alva et al., 2008; Srivastava, 2012; Steduto et al., 2012). Ballester et al. (2011) reported that deficit irrigation may save 20% of the irrigation water without yield reduction, compared to 100% ET irrigation. However, a reduction with 44% relative to the 100% ET irrigation level led to a yield reduction of 17% (Gonzalez-Altozano and Castel, 1999). The sensitivity to water stress also differs between growth stages. The optimal N input varies with variety and orange yield. For a yield of 40 ton ha^{-1}, the optimal N input is around 150 to 200 kg ha^{-1}. For a yield level of 80 ton ha^{-1}, the optimal N input is around 250 kg ha^{-1} (Alva et al., 2006b; Quiñones et al., 2007).

The available information on the effects of water and N inputs and of their possible interactions in orange yield, water use efficiency (WUE) and N use efficiency (NUE) have not been systematically analyzed and synthesized yet. Such integrative analyses may increase the quantitative understanding of the effects of water and N inputs on orange yield, WUE and NUE, and may contribute to improved recommendations for irrigation and fertilization of orange orchards. The objectives of this study were therefore (i) to review and summarize the information in literature on water and N use in orange production systems, (ii) to quantify the relationships between water and N inputs on yield, WUE and NUE, and (iii) to explore the options for increasing yield, WUE and NUE in orange production system. In particular, we were interested in possible interactions between water and N inputs in yield, WUE and NUE, as the optimization of water and N inputs in separated studies will likely neglect such interactions.

5.2. Materials and methods

5.2.1. Data collection

We searched in peer-reviewed literature for publications that reported water and N use in orange production, using Scopus (Elsevier; access date 01-May-2015). Search terms included ‘orange’ and/or ‘citrus’, ‘water’ and/or ‘nitrogen’, ‘evapotranspiration’, ‘irrigation’ or ‘fertigation’ in the article title, abstract, and keywords. Conference proceedings and non-English language publications were excluded. We screened the publications on the basis of the following criteria: (1) orange yields, water and N inputs were documented; (2) experimental site and year were provided, and (3) age and cultivar of the orange tree were indicated. The final analysis was based on 1009 yield observations from 55 studies conducted in 11 countries.

5

5.2.2. Definitions

Water use efficiency (WUE, in kg m^{-3}) was defined as:

$$WUE = Y / W \tag{1}$$

where Y is orange yield (in ton ha^{-1}), W is the sum of rain and irrigation water (in mm). We used W as denominator because W represents the actual water input to the system. W can be larger than ET because surface runoff and leaching (belowground drainage) may occur. Possible changes in soil moisture between growing seasons were neglected, mainly because orange tree is a perennial crop.

Nitrogen (N) use efficiency (NUE, kg kg^{-1} or in %) was defined as:

$$NUE = Y/N \tag{2}$$

where N is the N fertilizer input (kg ha^{-1}). Possible N inputs from atmospheric deposition, bio-fixation and net mineralization of organically bound soil N were neglected, because these inputs were likely small, difficult to manage, and because most studies did not report these inputs.

5.2.3. Data analysis

Estimating the mean effects of multiple independent variables

The effects of water and N inputs, tree age and mean temperature on orange yield, WUE and NUE) were analysed with a mixed-effects model via the R package "nlme" (Pinheiro et al., 2013; R Core Team, 2013):

$$Y = \alpha + \beta_1 * W + \beta_2 * N + \beta_3 * \mathrm{A} + \beta_4 * \mathrm{T} + \beta_5 * W * N + error \tag{3}$$

where Y is yield (in ton ha^{-1}), $b_{1\text{-}5}$ represent the response due to changes in a variable, W is total water input (rainfall + irrigation), N is fertilizer N input, A is tree age, T is mean air temperature during the growing season (°C), W*N is the water input x N input interaction and *error* is the residual that was not explained by the independent variables. Note that all independent variables are continuous variable.

Similar analyses were also made for WUE and NUE:

$$WUE = \alpha + \beta_1 * W + \beta_2 * N + \beta_3 * \mathrm{A} + \beta_4 * \mathrm{T} + \beta_5 * W * N + error \tag{4}$$

$$NUE = \alpha + \beta_1 * W + \beta_2 * N + \beta_3 * \mathrm{A} + \beta_4 * \mathrm{T} + \beta_5 * W * N + error \tag{5}$$

5

Relationships and sub-groups analysis

To facilitate the understanding of interactions between water and N inputs on orange yields, WUE and NUE, we conducted sub-groups analysis; in the relationships between water inputs and dependent variables (i.e., yield, WUE and NUE), we compared the regression lines (intercepts and slopes) between high and low N input (here data points were sub-grouped into two equal sub-datasets according to N input levels); whereas in the relationships between N inputs and dependent variables, we compared the regression lines between high and low water input (here data points were sub-grouped into two equal sub-datasets according to water input levels). Linear regression was conducted for each sub-dataset, respectively, using ordinary least squares (OLS) method.

Quantile regression

Quantile regression (QR) allows the estimation of the responses of dependant variable at different quantiles to the independent variables; i.e., several sets of intercepts and slopes can be provided by QR, depending on the number of quantiles considered. For large scattered datasets, a QR plot can provide a better understanding of data structure than OLS because it provides the regression also for the extremes (Koenker and Hallock, 2001). Quantile regression plots were made for the relationships between water and N inputs on the one hand and orange yield, WUE and NUE at the other hand, for quantiles and extremes of the data set, using the methods described by (Koenker, 2013; R Core Team, 2013).

Estimating the effects of sub- and over-optimal water and N input on yield, WUE and NUE

Both sub-optimal and over-optimal water and N input levels may lead to reductions of yield, WUE and NUE. To have a robust estimate of the magnitude in yield reductions, and reductions in WUE and NUE due to sub-optimal and over-optimal water and N supply, we conducted a side-by-side comparison (to derive the effect size) between the observed yield and the highest yield for each experimental year and study. Optimal water and N inputs for each experimental year and study were derived from the least input levels that produced the highest yield.

These side-by-side comparisons were made because orange yield often varies greatly between years within a study. For a side-by-side comparison, the dataset must contain at least two levels of water inputs and/or two levels of N inputs. Hence, the dataset was rearranged into two sub-datasets; one was related to water input and consisted of 818 observations from 44 studies, and the other was related to N input and consisted of 487 observations from 17 studies.

5

The magnitude (effect size) of sub-optimal and over-optimal water and N input levels on yield was estimated from the natural logarithm of the response ratio (*R*) (Hedges et al., 1999) for each study, according to:

$$\ln R_{\mathrm{Y}} = \ln\,(Y_{\mathrm{obs}}/Y_{\mathrm{ref}}) \tag{6}$$

where Y_{obs} is the observed yield in a study, and Y_{ref} is the highest yield with optimal water and N inputs, set as reference to be compared with.

Similarly, the magnitude of sub-optimal and over-optimal water and N input levels on WUE and NUE were estimated for each study as:

$$\ln R_{\mathrm{WUE}} = \ln\,(WUE_{\mathrm{obs}}/WUE_{\mathrm{ref}}) \tag{7}$$

$$\ln R_{\mathrm{NUE}} = \ln\,(NUE_{\mathrm{obs}}/NUE_{\mathrm{ref}}) \tag{8}$$

where WUE_{obs} and NUE_{obs} are the observed WUE and NUE in a study, and WUE_{ref} and NUE_{ref} are the reference WUE and NUE with optimal water and N inputs.

For estimating the overall mean effect of sub- and over-optimal water input levels, we analyzed the effect sizes (ln R) with mixed-effects model, using the R package "nlme" (Pinheiro et al., 2013; R Core Team, 2013):

$$\ln R = \alpha + \beta_1 * W + error \tag{9}$$

where α is the intercept with the same dimension as ln$R$, b_1 represents the response due to the water input levels (W) and *error* represents the residual that was not explained by the water input. In the mixed-effects model, water input levels (i.e., over-optimal, optimal, sub-optimal) were set as fixed effects and studies were set as random effects. Note that W here is a categorical variable, which is different than W in Eqs. 3, 4 and 5. Equal weight was given to each calculated effect size of ln$R$.

The same approach was used for estimating the overall mean effect of sub-optimal and over-optimal N input levels:

$$\ln R = \alpha + \beta_1 * N + error \tag{10}$$

In the model, N input levels (i.e., over-optimal, optimal, sub-optimal) were set as fixed effects and studies were set as random effects. Note that N here is a categorical variable, which is different than N in Eqs. 3, 4 and 5.

Estimating water and N saving potentials

Some studies reported that, compared to normal farming practice (i.e., full and/or slightly over-supply of water and N), water and N supply can be reduced to a certain level without yield reduction (Alva et al., 2006b; Ballester et al., 2011, 2013). However, the extent of water and N saving may largely vary between regions. To have a quantitative overview of the extent on water and N saving, here we introduced the concepts of water and N saving potentials (WSP, NSP). The water saving potential in absolute value (WSP, mm) was defined as:

5

$$\mathrm{WSP} = W_{+} - W_{opt} \tag{11}$$

where W_+ represents over-optimal water input, and W_{opt} represents the optimal water input level that produced the highest yield.

The water saving potential in relative percentage (WSP, %) was defined as:

$$\mathrm{WSP} = \left(\frac{W_{+}}{W_{\mathrm{opt}}} - 1 \right) 100\% \tag{12}$$

Similarly, the N saving potential in absolute value (NSP, mm) was defined as:

$$\mathrm{NSP} = N_{+} - N_{opt} \tag{13}$$

where N_+ represents over-optimal N input, and N_{opt} represents the optimal N input level that produced the highest yield.

The N saving potential in relative percentage (NSP, %) was defined as:

$$\mathrm{NSP} = \left(\frac{N_+}{N_{\mathrm{opt}}} - 1\right)100\% \quad (14)$$

5.3. Results

5.3.1. Overview of orange yields, water and N input, WUE and NUE

Variations in orange yields, WUE, NUE, total water inputs, irrigation and fertilizer N inputs were large (Figure 2), mainly because the studies were conducted in different regions and used different cultivars and orchards of different tree age. Orange yields had a normal distribution and ranged from 2 to 90 ton ha^{-1}. WUE ranged from 0.1 to 17 kg m^{-3} and NUE from 5 to 800 kg kg^{-1}. Total water input (rain + irrigation) ranged from 200 to 2500 mm, and irrigation from 100 to 1000 mm. Fertilizer N input ranged from 0 to 450 kg ha^{-1}.

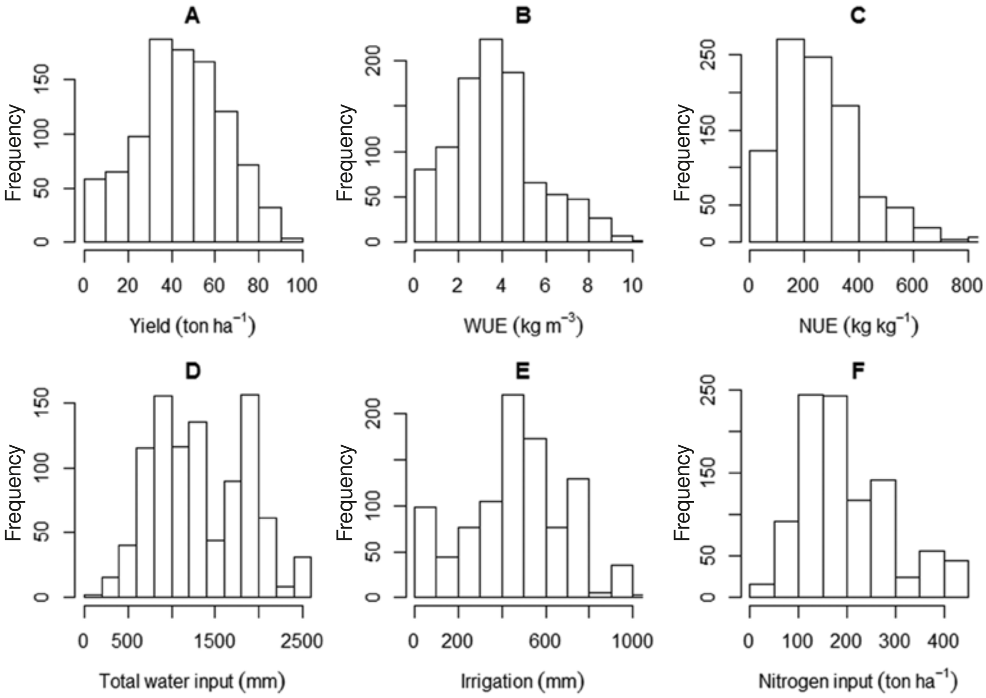


Figure 2. Frequency distributions of orange yields (A), water use efficiency (B), nitrogen use efficiency (C), total water input (D), irrigation (E) and nitrogen input (F) based on the whole dataset.

5

Median yields per country ranged between 20 and 60 tons ha^{-1} yr^{-1} (Figure 3), which is significantly higher than the global mean yields of 15 to 20 tons ha^{-1} yr^{-1} during the last decades (Figure 1). Median WUE ranged between 2 and 5 kg m^{-3}, and median NUE ranged between 100 and 350 kg kg^{-1} (Figure 3).Variations in yield, WUE and NUE within studies were larger than the differences between countries. Countries with relatively high median yield tended to have also relatively high WUE and NUE. For example, the studies conducted in USA and Brazil had relatively high median yield, WUE and NUE. The studies conducted in Spain had high WUE but low NUE.

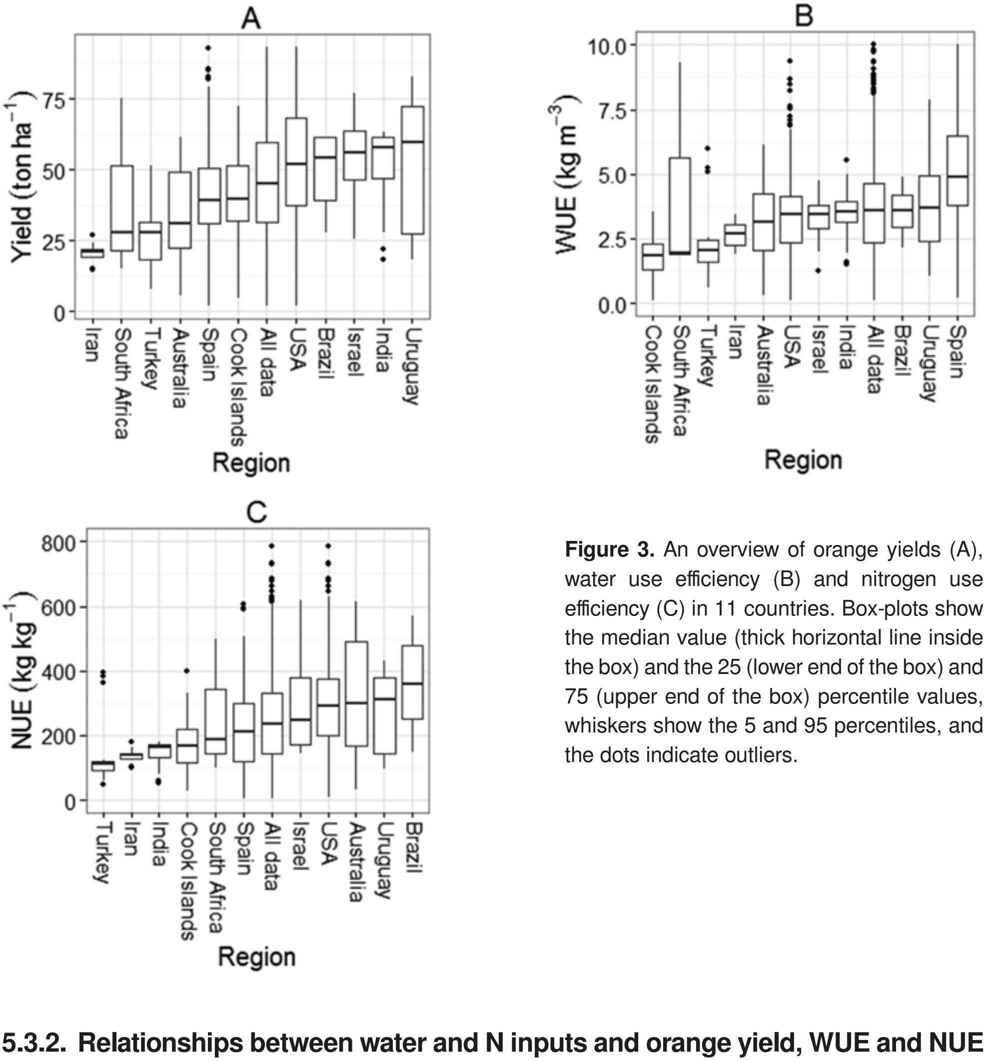


Figure 3. An overview of orange yields (A), water use efficiency (B) and nitrogen use efficiency (C) in 11 countries. Box-plots show the median value (thick horizontal line inside the box) and the 25 (lower end of the box) and 75 (upper end of the box) percentile values, whiskers show the 5 and 95 percentiles, and the dots indicate outliers.

5.3.2. Relationships between water and N inputs and orange yield, WUE and NUE

Table 1 summarizes the results of the statistical analyses using the mixed-effects model for the whole dataset. There was a positive interaction between water and N inputs in orange yield. This positive interaction has to be considered with the negative relationship between water input and yield, and the non-significant relationship between fertilizer N input and orange yield. This suggests that the effect of water and N inputs were only positive when either one or both had a sufficiently high input. As expected, tree age had a strong effect on yield, but mean annual temperature did not have significant effects on yield.

Water use efficiency was negatively related to water input (Table 1). Effects of fertilizer N input and the interaction (water x N input) on WUE were not significant. Interestingly, NUE was negatively related to both water input and fertilizer N input, but these relationships have to be considered with a significant positive interaction between water input x N fertilizer input (Table 1). WUE was positively related to tree age, and NUE not.

The relationships between independent variables (i.e., water and N input) and dependent variables (i.e., yield, WUE and NUE) are shown in Figure 4 for split datasets. There were positive relationships between water input and yield, but no significant differences between high and low N inputs (Figure 4A). Relationships between water input and WUE were negative; differences between high and low N inputs were not significant (Figure 4B). Increasing water input led to higher NUE, with significant differences between high and low N input (Figure 4C).

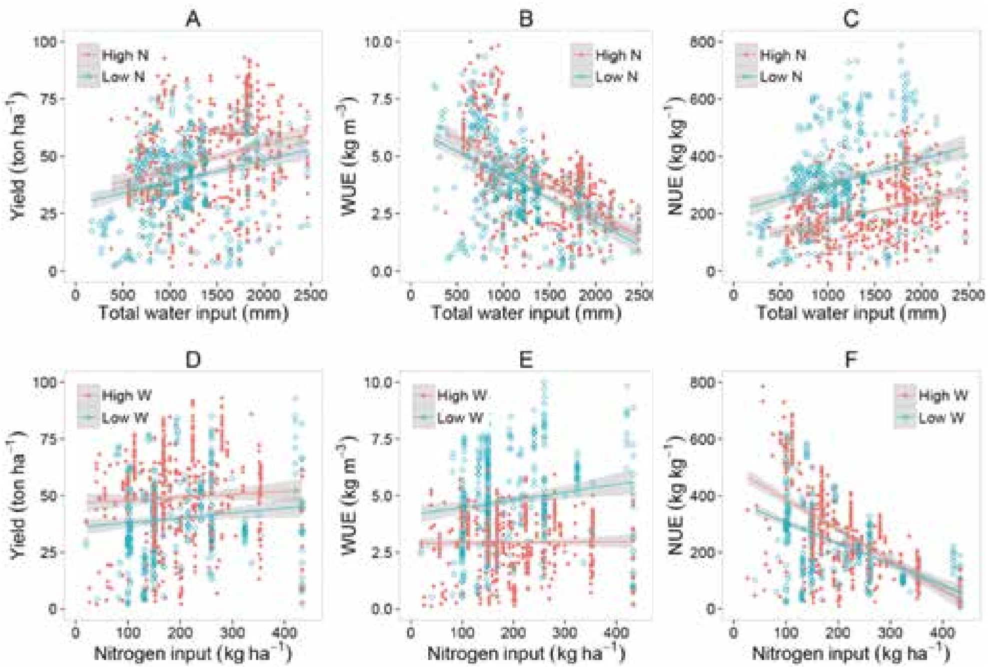


Figure 4. Relationships between total water input and orange yields, WUE, and NUE (A, B and C) at different N input levels, and between nitrogen input and orange yields, WUE, and NUE (D, E and F) at different water input levels. Data points were split into two equal parts according to N and water input levels, respectively (denoted in the figures). Linear regressions were made for the sub-datasets accordingly, using ordinary least square method. Grey areas indicate the 95% confidence intervals.

5

The relationship between N input and yield was positive. Regression lines differed in slopes for the high and low water input data, but not in slope, indicating that there were no strong interactive effects (Figure 4D). WUE was positively related to N input when the water input was relatively low, but not at relatively high water input levels (Figure 4E). NUE was negatively related to N input; the slope of high water input regression lines significantly differed for the low and high water input data, indicating that NUE decreased more rapidly with high water input (Figure 4F).

The results of quantile regression analysis (for five quantiles: 0.05, 0.25, 0.5, 0.75 and 0.95) are summarized in Figure SI-1. For the relationships between water input and yields, and between water input and NUE, there were clear differences in the intercepts between quantiles, but not in slopes (Figure SI-1A and C). The same applies to the relationships between N input and yield, and N input and WUE (Figure SI-1D and E). However, for the relationships between water input and WUE, and between N input and NUE, both intercepts and slopes differed between quantiles, with larger intercepts and slopes at the high quantiles.

Table 1. The effects of water and nitrogen inputs, the age of the orange orchards, and mean air temperature on orange yield, WUE and NUE; results of the analysis with the mixed-effects model presented in Eqs. 3, 4 and 5.

Dependent variable*	Items†	Value	Std.Error	DF	t-value	p-value	Sign. ‡
Yield (ton ha^{-1})	α (Intercept)	18.07	17.13	947	1.05	0.29	NS
	β_1 (Total water)	-0.01	0.00	947	-2.22	0.03	***
	β_2 (N)	0.01	0.02	947	0.39	0.70	NS
	β_3 (Age)	0.37	0.11	947	3.36	0.00	***
	β_4 (Temperature)	0.84	0.86	947	0.97	0.33	NS
	β_5 (W*N)	3E-05	0.00	947	2.25	0.02	***
WUE (kg m^3)	α (Intercept)	6.95	1.70	947	4.10	0.00	***
	β_1 (Total water)	-2E-03	0.00	947	-7.58	0.00	***
	β_2 (N)	1E-03	0.00	947	0.76	0.45	NS
	β_3 (Age)	0.02	0.01	947	2.34	0.02	***
	β_4 (Temperature)	-0.09	0.09	947	-1.02	0.31	NS
	β_5 (W*N)	1E-06	0.00	947	0.80	0.42	NS
NUE (kg kg^{-1})	α (Intercept)	950.86	242.42	921	3.92	0.00	***
	β_1 (Total water)	-0.22	0.03	921	-6.66	0.00	***
	β_2 (N)	-3.63	0.26	921	-14.15	0.00	***
	β_3 (Age)	1.35	1.15	921	1.18	0.24	NS
	β_4 (Temperature)	-0.10	12.20	921	-0.01	0.99	NS
	β_5 (W*N)	1E-03	0.00	921	7.58	0.00	***

†See text for explanation of the regression formulas and items. ‡ *** means $p < 0.05$ and NS means not significant.

5.3.3. Estimations of the water and N fertilizer saving potentials

Over-optimal and sub-optimal supply of water both led to a significant reduction in yield and NUE of about 20% (Figure 5A). On average, over-optimal water supply led to 30% lower WUE, while sub-optimal water input led to a non-significant decrease of WUE with 5%.

Over-optimal and sub-optimal supply of N fertilizer led to significant reduction in yield and WUE of about 15% (Figure 5B). On average, over-optimal fertilizer N supply decreased NUE by 40%, whereas a sub-optimal fertilizer N increased NUE by 10%, but decreased yield and WUE.

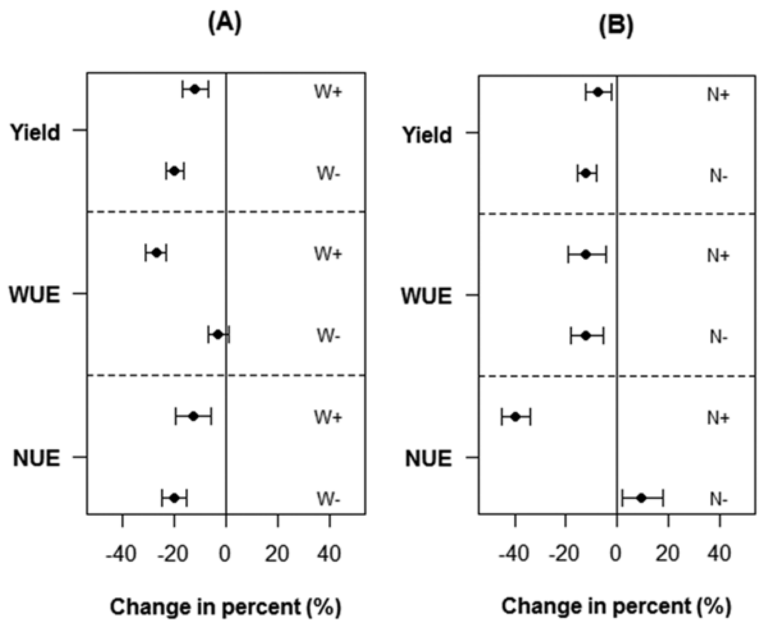


Figure 5. The effects of an over-optimal and a sub-optimal input of water (A) and N (B) on orange yield (upper panel), WUE (middle panel) and NUE (bottom panel). Panel A was based on 818 observations, and 44 studies; panel B was based on 487 observations and 17 studies. Dots show means, error bars represent 95% confidence intervals. Vertical line at 0 represents the reference levels of yield, WUE and NUE at the optimal water and N input, which were defined as the water and N input that produced the highest yield in a specific year of a study. The water levels that were above or below optimal water input were defined as over-optimal and sub-optimal water inputs, denoted as W+ and W-, respectively, and over-optimal and sub-optimal N inputs were denoted as N+ and N-, respectively.

Table 2 summarizes the calculated water saving potentials (WSP) per country. Overall mean WSP was 33%, suggesting that water input can be reduced by up to 33% without yield reduction. There was a large variation between countries; WSP for Spain and USA was in the range of 19 to 22% and for Brazil 34%. Table 3 summarizes the calculated N saving potentials (NSP) per country. Overall mean

NSP was 64%, suggesting that N input can be reduced by up to 64%, without yield reduction. The NSP was relatively large for USA and Brazil. Differences between the water and nitrogen data sets in mean water input (1300 vs 1420 mm, mean N input (176 vs 198 kg ha^{-1}), mean orange yield (45 vs 47 ton ha^{-1}), mean WUE (4 vs 4 kg m^{-3}) and mean NUE (300 vs 276 kg kg^{-1}) were relatively small, indicating that the two data-sets were rather similar.

Table 2. Estimated mean water saving potentials (WSP) per country based on the water sub-dataset (818 observations from 44 studies). Optimal water input (rainfall + irrigation) indicates the minimal water input that produced maximum yields per country. N input, yield, WUE and NUE indicate the values associated with the optimal water input, respectively.

Country	Optimal water input (mm)	N input (kg ha^{-1})	Yield (ton ha^{-1})	WUE (kg m^{-3})	NUE (kg kg^{-1})	WSP (mm)			WSP (%)		
						Mean	Min	Max	Mean	Min	Max
Turkey	1275	217	32	2.7	164	158	48	332	13	6	23
Spain	876	213	44	5.3	231	139	6	453	19	1	64
Brazil	1220	168	52	4.3	442	412	43	1587	34	3	126
USA	1619	211	57	3.7	387	255	34	1006	22	2	138
Iran	796	150	21	2.6	140	70	49	92	9	6	11
Uruguay	1580	192	57	3.8	298	240	73	461	19	6	39
Australia	1221	100	40	3.2	390	1408	807	2008	124	71	178
Israel	1763	158	55	3.3	350	319	113	525	23	6	39
Mean	**1294**	**176**	**45**	**4**	**300**	**375**	**147**	**808**	**33**	**13**	**77**

Table 3. Estimated N saving potentials (NSP) based on the nitrogen sub-dataset (487 observations from 17 studies). Optimal N input indicates the minimal N input that produce maximum yields per country. Water input, yield, WUE and NUE indicate the values associated with the optimal N input, respectively.

Country	Optimal N input (kg ha^{-1})	Water input (mm)	Yield (ton ha^{-1})	WUE (kg m^{-3})	NUE (kg kg^{-1})	NSP (mm)			NSP (%)		
						Mean	Min	Max	Mean	Min	Max
USA	209	1617	59	3.8	349	65	0	131	96	0	282
Spain	240	692	48	8.1	202	-	-	-	-	-	-
Brazil	180	1156	49	4.1	360	120	80	160	120	80	160
Cook Islands	270	2374	42	1.9	170	111	61	184	54	37	110
Australia	133	1037	28	2.6	204	85	21	190	73	14	155
Israel	158	1763	56	3.4	361	123	93	160	79	57	100
Mean	**198**	**1426**	**47**	**4**	**276**	**120**	**55**	**220**	**64**	**28**	**125**

5.4. Discussion

Evapotranspiration (*ET*) of orange roughly ranges from 800 to 1500 mm, depending on regions (Steduto et al., 2012). The total water input (sum of rainfall and irrigation) in the studies reviewed here ranged from 500 – 2500 mm. Total water input was larger than 1500 mm in more than one-third of the observations, i.e., larger than the reported upper level for *ET*. The apparent over-optimal supply of water may be due in part to uncontrollable rainfall, in part also due to poor irrigation management. Irrigation requirement is often based on the calculated *ET* for a specific crop in a specific region, and the mean rainfall based on long-term weather data (Allen et al., 1998b; Kang et al., 2009; Steduto et al., 2012; Zhang et al., 2011). Farmers know however that actual rainfall can be significantly different from the long-term mean, and therefore tend to irrigate for dry years instead of for mean years. Not surprising is the finding of Consoli et al. (2014) therefore, that deficit irrigation did not lead to a reduction in yield and saved up to 41% irrigation water relative to *ET* irrigation. However, when the actual rainfall was less than the long-term mean value, and deficit irrigation increased to 44% *ET*, crop yield decreased by 17% (Gonzalez-Altozano and Castel, 1999). Ballester et al. (2011) reported that deficit irrigation may save about 20% of the irrigation water without yield reduction, compared to 100% *ET* irrigation, which is similar to our estimate (Figure 5).

The maximum N uptake recorded in the reviewed studies was 287 kg ha^{-1}, which was associated with an orange yield of 115 ton ha^{-1} (Alva et al., 2006a). In this case, N uptake was equal to the fertilizer N input of 280 kg ha^{-1}, indicating a very high recovery efficiency of fertilizer N. Evidently, such a high yield and high NUE (410 kg kg^{-1}) can only be realized with high-yielding varieties, a mature orchard, excellent climatic conditions and optimized water and N fertilizer inputs. Alva et al. (2006b) recommended a fertilizer N input of 260 kg ha^{-1} for high-yielding orange orchards (60 to 90 ton ha^{-1}). About one-third of the reviewed studies had a fertilizer N input >260 kg ha^{-1}, with yields ranging from a low 10 ton ha^{-1} to a high 90 ton ha^{-1}, suggesting that fertilizer N supply was often over-optimal. Many of these studies report that the high water and N inputs reflect farmers' practice.

5

5.4.1. Optimization of water and fertilizer N inputs

The statistical significant interactions between water and fertilizer N inputs in orange yield and NUE (Table 1; Figure 4) points at the need for a simultaneous optimization of water and fertilizer N inputs in orange production. Disregarding interactions will either lead to yield reductions or to relatively low WUE and NUE, and/or excessive N losses. The relative neglect of interactions between irrigation and N fertilization in yield likely follows from specialization in research, and from the complexities involved with the optimization of irrigation and N fertilization simultaneously (Phogat et al. (2013a). The simultaneous optimization of water and fertilizer N inputs is challenging due to uncontrollable rainfall, temperature, soil N mineralization, and incidental pest and diseases. Irrigation and fertigation management must consider incidental rains during the irrigation period and also beyond the irrigation periods. Most of the reviewed studies did not consider rains that fell before and beyond the irrigation period. Only few studies reported the timing of the N applications.

Our analysis suggests that improving irrigation management may increase WUE and NUE by 30% and 20%, respectively (Figure 5). A sub-optimal water input leads to a reduction in yield and thereby also to a reduction in WUE and NUE. Over-optimal water input leads to drainage and N leaching losses, and thereby to low WUE and NUE. However, a slight sub-optimal irrigation and N fertilization may contribute to high WUE and NUE. Decreasing water input to 75% of *ET* may reduce N leaching (Alva et al., 2003; Alva et al., 2006b; Quiñones et al., 2007), and may increase NUE (Phogat et al. (2013a). A drastic decrease in fertilizer N input will greatly increase NUE (Figure 4) and decrease N leaching losses, but will also decrease yield. Hence, the optimization of water and N input has to be based on a consideration of both yield, WUE, NUE and N losses (or N surplus).

Optimization of water and fertilizer N inputs will likely contribute to closing the gap between actual yield and attainable yield. Mean actual orange yields roughly vary between 10 and 30 tons ha^{-1} (Figure 1C), median yields in the studies reviewed here ranged from 30 to 60 tons ha^{-1} (Figure 3A), while attainable yields may range between 60 and 90 tons ha^{-1} for most of the dominant production areas in the world (Alva et al., 2006b). The large variations in yield are in part related to differences in cultivars and age of trees. For example, the differences in yield between mature and immature trees can be 50 ton ha^{-1} or more (Morgan et al., 2009). Differences in WUE may be related also to differences in the age of the trees (Kusakabe et al., 2006); WUE increases when trees become mature (Morgan et al., 2009). Timely pruning, weed and pest control and micronutrient fertilization are also important for achieving high yields. Our study does not allow estimating the contribution of poor water and N fertilizer management to the aforementioned yield gap, but based on other studies (e.g., Mueller et al., 2010), it is likely that optimization of water and fertilizer N management will increase yields and contribute to closing the yield gap. Orange trees with high yields were often fertigated, i.e., water and fertilizer N were supplied simultaneously (Alva et al., 2006b). Fertigation technically allows synchronizing water and N supply to the water and N demands by the crop over time, and thereby contributes to increasing yields (Alva et al., 2008). However, drip irrigation and fertigation facilities are not available yet in many orange production systems.

The huge gap between actual and attainable yields is in part also related to the rapid increase in the harvested area (Figure 1B) and hence the relatively large area of young trees with still low yields. The rapid expansion of the orchard area (Figure 1B) is likely related to the relatively high economic value of oranges (~900 US$ ton^{-1}), compared to for example cereal crops (~200-350 US$ ton^{-1} for wheat and maize) (FAO, 2014). This indicates that the gross income is more than 10 times higher for a unit area of oranges than for a similar area of wheat.

Rainwater harvesting technologies have been proven to be effective in reallocating water distribution during the growing season, thereby increasing yield and WUE (Li et al., 2008; Mavimbela and van Rensburg, 2012; Tian et al., 2003; Van Rensburg et al., 2012). However, these technologies have not been considered in the reviewed studies related to orange production. Selecting drought-tolerant rootstocks can also minimize the negative impacts of water stress on fruits yields, and can help growers to save irrigation water (Perez-Perez et al., 2008a, b).

5.4.2. Uncertainties

Our analysis is based on 1009 observations collected from 55 experimental studies and 11 countries. The factorial field experiments often included farmers' practice as one of the (reference) treatments. Other treatments were often related to improved or best management practices or simply differed in water and/or N input. The experiments aimed at the optimization of either irrigation or N fertilization. As a consequence, there is a risk that target irrigation levels were derived at over-optimal or sub-optimal N fertilization levels and vice versa. This holds also for the estimated WSP (Table 2) and NSP (Table 3). The results of our meta-analysis indicate that interactions between irrigation and N fertilization in yield and NUE must be considered to be able to derive sound recommendations.

A large dataset provides a good basis for conducting a meta-analysis. However, the reviewed studies were conducted in 11 different countries and often had different objectives. Some studies had rather extreme treatment values, for experimental purposes. Such extreme treatments may affect the outcome of our study, as we did not exclude (extreme) treatments. Hence, the estimated reductions in yield, WUE and NUE due to over-optimal or sub-optimal water input and N input (Figure 5) do not necessarily reflect the situation in farmers' practice.

To address our specific objectives, we used a range of statistical approaches including quantile regression (QR). In Figures 4 and S1, we clearly showed that the relationships between water inputs and orange yield, WUE and NUE, and between N input and yield, WUE and NUE indeed varied for different sub-datasets and for different quantiles. For large datasets, it may be justified to conduct in-depth analysis for a range of quantiles, so that the differences in intercepts and slopes are better understood. In our study, we used up to five quantiles. The results of the 0.5 quantile in most cases were comparable with the results of OLS methods; results of OLS were therefore not presented.

In meta-analysis studies, the effect size can be weighted by many ways (Hedges et al., 1999; Hungate et al., 2009; van Groenigen et al., 2014). The effect size can be weighted equally (or unweighted), weighted with sample size or weighted with number of replicates. These three methods are commonly used when the studies did not report standard errors. However, the weighing strategies often do not significantly affect the outcome of the analysis, especially for big size dataset (van Groenigen et al., 2006). Therefore, we decided not to weight the effect size neither for the sample size nor the number of replications.

5.5. Conclusions

Our meta-analysis of water and N use efficiencies in orange production system deals with 1009 yield observations from 55 studies. They cover the most important orange producing countries in the world, with the exception of China. Most studies were conducted to optimize either irrigation input or N fertilization level, and only few studies focussed on the simultaneous optimization of water and N inputs. Median orange yields of countries (range 30-60 ton ha^{-1}) were in between average global yields (range 10-30 ton ha^{-1}) and attainable yields (range 60-90 ton ha^{-1}). Median WUE of countries ranged from 2.5 to 5 kg m^{-3} and median NUE from 150 to 350 kg kg^{-1}.

There were statistical significant interactions between water and fertilizer inputs in yield and NUE, but not in WUE. This indicates that studies aimed at the optimization of water and fertilizer N inputs must consider interactions and must optimize water and fertilizer N inputs simultaneously. We speculate that the simultaneous optimization of water and fertilizer N inputs may greatly contribute to closing the gap between actual and attainable yields.

Based on our analyses, we estimate that reducing over-optimal irrigation to optimal irrigation may increase orange yield by 20%, WUE by 30% and NUE by 15%. Similarly, reducing over-optimal N fertilization to optimal N fertilization may increase yield by 10%, WUE by 15% and NUE by 40%.

Orange production is booming, because of the high value of the harvested fruits. The high gross income will allow making investments in precision irrigation and fertigation techniques. Results of this study indicate that there is room for a significant increase in yield, WUE and NUE through the simultaneous optimization of water and fertilizer N inputs via precision fertigation.

Acknowledgements

This study was carried out within the project EFFIDRIP funded by the 7th Framework Programme of the European Union, under the programme Research for the benefit of SMEs; EU FP7-SME-2011, grant 286807. We thank Yang Yu, from Wageningen University and Research Centre, for many useful discussions and helps on quantile regression, mixed effects model and meta-analysis.

Supplementary information

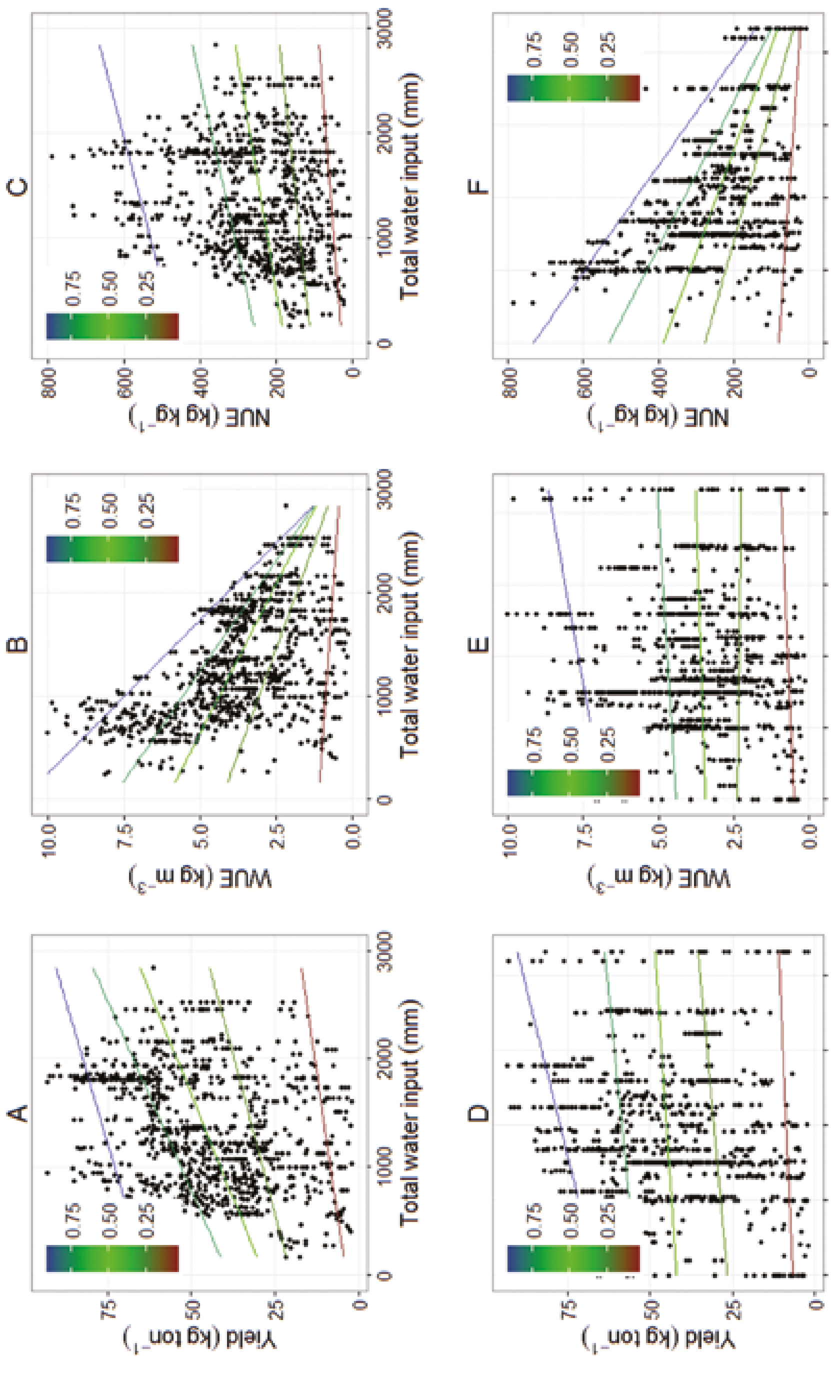


Figure SI-1. Relationships between total water input and orange yields, WUE, and NUE (A, B and C), and between nitrogen input and orange yields, WUE, and NUE (D, E and F). Linear regressions were made using quantile regression. Lines are linear regression of 0.95, 0.75, 0.5, 0.25 and 0.05 quantiles (from the top to the bottom), respectively. Detailed information of intercepts and slopes are summarized in Table SI-1.

Table SI-1. The responses of orange yield, WUE and NUE to water and N input, respectively, using quantile regression analysis (results of the 0.05, 0.5 and 0.95 quantiles are presented).

Dependent variable	Quantile	Item	Value	Std. Error	t-value	p-value	Sign.
Yield (ton ha^{-1})	0.05	α (Intercept)	5.7	2.0	2.9	0.004	***
		$β_1$ (Water)	2E-03	0.0	1.6	0.114	NS
	0.5	α (Intercept)	30.6	2.3	13.1	0.000	***
		$β_1$ (Water)	1E-02	0.0	6.1	0.000	***
	0.95	α (Intercept)	65.0	4.5	14.4	0.000	***
		$β_1$ (Water)	9E-03	0.0	2.9	0.003	***
Yield (ton ha^{-1})	0.05	α (Intercept)	5.5	1.6	3.5	0.001	***
		$β_1$ (N)	1E-02	0.0	1.7	0.099	NS
	0.5	α (Intercept)	40.1	2.4	16.5	0.000	***
		$β_1$ (N)	2E-02	0.0	2.0	0.046	***
	0.95	α (Intercept)	65.8	2.6	25.1	0.000	***
		$β_1$ (N)	0.1	0.0	4.1	0.000	***
WUE (kg m^{-3})	0.05	α (Intercept)	1.1	0.2	5.4	0.000	***
		$β_1$ (Water)	-3E-04	0.0	-2.6	0.010	***
	0.5	α (Intercept)	6.1	0.2	31.1	0.000	***
		$β_1$ (Water)	-2E-03	0.0	-14.9	0.000	***
	0.95	α (Intercept)	10.6	0.2	46.4	0.000	***
		$β_1$ (Water)	-3E-03	0.0	-26.3	0.000	***
WUE (kg m^{-3})	0.05	α (Intercept)	0.4	0.1	3.1	0.002	***
		$β_1$ (N)	1E-03	0.0	2.1	0.032	***
	0.5	α (Intercept)	3.4	0.2	16.0	0.000	***
		$β_1$ (N)	9E-04	0.0	0.9	0.372	NS
	0.95	α (Intercept)	6.7	0.4	18.7	0.000	***
		$β_1$ (N)	5E-03	0.0	2.6	0.008	***
NUE (kg kg^{-1})	0.05	α (Intercept)	42.7	9.3	4.6	0.000	***
		$β_1$ (Water)	5E-03	0.0	0.8	0.436	NS
	0.5	α (Intercept)	186.4	15.7	11.9	0.000	***
		$β_1$ (Water)	4E-02	0.0	3.4	0.001	***
	0.95	α (Intercept)	455.0	98.0	4.6	0.000	***
		$β_1$ (Water)	0.1	0.1	1.4	0.176	NS
NUE (kg kg^{-1})	0.05	α (Intercept)	76.6	13.4	5.7	0.000	***
		$β_1$ (N)	-0.1	0.0	-2.8	0.005	***
	0.5	α (Intercept)	400.1	15.0	26.7	0.000	***
		$β_1$ (N)	-0.7	0.1	-13.1	0.000	***
	0.95	α (Intercept)	826.3	22.5	36.8	0.000	***
		$β_1$ (N)	-1.6	0.1	-26.3	0.000	***

Wei Qin
Marius Heinen
Falentijn B.T. Assinck
Oene Oenema

Chapter 6

Exploring optimal fertigation strategies for orange production, using soil-crop modelling

This paper has been submitted for publication

Abstract

Water and nitrogen (N) are two key limiting factors in orange (*Citrus sinensis*) production. The amount and the timing of water and N application are critical, but optimal strategies have not yet been well established. This study presents an analysis of 47 fertigation strategies examined by a coupled soil-crop model, including 27 main scenarios (a factorial design of 3 irrigation levels (80%, 100% and 120% *ET-R*), 3 N input levels (100, 200 and 300 kg ha^{-1}) and 3 split applications (N fractionations) and 20 additional scenarios testing fine-turning N fractionation applications, extreme rainfall years (dry and wet) and for different soil textures.

Orange yields were strongly influenced by N input levels but not by water input levels. Increasing water and N input levels led to increased N losses (via leaching and denitrification), and there were significant positive interactions between water and N inputs with respect to N losses. On average, low N input (100 kg ha^{-1}) led to relatively low N losses (16 kg ha^{-1}, 16% of N input) but resulted in low yield (33 ton ha^{-1}, 25% yield reduction). High N input (300 kg ha^{-1}) produced a high yield (43 ton ha^{-1}) but led to large N losses (104 kg ha^{-1}, 35% of N input). Optimal N input (200 kg ha^{-1}) significantly reduced N losses (45 kg ha^{1}) without yield reduction. Importantly, within optimal N input, improving N fractionation significantly increased yield by 13% and reduced N losses by 40%.

The statistical significant interactions between water and N inputs and N fractionation regime in yield, WUE, NUE and N losses indicate that the optimization of fertigation strategies must consider these three key variables simultaneously. Our results clearly show that over-optimal water and N inputs lead to high water and N losses. Reduced irrigation (80% *ET-R*) and N input (200 kg ha^{-1}) can significantly reduce N losses (43%) without yield reduction. N fractionation strategies should be adjusted to the N demand by the crop during the growing season. Our study focused a Mediterranean climate, but the principle can be applied to other situations in the world.

Keywords: *Citrus sinensis,* denitrification, drip irrigation, efficiency, fertigation, leaching, nitrogen, orange, water, yield.

Abbreviations: N – nitrogen; NUE –nitrogen use efficiency; WUE – water use efficiency; ET-evapotranspiration; R- rainfall

6.1. Introduction

World orange (*Citrus sinensis*) production increased by a factor of four in the last fifty years, from 16 million ton in 1961 to 68 million ton in 2012 (FAO, 2014b). Brazil, USA and China were the top three orange producing countries, accounting for 50% of the global production. Rapid development in orange production was driven by the increasing demand of nutritious and healthy food (oranges have high vitamin C content) (Foley et al., 2011; Godfray et al., 2010; Key et al., 2002; Liu et al., 2008), in part also supported by improvements in the processing and marketing industry (notably frozen concentrated orange juice), and improvements in crop husbandry, and water and nitrogen (N) management (Alva et al., 2008; Bar-Yosef, 1999).

Orange trees are perennial plants which can grow for decades. They grow in subtropical and tropical regions, because they are sensitive to low temperatures. In the Northern Hemisphere, the main vegetative growth occurs in February and March. Most cultivars produce flowers in spring, and fruits are harvested 6 to 8 months later (Steduto et al., 2012). Because of the long growing season and warm climate, orange trees require relatively large amounts of water and N.

Water and N are main limiting factors for plant growth and development (de Wit, 1958; Marschner, 1995). Water stress can lead to partial or fully stomatal closure that decreases plant transpiration (T), thereby constraining photosynthesis (Chaves et al., 2002). Low plant transpiration may decrease plant N uptake and lead to N deficiency. Plants with N deficiency are often small and develop slowly because of low chlorophyll content, which is key element for photosynthesis. Adequate N supply contributes to shoot and root growth, which enhances water and nutrient uptake by plant roots from soil, thereby increasing yield (Salvagiotti et al., 2008; Setiyono et al., 2010). Over-optimal supply of water and N leads to drainage and N losses, which can be detrimental to the environment (Guo et al., 2010; Ju et al., 2009; Liu et al., 2013; Sutton et al., 2011).

Fertigation allows the application of fertilizers through an irrigation system (mostly via drip irrigation), which provides the opportunity to supply optimal amounts of water and N simultaneously, according to crop demand (Alva et al., 2008; Bar-Yosef, 1999). It is an advanced and relatively expensive technology, mainly applied in high-value crops in horticulture, floriculture and orchards including orange orchards. Estimates indicate that some 9 million ha of cropland are under fertigation nowadays (FAO, 2014a). Fertigation allows the application of water and N close to plant roots at the right time and in the right amounts, whereby in theory a high water use efficiency (WUE) and high N use efficiency (NUE) can be achieved. Because only a relatively small fraction of the land area is irrigated, evaporation and N leaching losses are relatively low. In practice though, water and N supply are often based on guestimates rather than on accurately estimated plant demands, which then results in relatively large water and N losses (Treeby et al., 2012). Optimal fertigation strategies are difficult to establish because of the complexities involved; there are many interacting factors, such as weather conditions, soil type, plant species, and the age of the orchard, which affect the water and N demand of the crop during the growing season. The reported evapotranspiration (*ET*) in orange ranges from 800 to 1500 mm per year, depending on regions (Steduto et al., 2012). The reported optimal N input for orange trees ranges from 150 to 250 kg ha-1, but actual N inputs range from 20 to 350 kg ha-1 (Chapter 5).

Model simulation is an efficient way to explore the effects of different fertigation strategies (Phogat et al., 2013a). So far, most model studies have focused on the micro-scale, i.e., what is the effect of a single irrigation event (Cote et al., 2003; Gärdenäs et al., 2005; Hanson et al., 2006). Much less studies have examined fertigation strategies for the whole growing season, and the findings of these studies are contradictory. Cote et al. (2003) reported that N applications at the beginning of an irrigation cycle reduced N leaching, compared to fertigation at the end of the irrigation cycle. Gärdenäs et al. (2005) reported that N application at the beginning of the irrigation cycle increased N leaching and fertigation at the end of the irrigation cycle reduced N leaching. Hanson et al. (2006) found that fertigation at the end of an irrigation cycle led to higher N use efficiency, compared to fertigation at the beginning or middle of the growing season. Phogat et al. (2013a) reported that timing of N application in an irrigation event had little impact on N uptake. These contradictory results may be due to the use of different models, fertigation strategies (water and N application rate and time) and different pedo-climatic conditions.

The aim of the study reported here was to explore the agronomic and environmental effects of a range of fertigation strategies (different levels of water and N inputs and N fractionations in time) for a whole orange growing season, using soil-crop model simulations. We have chosen orange as a case study because it is one of the most important crops grown under advanced fertigation systems in the world. The used method is generic and applicable to other fruit trees and weather conditions.

6.2. Materials and methods

Water and nutrient dynamics in the soil were modelled with a three-dimensional version of the FUSSIM model (Heinen, 1997, 2001; Heinen and de Willigen, 1998). Orange crop growth was modelled with the AquaCrop model (Steduto et al., 2012; Steduto et al., 2009), and interactions between the two models were considered.

6.2.1. Modelling soil water dynamics and N uptake: FUSSIM3D

Water movement in soil was modelled according to the classical Richards-Darcy-Buckingham equation with the hydraulic properties given by the Mualem (1976) – van Genuchten (1980) equations. Nitrogen (N; only NO3-N is considered) transport was modelled by the classical advection-dispersion equation. Mineralization was disregarded in this study because the soil organic matter contents are relatively low (<1%) in fruit orchards (Cerda and Jurgensen, 2008). Denitrification was quantified using a simple process model described by Heinen (2006). Uptake of water and N from the root zone was modelled according to the models of (de Willigen and van Noordwijk, 1987, 1994). Here a three-dimensional root length distribution Lrv (see Figure 1) was used, according to Heinen (2014), with Xm = 4 m , Ym = 2 m, Zm = 0.75 m, x* = 2.3 m, y* = 2 m, z* = 0.15 m, px = 12, py = 1, pz = 5, and L0 = 3 (cm cm3).

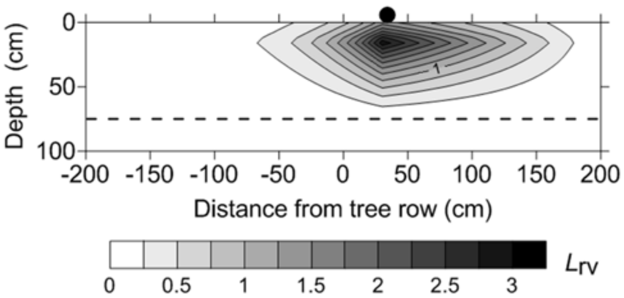


Figure 1. Imposed root length density (Lrv, cm cm-3) distribution underneath a tree. The location of the drip line is indicated by the black dot. The dashed line represents the maximum rooting depth.

Roots are concentrated below the dripper as often observed in drip-irrigated orchards (Abrisqueta et al., 2008; Celano et al., 1998; Fernández and Moreno, 1999; Girona et al., 2006; Ruiz-Canales et al., 2006; Ruiz-Sánchez et al., 2005). A bell-shaped N demand curve during the growing season was used, according to Legaz and Primo-Millo (2000) and (Quiñones et al., 2003) (Figure 2). For mature orange trees, the annual N uptake may range from 220 to 450 g tree^{-1} yr^{-1} (Legaz and Primo-Millo, 2000; Martínez-Alcántara et al., 2012). This large range may be due to different tree configurations and different tree cultivars. Here, the N demand was set at 400 g tree^{-1} yr^{-1}, which is equivalent to 200 kg ha^{-1} yr^{-1}.

6.2.2. Modelling orange production: AquaCrop

AquaCrop is a water-driven crop growth model that can separately calculate evaporation (*E*) from soil and transpiration (*T*) by plants, and it simulates the crop yield as a function of water use under pre-defined soil fertility levels (Steduto et al., 2012; Steduto et al., 2009). The AquaCrop model uses canopy ground cover as the basis to calculate *T* and to separate *E* and *T*. Crop yield is then calculated as the product of biomass production and harvest index (*HI*). AquaCrop requires 4 main sets of input

6

data, i.e. climate data (rainfall, minimum and maximum temperature and reference evapotranspiration (ET_o)), crop parameters, soil data and field management data. Compared to some other crop growth models, AquaCrop requires relatively few input parameters but still provides robust outcomes, mainly because of using a normalized water productivity to calculate biomass (Steduto et al., 2009; Todorovic et al., 2009). Such a limited number of input parameters facilitates model calibration and utilization for different crops and under different management strategies (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2012; Steduto et al., 2009; Todorovic et al., 2009). Parameters were calibrated on the basis of literature data and modelling results from FUSSIM3D. The crop parameters include crop development, canopy coverage and stress to fertility levels. The full set of crop parameters are summarized in Table SI-1.

6.2.3. Reference orange yield and relationship with N uptake

We used 'Clementine mandarin' and the Mediterranean climate as references for orange production. The yield of 'Clementine mandarin' is about 43 ton ha^{-1} in the Mediterranean climate, using a N application of 192 kg ha^{-1} (Hammami et al., 2010). Fruit yield of mature orange trees is linearly correlated to the N uptake. Therefore, a linear relationship between fruit yield and N uptake was adopted (Hammami et al., 2010):

$$Y = 16.7 + 0.13N_{\mathrm{uptake}} \tag{1}$$

where Y is fruit yield (ton ha^{-1}), and N_{uptake} is plant N uptake (kg ha^{-1}).

6.2.4. Model coupling procedure

The two models, FUSSIM3D and AquaCrop, were run in sequence. First, the plant N uptakes for different scenarios were simulated by FUSSIM3D, and orange yields were calculated using Eq. [1]. With each calculated orange yield, AquaCrop calculates soil evaporation (E) and plant transpiration (T).When N uptake simulated by FUSSIM3D was less than crop demand (200 kg ha^{-1}), yields were reduced, which led to a reduction in T, the partitioning between E and T, and in water (ET) and N uptake. To consider the possible effects of reduced water and N uptake and consequently reduced crop growth, the following modelling sequence was applied so as to create feedback between the models.

6

1. The crop parameters of orange were calibrated in AquaCrop, assuming unrestricted water and N uptake with a maximum fruit yield of 43.5 ton ha^{-1} (Hammami et al., 2010).
2. Based on climate and soil data, FUSSIM3D simulated the water and N uptake. Hereby, FUSSIM3D took into account the water and N status of the soil, the soil

properties and the imposed fertigation management practice for the fertigation strategies (described later).

3. Simulated N uptake by FUSSIM3D was used to calculate expected yields using Eq. (1). Then the soil fertility levels were calibrated in AquaCrop to simulate these expected yields. Accordingly, water balance (e.g. E and T) were simulated.
4. The simulated E and T from AquaCrop were used as input for FUSSIM3D for a second (and final) simulation. The other inputs were kept the same as previous runs.

The differences between the simulated N uptake by FUSSIM3D in steps 2 and 4 were marginal (<1%) because only the partitioning of ET between E and T slightly differed between step 2 and 4, and water and N related processes were not significantly influenced. One run lasted about 24 hrs.

6.2.5. Description of simulation setup

An orange orchard was considered with a planting density of 4 x 5 m (500 trees ha^{-1}). Along the tree rows a single drip line was located with inter-dripper distance of 0.6 m and an emitter rate equal to 2.5 L h^{-1}. It was assumed that the root distribution along the tree row and dripper line was uniform. Then, due to symmetry, only a soil compartment of 0.3 x 4 m was modelled, with a soil depth of 3 m where a free drainage condition at the bottom was assumed. A loamy soil was considered with characteristics taken from the HYPRES database (Wösten et al., 1999). The initial water content at the start of growing season (in January) was set at 85% of field capacity (because of abundant rain during winter in the Mediterranean regions). Based on results of preliminary simulations with FUSSIM3D, we set the fraction wetted irrigation area at 25% (also input for AquaCrop). Initial soil mineral nitrate-N content of the soil was set at 52.5 kg ha^{-1} uniformly distributed in the top 1 m of the soil column. Denitrification parameters were derived from Heinen (2006): dry bulk density 1500 kg m^{-3}; potential denitrification rate D_p = 0.9 mg kg^{-1} d^{-1} (0-25 cm) and D_p = 0.45 mg kg^{-1} d^{-1} (25-50 cm) and zero below 50 cm, K_N = 22 mg kg^{1}, w_1 = 0.62, w_2 = 1.74, Q_{10} = 3.0, and T_{ref} = 20.0 ^{0}C. Leaching was defined as the net loss across the horizontal plane at the bottom of the root zone.

6

6.2.6. Climatic condition and irrigation scheduling

The 30-year average climatic conditions for southern Spain were considered (Table SI-2). For citrus, (Goldhamer et al., 2012) listed monthly K_c values from six studies. Two of these studies were performed in Spain, for which the average monthly values were calculated (Table SI-2). The yearly ET_c was estimated at 814 mm. Average rainfall was 533 mm. The dual crop coefficient approach (Allen et al., 1998) was used to estimate ET_c and to split-up evapotranspiration in transpiration by the crop and evaporation from the soil surface. This approach is required for fruit tree cropping systems where part of the orchard is not covered by the tree canopy.

The irrigation season was based on the period in which rainfall was less than evapotranspiration, i.e., from March 1st until October 31st. For January, February, November and December, rainfall was the only water supply. The monthly rainfall was equally distributed over all days of the month. During the irrigation period the irrigation amount was calculated as:

$$I = f\left(ET_C - R\right) \tag{2}$$

where I is the irrigation (mm), ET_c is the evapotranspiration (mm), R is the rainfall (mm), and f is a factor determining excess irrigation. Three values for f were considered: 0.8 (deficit irrigation), 1.0 (balanced irrigation), and 1.2 (excessive irrigation).

6.2.7. Fertigation strategies

During each irrigation event N was applied as fertigation. Three levels of total N supply were considered: 50%, 100% and 150% of the total N demand, i.e. 100, 200, and 300 kg ha^{1} yr^{-1}. Three equal time periods were defined for the irrigation season, and three different fractionations of the N supply were defined for these periods (Figure 3):

- 3/6th, 2/6th and 1/6th, respectively, further denoted as 3-2-1;
- 1/6th, 2/6th and 3/6th, respectively, further denoted as 1-2-3;
- 2/6th, 2/6th and 2/6th, respectively, further denoted as 2-2-2.

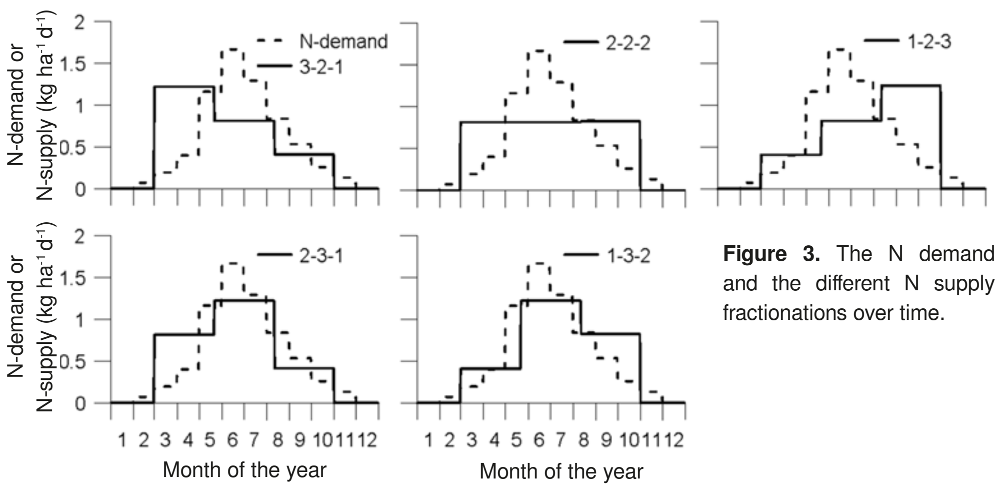


Figure 3. The N demand and the different N supply fractionations over time.

The three periods were Mar 1st – May 21st, May 22nd – Aug 11th, Aug 12th – Oct 31th. Since the amount of irrigation differed from day to day and the N supply per day should be constant, the concentration of the fertigation water differed from day to day. It was assumed that this would be technically possible in practice. In total, we analyzed 27 main scenarios based on the 3 irrigation levels, 3 N supply amounts, and 3 N supply fractionations (Table SI-3). All fertigation strategies were run with the 30-year average climatic conditions for southern Spain.

Two additional fractionations of the N supply were considered (Figure 3):

- 1/6th, 3/6th and 2/6th, respectively, further denoted as 1-3-2;
- 2/6th, 3/6th and 1/6th, respectively, further denoted as 2-3-1;

These two additional fractionations were combined with balanced irrigation (f = 1.0) and balanced fertilization (N supply = 200 kg ha^{-1}) only.

For balanced irrigation (f = 1.0) and balanced fertilization (N supply = 200 kg ha^{-1}) we also considered two additional climatic years for fractionations 3-2-1, 2-2-2 and 1-2-3: a dry and a wet year, i.e. 1981 (annual rainfall 318 mm) and 1996 (annual rainfall 905 mm), compared to the average rainfall of 533 mm.

6.2.8. Definitions of WUE and NUE

For each scenario the water use efficiency (WUE) and nitrogen use efficiency (NUE) were calculated. These are defined as the yield per unit of input, i.e., WUE in kg m^{-3}, and NUE in kg kg^{-1}:

$$\mathrm{WUE} = \frac{Y}{I + R} \qquad (3)$$

and

$$\mathrm{NUE} = \frac{Y}{N} \qquad (4)$$

where Y is yield (kg ha^{-1}), I is irrigation amount (mm), R is rainfall amount (mm) and N is the nitrogen input via fertigation (kg ha^{-1}). Possible N inputs via atmospheric deposition and biological N_2 fixation were not considered.

6.2.9. Statistical analyses

Analysis of variance was performed to compare the effects of irrigation levels, N input levels and N fractionation strategies, and their (two-way) interactions on yield, NUE, WUE, N leaching and denitrification. The significance was calculated based on results of F-tests and least significant differences (LSD) at the 0.05 probability level.

Analysis of variance was performed using Genstat 17 (VSNI, http://www.vsni.co.uk/).

The effects of irrigation levels, N input levels and N fractionation strategies, and their (two-way) interactions on yield were test as:

$$Y = \alpha + \beta_1 * W + \beta_2 * N + \beta_3 * F + \beta_4 * W * N + \beta_5 * N * F + error \quad (5)$$

where *Y* is yield (kg ha^{-1}), *W* is irrigation levels (80%, 100% and 120% ET), *N* is N input levels (100, 200, 300 kg ha^{-1}) and *F* is N fractionation strategies. Note that *W*, *N* and *F* are set as categorical variables; so *W* is different than I in Eq.[2]. α is the intercept, $b_{1\text{-}3}$ represent the effects of *W, N* and *F*, and $\beta_{4\text{-}5}$ represent the effects of *W*N* and *N*F* interactions, respectively. *W*F* interactions were small therefore neglected. The same approach was applied to other dependent variables, such as WUE, NUE, N leaching and denitrification. The statistical analysis was performed using R (R Core Team, 2013).

6.3. Results

6.3.1. Orange yields

Orange yields ranged from 31.8 to 43.5 ton ha^{-1} (Figure 4). Differences in yield between irrigation levels were small and not statistically significant except for the high N input level. The effect of irrigation was small because the three water input levels were all larger than maximum ET_c (814 mm), suggesting that there was no water stress for orange growth. Input of N had a very strong effect on yield. Mean yield was 32 ton ha^{-1} at a N input of 100 kg ha^{-1}, 42 ton ha^{-1} at a N input of 200 kg ha^{-1}, and 43.5 ton ha^{-1} at a N input of 300 kg ha^{-1}. At low and near optimal N input, highest yield was obtained with deficit irrigation (f = 0.8), while at high N input, over-optimal irrigation (f = 1.2) gave the highest yield (Table 1).

Fractionation of the N supply over the growing season also had significant effects on yield, when N input was below or near optimal levels (Table 2). Yields were relatively low with N fractionation 1-2-3 and relatively high with 3-2-1. Differences in yield between the N fractionations were negligible at the high N input level, because there was sufficient N for growth and development, irrespective of N fractionation. Results of statistical analysis confirm that there were strong N input x fractionation interactions in both yield and N losses, and strong N input x water input interactions in N losses (Table 3).

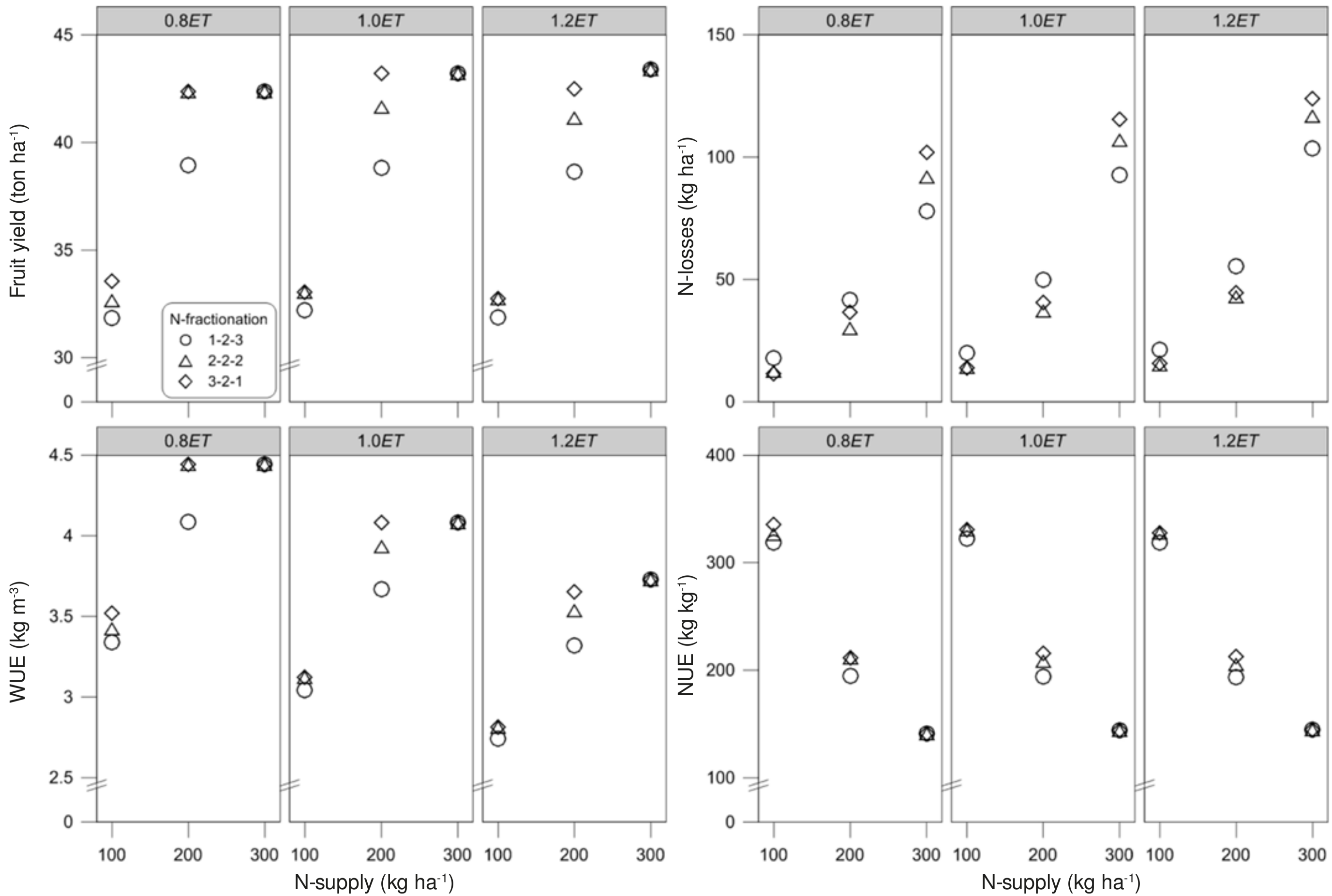


Figure 4. Effects of three levels of water input (f = 0.8, 1.0 and 1.2), N input (100, 200 and 300 kg ha^{-1}) and N fractionation (1-2-3, 2-2-2 and 3-2-1) on orange fruit yield, WUE, N losses and NUE. Data were grouped by water inputs and shown in panels, X axis shows N inputs and N fractionation were indicated by different shape of the dots.

6

Table 1. Simulated yield, WUE, NUE, soil evaporation (E), drainage (L_w), N uptake (N_{act}), nitrate leaching losses (L_N), nitrate-N concentration in the leachate (C_N), denitrification (D_N), and residual soil mineral N (N_{stor}), as function of N input and irrigation level (f). Values are the means of 3 N input fractionations (i.e., 3-2-1; 1-2-3; 2-2-2).

N input (kg ha^{-1})	f	Yield (ton ha^{-1})	WUE (kg m^{-3})	NUE (kg kg^{-1})	E (mm)	L_w (mm)	N_{act} (kg ha^{-1})	L_N (kg ha^{1})	C_N (mg L^{-1})	D_N (kg ha^{-1})	N_{stor} (kg ha^{-1})
100	0.8	32.7a	3.4c	326.9c	93.8e	204.0b	124.1b	7.8a	3.8a	6.3a	3.7a
100	1	32.7a	3.1b	327.7c	298.6e	288.3e	2.7ab	9.2b	3.2a	6.8a	2.9a
100	1.2	32.5a	2.8a	324.6c	308.0f	384.4h	21.7a	10.3b	2.7a	7.1a	2.5a
200	0.8	41.3b	4.2h	206.1b	37.1bc	79.8a	88.8e	23.3c	13.0c	12.7b	17.1d
200	1	41.2b	3.9f	206.1b	248.9d	253.7d	186.8d	27.6d	0.8b	14.9c	12.5c
200	1.2	40.7b	3.5d	203.8b	254.5d	46.3g	184.3c	31.6e	9.1b	16.1d	9.9b
300	0.8	42.4c	4.4i	41.2a	229.4a	77.5a	200.0f	67.4f	38.0f	23.2e	51.5g
300	1	43.2d	4.1g	144.0a	236.4b	246.3c	200.0f	76.5g	1.1e	28.6f	36.8f
300	1.2	43.4d	3.7e	144.6a	242.8c	330.1f	200.0f	83.6h	5.3d	31.1g	27.1e
lsd (5%)		0.7	0.1	4.8	5.7	5.5	1.5	1.0	2.1	0.9	1.9

Note: Significance differences according to the 5% lsd values provided in the bottom row within a column are indicated by different letters.

Table 2. Simulated yield, WUE, NUE, soil evaporation (E_{act}), drainage (L_w), N uptake (N_{act}), nitrate leaching losses (L_N), nitrate-N concentration in the leachate (C_N), denitrification (D_N), and residual soil mineral N (N_{stor}), as function of N input and N input fractionation. Means of 3 irrigation levels (f=0.8; 1.0; 1.2).

N input (kg ha^{-1})	Fractionation	Yield (ton ha^{-1})	WUE (kg m^{-3})	NUE (kg kg^{-1})	E_{act} (mm)	L_w (mm)	N_{act} (kg ha^{-1})	L_N (kg ha^{1})	C_N (mg L^{-1})	D_N (kg ha^{-1})	N_{stor} (kg ha^{-1})
100	3-2-1	33.1b	3.2b	331.2f	297.2c	291.1d	126.3b	8.2a	2.9a	5.6a	1.6a
100	1-2-3	32.0a	3.0a	319.8e	305.9d	295.0d	116.6a	11.3b	4.0a	8.5b	5.4b
100	2-2-2	32.8b	3.1b	328.2f	297.3c	290.6d	125.6b	7.9a	2.8a	6.1a	2.1ab
200	3-2-1	42.7e	4.1e	213.4d	237.6a	252.7a	197.8e	28.0d	11.5c	12.6c	3.6b
200	1-2-3	38.8c	3.7c	194.0b	262.1b	267.0c	169.0c	31.7e	12.4c	17.2e	23.8d
200	2-2-2	41.7d	4.0d	208.6c	240.8a	260.1b	193.2d	22.8c	9.0b	13.9d	12.0c
300	3-2-1	43.0e	4.1e	143.3a	236.2a	251.3a	200.0f	87.0h	36.2f	26.8f	28.4e
300	1-2-3	43.0e	4.1e	143.3a	236.2a	251.3a	200.0f	63.8f	26.3d	27.6fg	50.3g
300	2-2-2	43.0e	4.1e	143.3a	236.2a	251.3a	200.0f	76.8g	31.9e	28.5g	36.7f
lsd (5%)		0.7	0.1	4.8	5.7	5.5	1.5	1.0	2.1	0.9	1.9

Note: Significance differences according to the 5% lsd values provided in the bottom row within a column are indicated by different letters.

Table 3. Simulated yield, WUE, NUE, N leaching and denitrification, as function of irrigation level, N input, N fractionation, interactions between water and N input and integrations between N input and N fractionation. Intercepts are the values at the scenario of 0.8ET, N100 and F1-2-3. $\beta_{1\text{-}5}$ show the difference to the intercepts.

Dependent Variable	Item	Value	Std.Error	DF	t-value	p-value	Sign.
	α (intercept)	32	0.2	12	136.0	0.00	***
	β_1 (1.0ET)	0.0	0.3	12	0.1	0.90	NS
	β_1 (1.2ET)	-0.2	0.3	12	-0.8	0.45	NS
	β_2 (N200)	7.0	0.3	12	21.0	0.00	***
	β_2 (N300)	10.4	0.3	12	31.2	0.00	***
	β_3 (F2-2-2)	0.9	0.3	12	3.4	0.01	***
	β_3 (F3-2-1)	1.2	0.3	12	4.5	0.00	***
Yield	β_4 (1.0ET*N200)	-0.1	0.4	12	-0.3	0.79	NS
	β_4 (1.2ET*N200)	-0.3	0.4	12	-0.9	0.38	NS
	β_4 (1.0ET*N300)	0.8	0.4	12	2.1	0.06	NS
	β_4 (1.2ET*N300)	1.2	0.4	12	3.3	0.01	***
	β_5 (N200∗F2-2-2)	2.0	0.4	12	5.6	0.00	***
	β_5 (N300∗F2-2-2)	-0.9	0.4	12	-2.4	0.04	***
	β_5 (N200∗F3-2-1)	2.7	0.4	12	7.5	0.00	***
	β_5 (N300∗F3-2-1)	-1.2	0.4	12	-3.2	0.01	***
	α (intercept)	3.4	0.0	12	140.1	0.00	***
	β_1 (1.0ET)	-0.3	0.0	12	-12.8	0.00	***
	β_1 (1.2ET)	-0.6	0.0	12	-24.4	0.00	***
	β_2 (N200)	0.7	0.0	12	21.9	0.00	***
	β_2 (N300)	1.1	0.0	12	31.6	0.00	***
	β_3 (F2-2-2)	0.1	0.0	12	3.0	0.01	***
	β_3 (F3-2-1)	0.1	0.0	12	4.2	0.00	***
WUE	β_4 (1.0ET*N200)	-0.1	0.0	12	-2.5	0.03	***
	β_4 (1.2ET*N200)	-0.2	0.0	12	-4.7	0.00	***
	β_4 (1.0ET*N300)	0.0	0.0	12	-0.6	0.54	NS
	β_4 (1.2ET*N300)	-0.1	0.0	12	-1.8	0.10	NS
	β_5 (N200∗F2-2-2)	0.2	0.0	12	5.3	0.00	***
	β_5 (N300∗F2-2-2)	-0.1	0.0	12	-2.1	0.05	NS
	β_5 (N200∗F3-2-1)	0.3	0.0	12	6.8	0.00	***
	β_5 (N300∗F3-2-1)	-0.1	0.0	12	-3.0	0.01	***
	α (intercept)	320.3	1.6	12	200.8	0.00	***
	β_1 (1.0ET)	0.8	1.7	12	0.5	0.66	NS
	β_1 (1.2ET)	-2.3	1.7	12	-1.3	0.21	NS
	β_2 (N200)	-125.4	2.3	12	-55.6	0.00	***
	β_2 (N300)	-179.1	2.3	12	-79.4	0.00	***
	β_3 (F2-2-2)	8.4	1.7	12	4.8	0.00	***
	β_3 (F3-2-1)	11.5	1.7	12	6.6	0.00	***
NUE	β_4 (1.0ET*N200)	-0.8	2.5	12	-0.3	0.74	NS
	β_4 (1.2ET*N200)	0.0	2.5	12	0.0	0.99	NS
	β_4 (1.0ET*N300)	2.0	2.5	12	0.8	0.43	NS
	β_4 (1.2ET*N300)	5.7	2.5	12	2.3	0.04	***
	β_5 (N200∗F2-2-2)	6.1	2.5	12	2.5	0.03	***
	β_5 (N300∗F2-2-2)	-8.4	2.5	12	-3.4	0.01	***
	β_5 (N200∗F3-2-1)	7.9	2.5	12	3.2	0.01	***
	β_5 (N300∗F3-2-1)	-11.5	2.5	12	-4.6	0.00	***

N leaching	α (intercept)	10.0	0.4	12	25.9	0.00	***
	β_1 (1.0ET)	1.4	0.4	12	3.4	0.01	***
	β_1 (1.2ET)	2.5	0.4	12	5.9	0.00	***
	β_2 (N200)	17.6	0.5	12	32.3	0.00	***
	β_2 (N300)	45.4	0.5	12	83.6	0.00	***
	β_3 (F2-2-2)	-3.4	0.4	12	-8.1	0.00	***
	β_3 (F3-2-1)	-3.1	0.4	12	-7.4	0.00	***
	β_4 (1.0ET*N200)	2.8	0.6	12	4.7	0.00	***
	β_4 (1.2ET*N200)	5.8	0.6	12	9.7	0.00	***
	β_4 (1.0ET*N300)	7.7	0.6	12	12.9	0.00	***
	β_4 (1.2ET*N300)	13.7	0.6	12	23.1	0.00	***
	β_5 (N200∗F2-2-2)	-5.5	0.6	12	-9.2	0.00	***
	β_5 (N300∗F2-2-2)	16.4	0.6	12	27.6	0.00	***
	β_5 (N200∗F3-2-1)	-0.6	0.6	12	-1.0	0.33	NS
	β_5 (N300∗F3-2-1)	26.3	0.6	12	44.2	0.00	***
Denitrification	α (intercept)	8.0	0.5	12	16.2	0.00	***
	β_1 (1.0ET)	0.5	0.5	12	1.0	0.34	NS
	β_1 (1.2ET)	0.9	0.5	12	1.6	0.13	NS
	β_2 (N200)	7.4	0.7	12	10.6	0.00	***
	β_2 (N300)	15.2	0.7	12	21.8	0.00	***
	β_3 (F2-2-2)	-2.3	0.5	12	-4.3	0.00	***
	β_3 (F3-2-1)	-2.9	0.5	12	-5.3	0.00	***
	β_4 (1.0ET*N200)	1.7	0.8	12	2.2	0.05	***
	β_4 (1.2ET*N200)	2.5	0.8	12	3.2	0.01	***
	β_4 (1.0ET*N300)	4.8	0.8	12	6.3	0.00	***
	β_4 (1.2ET*N300)	7.0	0.8	12	9.2	0.00	***
	β_5 (N200∗F2-2-2)	-1.0	0.8	12	-1.3	0.23	NS
	β_5 (N300∗F2-2-2)	3.2	0.8	12	4.1	0.00	***
	β_5 (N200∗F3-2-1)	-1.8	0.8	12	-2.4	0.04	***
	β_5 (N300∗F3-2-1)	2.0	0.8	12	2.7	0.02	***

6.3.2. Water use efficiency

Water use efficiency (WUE) ranged from 2.7 to 4.4 kg m^{-3}. WUE decreased with increasing water input, and increased with increasing N input (Figure 4, Table 1). Increasing water input significantly increased water losses via evaporation and drainage. Low WUE at low N input level (100 kg ha^{-1}) was because of the low N uptake and thereby low yield. WUE increased with increasing N input from 100 to 200 kg ha^{-1}, but further increases in N input did not increase WUE much.

Fractionation of the N input over the growing season had statistical significant effects on WUE (Table 2). Fractionation 3-2-1 led to a relatively high WUE and fractionation 1-2-3 resulted in a relatively low WUE. Effects of N fractionations on WUE were negligible at high N input of 300 kg ha^{-1} (Table 2). Fractionation did not have much effect on evaporation and drainage.

6.3.3. Nitrogen use efficiency and N losses

Nitrogen use efficiency (NUE) ranged from 140 to 335 kg kg^{-1}. NUE decreased with increasing N input (Figure 4). Differences in NUE between different water input levels were small and statistically not significant (Table 1). Fractionation of the N supply over the growing season significantly affected NUE at sub-optimal and near optimal N input (Table 2). Fractionation 3-2-1 gave the highest NUE and fraction 1-2-3 the lowest NUE.

The main N loss pathway was leaching of nitrate. Losses via denitrification were proportional to N input and irrigation level, but were relatively low because of the well-drained soil with low soil organic carbon content. Total N losses (sum of N leaching and denitrification) ranged from 12 to 124 kg ha^{-1}, and increased with increasing N input (Figure 4, Table 2). Mean total N loss was 16 kg ha^{-1} (16% of the N input) at low N input (100 kg ha^{-1}), and was 104 kg ha^{-1} (35% of the N input) at high N input (300 kg ha^{-1}). Increasing water input significantly increased N leaching and denitrification at the N input levels of 200 and 300 kg ha^{-1}. As a consequence, the nitrate-N concentration in the leachate at the bottom of the root zone also differed significantly between water and N input levels. Significant amounts of residual mineral N were left in the soil by the end of the year, especially at high N input levels and deficit irrigation (Table 1).

Fractionation of the N supply over the growing season had additional effects on N leaching; fractionation 1-2-3 resulted in relatively high N losses at low and medium N input. Fractionation 2-2-2 gave lower leaching losses than 1-2-3 at N input levels of 100 and 200 kg ha^{-1} (Table 2). Fractionation had also significant effects on the amounts of residual mineral N in the soil; especially 1-2-3 resulted in high levels of soil mineral N.

6.3.4. Fine-tuning fractionation at near optimal N input level

Two additional N input fractionations were explored at a N input of 200 kg ha^{-1} with balanced irrigation (f = 1.0), namely 2-3-1 and 1-3-2, and the results are compared with the former three fractionations (Figure 5). Fractionation 2-3-1 gave equally high yield, WUE and NUE as fractionation 3-2-1, Fractionation 1-3-2 gave slightly lower yield, WUE and NUE, but lower N losses than fractionation 3-2-1. Based on these simulations, we conclude that fractionations 3-2-1 and 2-3-1 are superior to the other fractionations. This conclusion does not change when the rainfall or soil type changes.

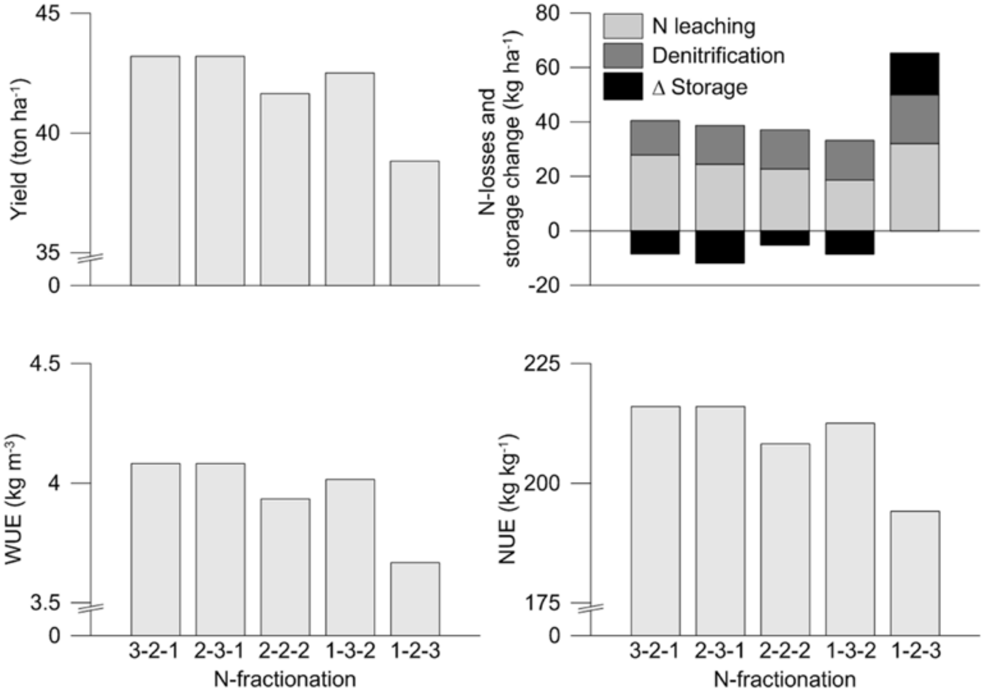


Figure 5. Effects of 5 N fractionations on yield, WUE, N losses and NUE with balanced irrigation and N input of 200 kg ha^{-1}.

Results presented in Figure 6 show that a dry versus wet year had significant effects on yield, WUE, NUE and N losses. Both dry and wet year produced relatively lower yield and NUE; WUE was relatively larger at dry year and N losses were larger at wet year. Results presented in Figure 7 show that soil type can also affect yield, WUE, N losses and NUE. Yield, WUE and NUE were similar at coarse and medium soils, which were relatively higher than fine soil. Fine soil produced relatively larger N losses, in which 70-80% was lost via denitrification; whereas N losses in coarse and medium soils were mostly via leaching (>95%) (Table SI-4). Clearly, fractionation 3-2-1 outperformed fractionation 2-2-2 and 1-2-3 in yield, WUE and NUE.

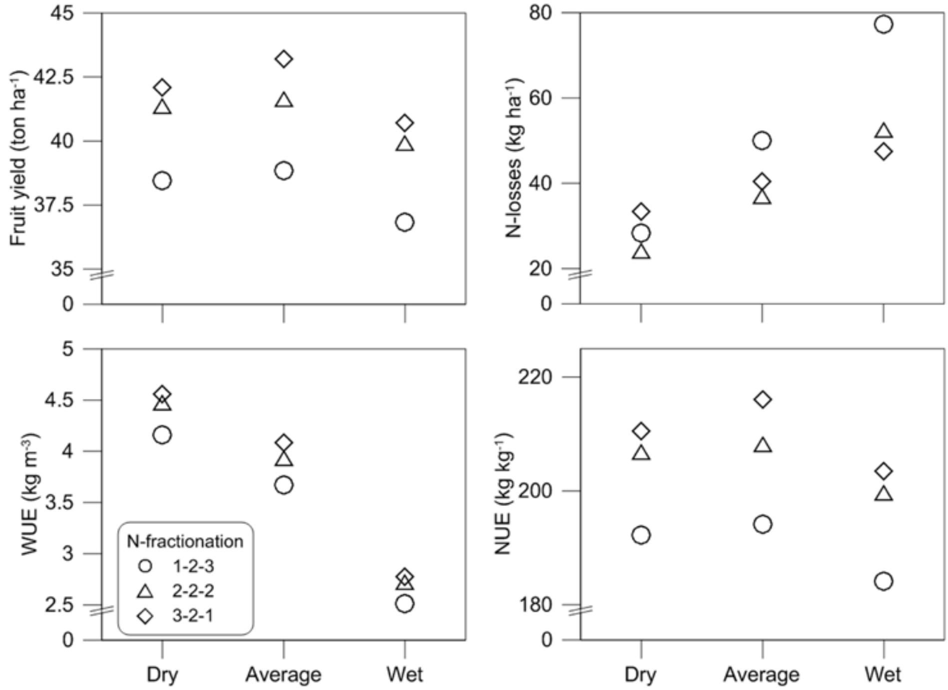


Figure 6. Effects of three rain scenarios (dry, average, wet) on yield, WUE, N losses and NUE with balanced irrigation and N input of 200 kg ha^{-1}.

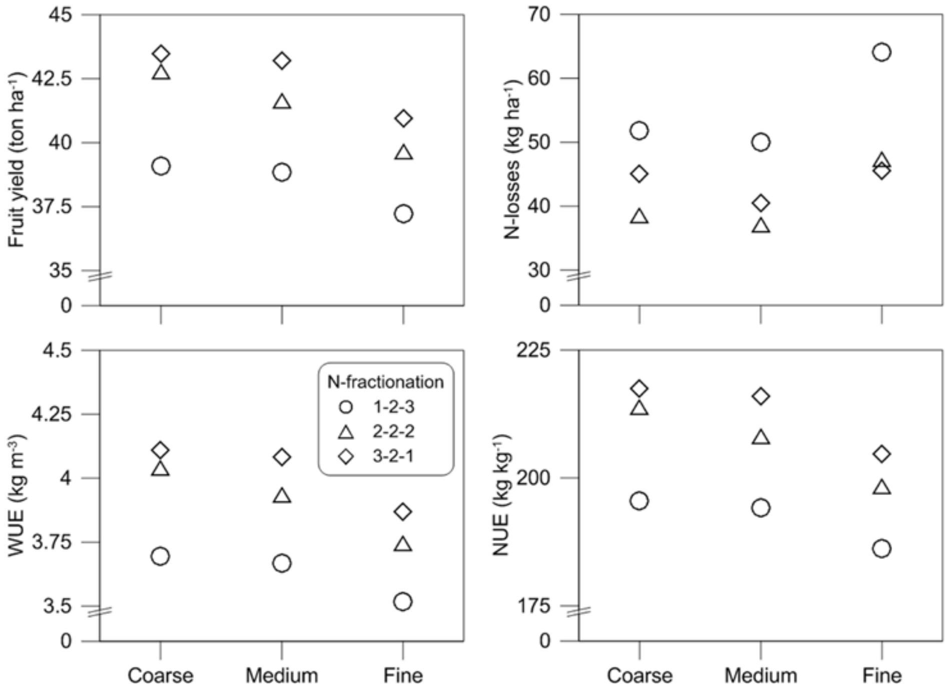


Figure 7. Effects of soil type on yield, WUE, N losses and NUE with balanced irrigation and N input of 200 kg ha^{-1}.

6

6.4. Discussion

We used a coupled soil-crop model (FUSSIM3D and AquaCrop) to test the effects of 47 drip fertigation strategies on orange yield, WUE, NUE and N losses for a whole growing season. Coupling was done in sequential iterative way by using the output of one model as input for the other and vice versa. This model combination provided detailed and unique insights of fertigation strategies on both agronomic impacts (i.e. yield, WUE and NUE) and environmental impacts (N leaching and denitrification losses, residual soil mineral N).

Effects of variations in N input were larger than the effects of variations in water input and N input fractionation over the growing season, mainly because of the relative large variation in N input. The near optimal N input was 200 kg ha^{-1}, which is not surprising given the fact that N demand was set at 200 kg ha^{-1}, and that the initial amount of soil mineral N was set at about 50 kg ha^{-1}. The mean N uptake ranged between 116 and 126 kg ha^{-1} at an N input of 100 kg ha^{-1}, and from 170 and 200 kg ha^{-1} at a N input of 200 kg ha^{-1}, indicating that the recovery of N from soil and fertigation in the crop was high under the conditions of little or no stress from water, pest and diseases. The N recovery fraction is at the upper end of values (close to 100% fertilizer N supply) reported in literature (Alva et al., 2006a), and indicate that our simulations results reflect near potential or attainable recovery efficiency, obtained with good management (Steduto et al., 2012).

Effects of variations in water input (range f = 0.8 to 1.2 of ET-R) were relatively small, as there was no real water stress with f = 0.8, mainly because of the relatively wet soil conditions at the start of the irrigation season and the evenly distributed irrigation schedule. The beneficial effects of deficit irrigation on yield and WUE at sub-optimal and near-optimal N input (Table 1) are in line with the findings from experimental studies (Ballester et al., 2011, 2013). Deficit irrigation (f = 0.8) also significantly reduced N leaching losses and increased the amount of soil mineral N in the soil relative to balanced irrigation (f = 1.0) (Table 2).

Variations in the fractionations of N supply over the growing season had a relatively large effect at near optimal N input levels (Table 2).

Effects of the N fractionation in yield was relatively small at an over-optimal N input of 300 kg ha^{-1} because N uptake was high, even at the less effective N fractionation regime 1-2-3. Apparently, the N input of 300 kg ha^{-1} is dominant over the effects of N fractionation; i.e., daily N demand by orange was met by the high N input, irrespective of N fractionation, resulting in high yields. Also because all N taken up by the crop was assumed to be converted into marketable orange yield according to a fixed ratio (see Eq. 1). Likely, this fixed ratio can be physiologically too simple for simulating rather extreme N fractionations as 1-2-3, as the bulk of the N may come late during the growing season.

Fractionations 3-2-1 and 2-3-1 turned out to be the best strategies for targeting high yield, NUE and minimal N losses. Fractionation regime 1-3-2 gave slightly lower yield than 3-2-1 and 2-3-1, but gave the lowest N losses (Figure 5). We hypothesize that fractionation 1-3-2 may give the best overall performance in multiple year simulation runs, when residual soil mineral N can be utilized in a next growing season. Residual soil mineral N can be utilized in the following growing season, and thereby have considerable impacts on yield, WUE, NUE and N losses, depending on root and mineral N distribution patterns in the soil and environmental conditions (Schröder et al., 2000). This requires further testing.

6.4.1. Optimization of fertigation strategies

There were clear trade-offs between yield and N losses, and there were statistical significant interactions between water and N inputs and N fractionation regime in yield, WUE, NUE and N losses (Tables 1, 2). This challenges the optimization of fertigation and the selection of optimal fertigation strategies. Table 4 presents the results of an attempt to rank the performance of the fertigation strategies using different criteria, i.e., prioritizing in achieving high yield or reducing N losses. The ranking was limited to in total 11 fertigation strategies which all had a near optimal N input of 200 kg ha^{-1}. Evidently, different performance criteria led to different rankings (Table 3). Interestingly, strategies with excess irrigation ($f = 1.2$) all had a relatively low ranking, irrespective of criteria. Deficit irrigation ($f = 0.8$) scored relatively better when the objective is minimizing N losses. Balanced irrigation ($f = 1.0$) scored relatively better when the objective was high yield. Fractionation regimes 3-2-1 and 2-2-2 had relatively high rankings, but the order depended greatly on the performance criteria, suggesting that fractionation regime is a sensitive variable in the optimization of fertigation strategies.

Water uptake, N uptake, N leaching and denitrification are related to the root, soil water and mineral N distribution patterns in the soil. This is illustrated for three fertigation strategies (ranked 1, 7 and 10 in the last column of Table 4) and for different times in the growing season in Figure 8. The first 60 days no fertigation took place, so that the NO_3-N distribution at that time was the same for all scenarios. At $t = 142$ d the distribution for the fractionation regimes 2-3-1 and 2-2-2 are identical, as during the first period equal amounts of N were applied. Differences between the three fertigation strategies (fractionation regimes) became evident at the end of the fertigation season ($t = 304$ d): low N concentration in the neighborhood of the dripper and rooted soil volume for N fractionation 2-3-1, and relatively high nitrate N concentrations for fractionation 2-2-2 near the dripper and in the rooted soil. In the middle of the growing season (t = 224 d), fractionations 1-2-3 and to a lesser extent 2-2-2 gave low nitrate N concentrations in the rooted soil volume, which resulted in a decreased N uptake and yield. Fractionation regime 1-2-3 resulted in high nitrate N concentrations at the bottom of the rooted soil volume at the end of the fertigation season and the end of the year. This latter distribution pattern was also observed by Phogat et al (2013) for fertigation strategies.

By comparing the effects of fertigation strategies in extreme dry and wet years, it was seen that fertigation can ensure high yield, WUE and NUE and low N losses during dry years. However, relatively low WUE and NUE and high N losses were obtained for the wet year, as fertigation cannot circumvent leaching and denitrification following heavy rainfall events.

We assumed that the monthly rainfall was evenly distributed over all days of the month. Some additional simulations were carried out in which the total monthly rainfall was assigned to randomly chosen days of the month. The results were comparable with those obtained for the evenly distributed rainfall (see Table SI-4). This indicates that the soil plays an important role in buffering the variation in water and N supply.

Fertigation (irrigation and N supply) was conducted daily, depending on the period of the season and the irrigation and N fractionation regimes (Figure 3). This choice was based in part on the results of Scholberg et al. (2002) who reported that high frequent applications doubled NUE compared with less frequent applications of a more concentrated nutrient solution. Additional simulations with pulse applications where all N was delivered during the first week of each of the three periods showed indeed that continuous applications outperformed pulse applications (Table SI-4).

Our study explored fertigation strategies for orange production in a Mediterranean climate. However, many of the findings may be applicable for other fertigated cropping systems in other regions of the world. The set-up of the simulations and the variables for climate, soil and fertigation management can be adjusted rather easily. Our modelling tool can be used also to identify fertigation strategies for experimental testing and for optimizing the measurements in the field studies with relatively large N inputs in the second half of the growing season.

Table 4. Ranking fertigation strategies in order of performance using different performance criteria. All fertigation strategies had a total N supply of 200 kg ha^{-1}, but varied in the fractionation of the N supply over the growing season (*Frac*) and in irrigation level (f = 0.8; 1.0; 1.2). Ranking was done in order of the highest yield (Y), the lowest N leaching from the root zone (L_N), the lowest denitrification (D_N), the lowest total N loss (L_N+D_N), and two combinations, i.e., $Y+L_N+D_N$ and $6Y+2L_N+D_N$). The best three strategies per column are printed bold.

f	N input	*Frac*	Yield (Y)		Leaching (L_N)		Denitrification (D_N)		N losses (L_N+D_N)		$Y+L_N+D_N$	$6Y+2L_N + D_N$
	(kg ha^{-1})		Rank	ton ha^{-1}	Rank	kg ha^{-1}	Rank	kg ha^{-1}	Rank	kg ha^{-1}	Rank	Rank
1.0	200	3-2-1	**1**	43.2	8	27.9	**3**	12.6	6	40.5	4	**2**
1.0	200	1-2-3	10	38.8	10	32.0	10	17.9	10	49.9	10	10
1.0	200	2-2-2	7	41.6	**3**	22.8	6	14.3	4	37.1	6	7
0.8	200	3-2-1	5	42.4	5	24.6	**1**	11.9	**3**	36.5	**3**	5
0.8	200	1-2-3	9	39.0	6	27.2	7	14.4	7	41.6	8	9
0.8	200	2-2-2	5	42.4	**1**	18.2	**2**	11.9	**1**	30.1	**1**	4
1.2	200	3-2-1	4	42.5	9	31.5	4	13.2	9	44.6	7	6
1.2	200	1-2-3	11	38.6	11	35.9	11	19.4	11	55.3	11	11
1.2	200	2-2-2	8	41.1	7	27.4	9	15.6	8	42.9	9	8
1.0	200	1-3-2	**3**	42.5	**2**	18.6	8	14.6	**2**	33.2	5	**3**
1.0	200	2-3-1	**1**	43.2	4	24.5	5	14.2	5	38.7	**2**	**1**

6

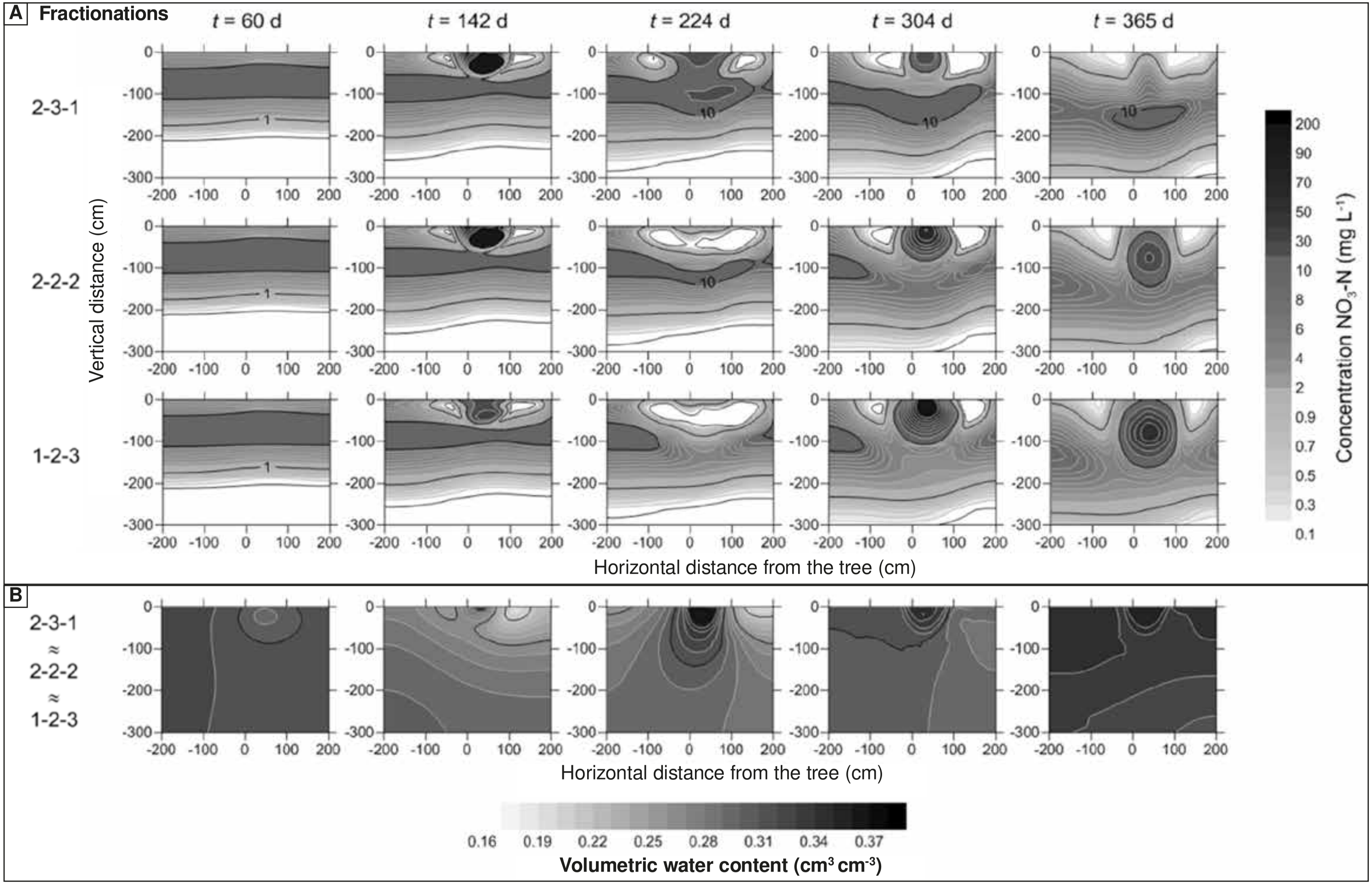


Figure 8. NO_3-N concentration distributions (note the logarithmic scale) in the soil for three typical fertigation fractionations as a function of time, and the corresponding volumetric water content distributions (bottom row) which were approximately the same for all three scenarios.

6.5. Conclusion

We coupled a mechanistic soil hydrological model to a water-driven crop model, and explored the agronomic and environmental impacts of 47 fertigation strategies in terms of orange yield, WUE, NUE and N leaching losses. Our simulations relate to situations of relatively good management conditions with a high N uptake recovery obtained with an N input of 300 kg per ha per year. Variations in N input had larger effects on yield, WUE, NUE and N losses than variations in irrigation level and the N input fractionation over the growing season. Deficit irrigation (80% of *ET-R*) led to relatively high yield, WUE, and NUE and relatively low N losses. The near optimal N input of 200 kg ha^{-1} gave a yield reduction of about 5% relative to the maximum yield (43.5 ton ha^{-1}). The sub-optimal N input of 100 kg ha^{-1} gave a yield reduction of on average 25%. These results are very much in line with results presented in literature.

The statistical significant interactions between water and N inputs and N fractionation regime in yield, WUE, NUE and N losses indicate that the optimization of fertigation strategies must consider these three key variables simultaneously. Given the observed trade-offs between yield and N losses, criteria and indicators have to be developed and tested (as suggested for example in Table 4) to allow an integrated evaluation on the performance of fertigation strategies.

Our simulation results may provide guidance to experimental studies and also to practice. Deficit irrigation at a level of 80% of *ET-R* could be a starting point for fertigation practice, provided the soil profile is wet at the start of the growing season and irrigation can be provided regularly. Balanced N fertilization, i.e., N supply is equal to N demand, could be another starting point, provided the soil has some minimum of mineral N at the start of the growing season, and the fractionation regime is adjusted to the N demand by the crop during the growing season. Our results clearly show that over-optimal water and N inputs lead to high water and N losses.

Acknowledgements

This study was carried out within the project EFFIDRIP funded by the 7th Framework Program of the European Union, research for the benefits of SME/SME-ags; EU FP7-SME-2011, grant 286807.

Supplemental information

Supplemental information belonging to "Exploring optimal fertigation strategies for orange production, using soil-crop modelling" by M. Heinen, W. Qin, F.B.T. Assinck, and O. Oenema.

35 scenarios have been presented in the main text, including 27 main scenarios consisting of 3 irrigation levels, 3 N supply levels, and 3 N fractionations, all for an average climatic year; 2 additional scenarios considered 2 alternative N fractionations; 3 scenarios were repeated for a dry year, and 3 scenarios were repeated for a wet year.

Additional scenarios included:

- 3 scenarios where the monthly rainfall was randomly assigned to the number of rainfall days for that month; the objective was to determine if rainfall events rather than evenly distributed rainfall has large impact on the results;
- 3 scenarios where N supply was performed during the first week of the three fertigation periods (pulse application); the objective was to determine if pulse application rather than evenly distributed application has large impact on the results;
- 3 scenarios were run for both a coarse (sand) and a fine (clay) soil; the objective was to determine the effect of soil type on the outcome.

Table SI-3 lists the description of all 47 scenarios. Scenarios 1-35 were presented in the main text and scenarios 36-47 were included in Supplemental Information only.

Table SI-4 lists all outcomes for the 47 scenarios: yield, potential and actual evaporation and transpiration, drainage of water and leaching of N (including concentration) below the root zone, actual N uptake, denitrification, and water and nutrient use efficiencies.

Table SI-1. Full set of crop parameters used in AquaCrop representing orange growth.

Parameters	Contents and values	Source
Crop development in calendar days		
Simulations start on 1 Jan	0 days	Steduto et al., 2012
to flowering	75 days	Steduto et al., 2012
to senescence	365 days	Steduto et al., 2012
to maturity	365 days	Steduto et al., 2012
Length for building up Harvest Index (HI)	290 days	Steduto et al., 2012
Duration of flowering	180 days	Steduto et al., 2012
Plant density	500 trees ha^{-1}	This study
Maximum root depth	0.75 m	This study
Reference HI	135% (indicative for fresh weight)	This study
Max HI	155%	This study
Crop water productivity	20 g m^{-2}	This study
Canopy development		
Initial canopy cover	53%	This study
Canopy expansion	0% day^{-1}	This study
Max. canopy cover	53%	This study
Canopy decline	4.3% day^{-1} (38 days)	This study
Thresholds temperatures		
Base temperature for biomass production	0 ^0C	This study
Upper temperature for biomass production	35 ^0C	This study
Range of cold stress for biomass production	0 - 11 ^0C	This study
Range of cold stress for pollination	-5 - 0 ^0C	This study
Range of heat stress for pollination	35 - 40 ^0C	This study
Water extraction pattern throughout the root zone		
Upper 1/4	40%	This study
Second 1/4	30%	This study
Third 1/4	20%	This study
Bottom 1/4	10%	This study
Water stresses		
Canopy expansion	Moderately tolerant (upper = 0.25, lower = 0.65, shape factor = 5)	This study
Stomata closure	Extremely sensitive (upper = 0.25, shape factor = 2.5)	This study
Early canopy senescence	Tolerant (upper = 0.75, shape factor =2.5)	This study
Aeration stress	Moderately tolerant (5 vol %)	This study
Evapotranspiration		
Soil evaporation coefficient	Effect of canopy shelter in late season = 25%	This study
Crop transpiration coefficient	0.68 (reduction with age = 0% day^{-1})	This study
Fertility stresses		
N uptake	N uptake simulated by FUSSIM3D	This study

6

Table SI-2. Thirty-year average monthly weather data for the region of Seville, Spain (Seville airport; Latitude: 37° 25’ 0’’ N - Longitude: 5° 52’ 45’’ W, Altitude: 34 m; 1971-2000): minimum and maximum daily temperature T_{min}, T_{max}, total rainfall *R*, number of days with significant rainfall *NR*, radiation *Rad*, relative humidity *RH*, vapor pressure deficit *VPD*, wind speed *W*, calculated reference evapotranspiration rate ET_0, and crop coefficient K_c (sources: Spanish Meteorological Service (www.aemet.es) and the “Atlas de Radiación Solar en España utilizando datos del SAF de Clima de EUMETSAT” (available at: www.aemet.es); K_c: Goldhamer et al., 2012). Data for the dry and wet years were obtained from the Centre for Environmental Data Archival (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_0c08abfc-f2d5-11e2-a948-00163e251233).

Month	T_{min} ^{0}C	T_{max} ^{0}C	*R* mm	*NR* d	*Rad* kJ m^{-2} d^{-1}	*RH* %	*VPD* kPa	*W* m s^{-1}	ET_0 mm d^{-1}	K_c	*R*, dry mm	ET_0, dry mm d^{-1}	*R*, wet mm	ET_0, wet mm d^{-1}
January	5.2	15.9	65	6	9792	72	0.914	1.15	0.86	0.600	0	1.5	276	1.5
February	6.7	17.9	54	6	13176	68	0.969	1.35	1.66	0.640	10	2.0	36	1.9
March	8.2	21.2	38	5	18108	61	1.016	1.55	2.91	0.565	36	3.0	46	2.8
April	10.1	22.7	57	7	22104	60	1.114	1.40	3.84	0.575	59	2.9	42	3.8
May	13.1	26.4	34	4	25164	57	1.305	1.35	4.91	0.515	20	4.4	91	4.7
June	16.7	31.0	13	2	28368	52	1.528	1.35	6.18	0.595	6	6.1	0	6.2
July	19.4	35.3	2	0	29160	47	1.699	1.30	6.92	0.635	2	6.9	0	6.8
August	19.5	35.0	6	0	25920	50	1.797	1.10	5.95	0.735	0	6.1	1	5.9
September	17.5	31.6	23	2	20808	54	1.655	1.10	4.40	0.680	30	4.8	28	4.4
October	13.5	25.6	62	6	14472	63	1.425	1.10	2.47	0.760	8	3.1	14	3.3
November	9.3	20.1	84	6	10512	71	1.183	1.15	1.22	0.740	1	2.5	69	2.0
December	6.9	16.6	95	8	8388	75	1.031	1.15	0.69	0.710	146	1.3	303	1.3

Table SI-3. Description of the 47 scenarios: i.e., irrigation level (*f*; Eq. [2] in main text), N input levels, N fractionations (N *frac*), soil type, fertigation application methods and rain type. By default all scenarios refer to the average climate conditions, except where indicated dry or wet. Scenarios 1-27 are the main scenarios, scenarios 28-47 are the additional scenarios.

Scenario	*f* (% ET)	N (kg ha^{-1})	N *frac*	Soil type	Method	Rain type
1	100	200	3-2-1	Medium	Even	Even
2	100	200	1-2-3	Medium	Even	Even
3	100	200	2-2-2	Medium	Even	Even
4	80	200	3-2-1	Medium	Even	Even
5	80	200	1-2-3	Medium	Even	Even
6	80	200	2-2-2	Medium	Even	Even
7	120	200	3-2-1	Medium	Even	Even
8	120	200	1-2-3	Medium	Even	Even
9	120	200	2-2-2	Medium	Even	Even
10	100	100	3-2-1	Medium	Even	Even
11	100	100	1-2-3	Medium	Even	Even
12	100	100	2-2-2	Medium	Even	Even
13	80	100	3-2-1	Medium	Even	Even
14	80	100	1-2-3	Medium	Even	Even
15	80	100	2-2-2	Medium	Even	Even
16	120	100	3-2-1	Medium	Even	Even
17	120	100	1-2-3	Medium	Even	Even
18	120	100	2-2-2	Medium	Even	Even
19	100	300	3-2-1	Medium	Even	Even
20	100	300	1-2-3	Medium	Even	Even
21	100	300	2-2-2	Medium	Even	Even
22	80	300	3-2-1	Medium	Even	Even
23	80	300	1-2-3	Medium	Even	Even
24	80	300	2-2-2	Medium	Even	Even
25	120	300	3-2-1	Medium	Even	Even
26	120	300	1-2-3	Medium	Even	Even
27	120	300	2-2-2	Medium	Even	Even
28	100	200	1-3-2	Medium	Even	Even
29	100	200	2-3-1	Medium	Even	Even
30	100	200	3-2-1	Medium	Even	dry
31	100	200	1-2-3	Medium	Even	dry
32	100	200	2-2-2	Medium	Even	dry
33	100	200	3-2-1	Medium	Even	wet
34	100	200	1-2-3	Medium	Even	wet
35	100	200	2-2-2	Medium	Even	wet
36	100	200	3-2-1	Medium	Even	Event
37	100	200	1-2-3	Medium	Even	Event
38	100	200	2-2-2	Medium	Even	Event

39	100	200	3-2-1	Medium	Pulse	Even
40	100	200	1-2-3	Medium	Pulse	Even
41	100	200	2-2-2	Medium	Pulse	Even
42	100	200	3-2-1	Coarse	Even	Even
43	100	200	1-2-3	Coarse	Even	Even
44	100	200	2-2-2	Coarse	Even	Even
45	100	200	3-2-1	Fine	Even	Even
46	100	200	1-2-3	Fine	Even	Even
47	100	200	2-2-2	Fine	Even	Even

Table SI-4. Simulated yield, potential and actual transpiration (T_{pot}, T_{act}), potential and actual soil evaporation (E_{pot}, E_{act}), drainage of water below the root zone (L_w), actual N uptake (N_{act}), leaching of N below the root zone (L_N), N concentration of the leaching water below the root zone (C_N), the amount of denitrification (D), water use efficiency (WUE; according to Eq. [3] in main text), and nutrient use efficiency (NUE; according to Eq. [4] in main text).

Scenario	Yield ton ha^{-1}	T_{pot} mm	T_{act} mm	E_{pot} mm	E_{act} mm	L_w mm	N_{act} kg ha^{-1}	L_N kg ha^{-1}	C_N mg L^{-1}	D kg ha^{-1}	WUE kg m^{-3}	NUE kg kg^{-1}
1	43.2	561.2	552.7	239.0	236.4	246.2	198.4	27.9	11.3	12.6	4.08	216.0
2	38.8	514.8	508.1	266.8	264.1	263.2	168.9	32.0	12.2	17.9	3.67	194.1
3	41.6	544.8	537.3	248.8	246.2	251.8	193.2	22.8	9.0	14.3	3.93	208.2
4	42.4	540.4	525.7	232.5	229.4	177.5	200.0	24.6	13.9	11.9	4.44	211.8
5	39.0	508.4	496.0	255.7	252.4	184.5	169.8	27.2	14.7	14.4	4.09	194.8
6	42.4	540.4	525.7	232.5	229.5	177.4	196.6	18.2	10.3	11.9	4.44	211.8
7	42.5	563.9	558.2	249.1	246.9	334.3	195.0	31.5	9.4	13.2	3.65	212.5
8	38.6	521.1	516.5	272.0	269.7	353.3	168.2	35.9	10.2	19.4	3.32	193.2
9	41.1	544.8	541.3	248.8	246.8	351.2	189.7	27.4	7.8	15.6	3.54	205.7
10	33.0	452.9	448.1	301.5	298.6	288.4	126.1	8.3	2.9	5.6	3.12	330.5
11	32.2	442.3	437.6	307.9	304.9	292.0	116.5	11.4	3.9	8.6	3.04	322.1
12	33.0	463.0	457.9	295.2	292.3	284.6	125.6	8.0	2.8	6.2	3.12	330.5
13	33.6	452.1	442.6	290.9	287.1	201.7	128.4	6.5	3.2	5.2	3.52	335.7
14	31.8	433.0	424.3	304.6	300.6	206.2	117.2	10.0	4.9	7.9	3.34	318.4
15	32.7	442.8	433.9	297.5	293.7	204.1	126.6	6.9	3.4	5.7	3.43	326.6
16	32.8	453.7	450.3	308.5	306.0	383.1	124.5	9.7	2.5	6.0	2.81	327.5
17	31.9	443.8	440.5	314.7	312.1	386.9	116.0	12.4	3.2	8.9	2.74	318.8
18	32.8	453.7	450.3	308.5	306.0	383.1	124.7	8.7	2.3	6.5	2.81	327.5
19	43.2	561.2	552.7	239.0	236.4	246.3	200.0	87.9	35.7	27.6	4.08	144.0
20	43.2	561.2	552.7	239.0	236.4	246.3	200.0	64.2	26.1	28.6	4.08	144.0
21	43.2	561.2	552.7	239.0	236.4	246.3	200.0	77.5	31.5	29.5	4.08	144.0
22	42.4	540.4	525.7	232.5	229.4	177.5	200.0	79.0	44.5	23.1	4.44	141.2
23	42.4	540.4	525.7	232.5	229.4	177.5	200.0	55.2	31.1	22.7	4.44	141.2

24	42.4	540.4	525.7	232.5	229.4	177.5	200.0	68.1	38.4	23.9	4.44	141.2
25	43.4	572.6	566.6	245.0	242.8	330.1	200.0	94.1	28.5	29.7	3.73	144.6
26	43.4	572.6	566.6	245.0	242.8	330.1	200.0	72.0	21.8	31.6	3.73	144.6
27	43.4	572.6	566.6	245.0	242.8	330.1	200.0	84.8	25.7	32.0	3.73	144.6
28	42.5	553.5	545.5	243.9	241.3	248.6	196.2	18.6	7.5	14.6	4.02	212.5
29	43.2	561.2	552.7	239.0	236.4	246.3	200.0	24.5	10.0	14.2	4.08	216.0
30	39.7	515.9	498.8	256.8	253.0	287.5	177.2	9.2	3.2	38.2	3.75	198.3
31	42.1	599.1	591.9	204.5	201.7	106.7	199.7	22.5	21.1	10.9	4.56	210.5
32	38.4	555.6	550.7	223.0	220.1	127.3	174.4	15.0	11.8	13.4	4.16	192.2
33	41.4	590.5	583.8	208.9	206.1	109.9	195.6	12.9	11.8	11.3	4.48	206.9
34	40.7	586.6	581.5	266.6	264.1	569.3	193.5	35.7	6.3	11.8	2.78	203.5
35	36.8	537.2	533.6	288.6	286.1	595.2	155.3	57.6	9.7	19.6	2.51	184.0
36	43.2	561.2	551.7	239.0	235.8	248.4	198.1	28.1	11.3	12.5	4.08	216.0
37	38.8	514.8	507.1	266.8	263.4	265.3	168.9	30.9	11.6	17.9	3.67	194.1
38	41.6	544.8	536.3	248.8	245.5	254.0	192.8	22.5	8.9	14.2	3.93	208.2
39	42.5	561.2	552.7	239.0	236.5	246.2	187.0	39.8	16.2	12.7	4.02	212.5
40	37.9	514.8	508.0	266.8	264.0	263.3	159.4	52.8	20.0	17.7	3.58	189.6
41	40.4	544.8	537.2	248.8	246.2	252.0	179.5	43.0	17.1	14.7	3.81	201.8
42	43.5	566.6	548.2	237.5	229.3	235.6	200.0	43.8	18.6	1.3	4.11	217.5
43	39.1	520.3	504.5	265.2	254.0	254.8	170.3	50.8	19.9	1.0	3.69	195.5
44	42.8	559.6	541.5	242.0	233.2	238.4	197.4	37.5	15.7	1.1	4.04	213.9
45	41.0	528.4	510.1	250.4	246.6	282.3	182.0	12.4	4.4	33.2	3.87	204.8
46	37.2	488.5	472.9	273.2	269.1	297.0	155.6	17.6	5.9	46.4	3.52	186.1
47	39.7	515.9	498.8	256.8	253.0	287.5	177.2	9.2	3.2	38.2	3.75	198.3

6

Effects of rain event simulations

In all our scenarios, we used evenly distributed monthly rainfall as model input. Here, we show that there were no significant differences in yield, WUE, N losses and NUE between evenly distributed rainfall ('even') and randomly distributed rainfall ('event'). (Figure SI-1).

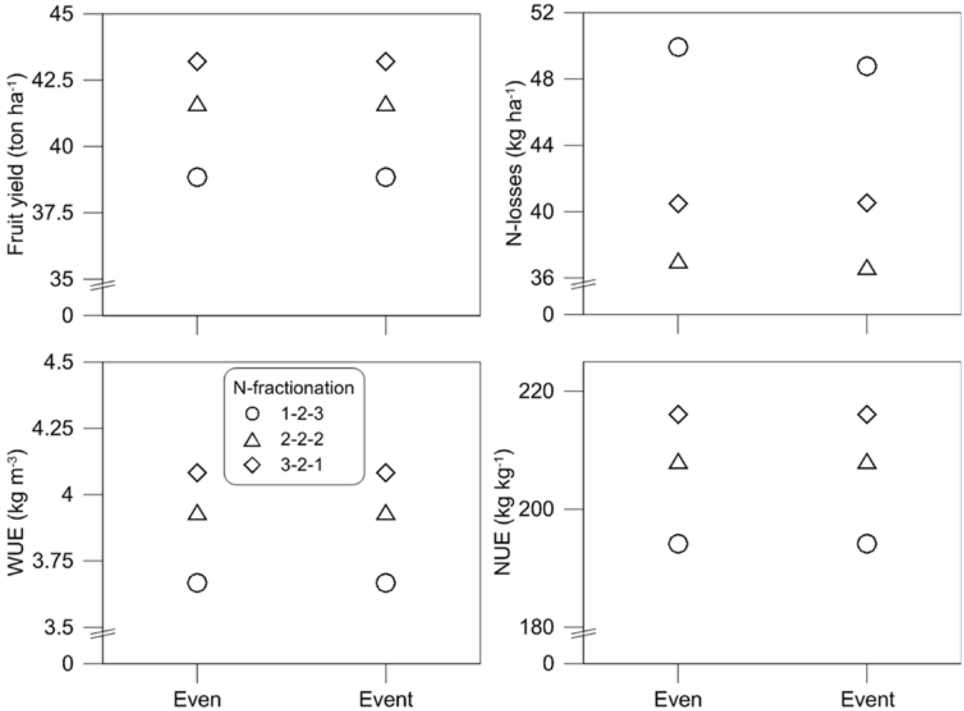


Figure SI-1. Effects of two rainfall distribution scenarios (even/event) on yield, WUE, N losses and NUE with balanced irrigation and N input of 200 kg ha^{-1}.

Effects of pulse application

Figure SI-2 presents the effects of 2 application methods (even and pulse) on yield, WUE, N losses and NUE. Overall, even application was better than pulse application in terms of yield, WUE, N losses and NUE, which was mainly because pulse application led to larger N losses (mostly via N leaching) and low N uptake, thereby lowering yield, WUE and NUE. These 2 application methods did not differ in terms of plant transpiration, soil evaporation and drainage (Table SI-4).

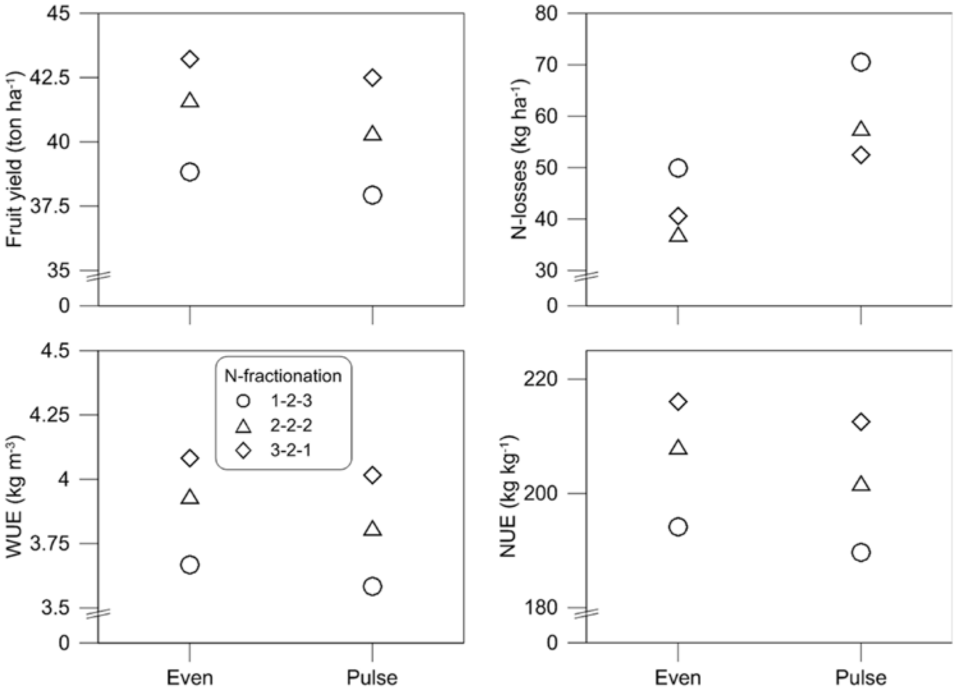


Figure SI-2. Effects of application method on yield, WUE, N losses and NUE with balanced irrigation and N input of 200 kg ha-1.

Chapter 7

General discussion

Water and nitrogen (N) are main crop yield limiting factors (de Wit, 1958; Marschner, 1995; Mueller et al., 2012), and many studies have been carried out to estimate the amounts of water and N inputs required for achieving high crop yield and quality, as function of crop type, variety, climate, and soil type. The optimization of water and N use is often studied separately, and possible interactions between water and N use in crop yield, water use efficiency (WUE) and N use efficiency (NUE) are often neglected. As a result, there is little quantitative information about the possible interactions between water and N use in crop yield, WUE and NUE.

The main objective of this thesis research was 'to increase the understanding of the interactions between water and N use in crop yield, WUE and NUE of main cropping systems'. Specific objectives were (i) to quantify the effects of water and N use and their interactions in crop yield, WUE and NUE, and (ii) to explore options for increasing crop yield, WUE and NUE simultaneously. Two contrasting crop production systems were chosen, i.e., annual cereal-based production systems and perennial orange production systems. Rain-fed wheat and maize production systems were chosen because of their importance in ensuring global food and feed supply. Figure 1 shows that wheat and maize yields have increased steadily during the last five decades, but differences between the means per continent are large. These differences are related to a range of factors, including climate and the management of water and N resources (Mueller et al., 2012; Rockstrom et al., 2010; Vitousek et al., 2009). Orange production systems were chosen because of their increasing importance in the global fruit market, and because of the high economic value of high-quality fruit, which allows making investments in drip irrigation/fertigation systems and in the optimization op water and N use. Orange yields have also increased steadily during the last five decades (Figure 1 in Chapter 5).

The main research questions of my thesis were:

- What are the effects of soil mulching on cereal yields, WUE and NUE?
- What are the effects of soil organic amendments and mineral fertilizers on cereal yields, WUE and NUE?
- What are the potentials of increasing yield, WUE and NUE in orange production?
- What are possible fertigation strategies for improving WUE and NUE in orange production?

Below, I discuss the main findings of the research and their implications for the optimization of water and N use in crop production. The main limitations of my study are also discussed.

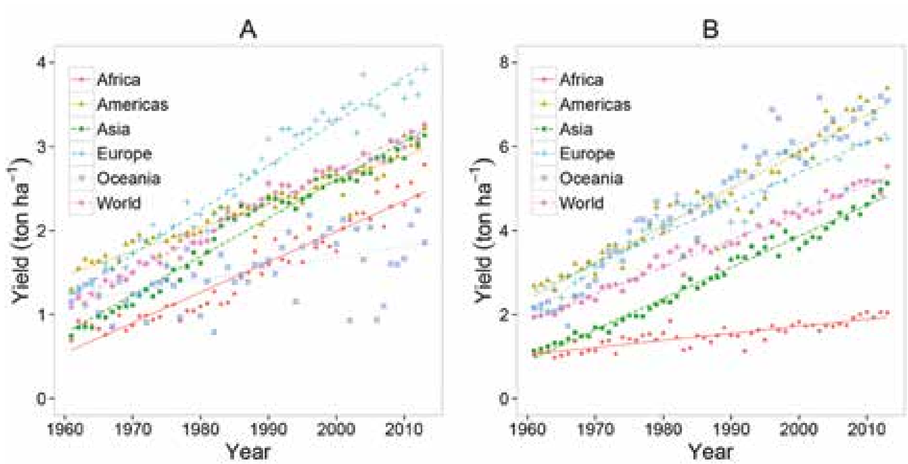


Figure 1. Changes in the yield of wheat (A) and maize (B) per continent and the world during the period 1961 to 2013 (data source: FAO, 2014). Lines are the regressions of the data points, using ordinary least squares method.

7.1. Main findings

Chapter 2 presents a meta-analysis of the effects of soil mulching on wheat and maize yields. Soil mulching is practiced by many farmers in the world, because soil mulching may reduce erosion, soil slaking and evaporation, suppress weed infestations, and modulate soil temperature. Straw mulching is one of the three pillars of soil conservation (Pittelkow et al., 2014). The use of plastic film covers is facilitated in China and India through governmental subsidies to increase crop yield. The analysis was based on 1310 yield observations from 74 studies conducted in 19 different countries. The results indicate that soil mulching significantly increased crop yields, WUE and NUE, by 20 to 60%, compared with the no-mulching treatment.

Effects of plastic covers were two times higher for maize than wheat. This may be related to the much wider plant spacing in maize compared to wheat. Also, maize is a C4 crop and more efficient in photosynthesis and water use than wheat as C3 crop (Long et al., 2006). Plastic film performed better at relatively low temperature than at relatively high temperature, while straw mulching showed the opposite trend. This is likely related to the fact that plastic film increases soil temperature while straw mulch tends to decrease soil temperature, which may slow root growth and reduce yield (Chakraboyty et al., 2008; Chen et al., 2007).

Soil mulches changed the relationships between water input level and crop yield, WUE and NUE, as well as the relationship between N input and crop yield, WUE and NUE (Figure 2 and 3). There were some significant differences in the slope of the calculated linear regression lines, suggesting interactions. This is most clearly shown for the relationship between water input and maize yield for the plastic cover treatment relative to the control treatment at relatively high N input (Figure 3A); high maize yields were obtained with plastic cover and with relatively high water and N inputs. The slopes were small at relatively low N input level; the effect of plastic cover increased maize yield by about 3 tons ha^{-1}, irrespective of water input level. These results indicate that the effects of plastic covers on yield are relatively robust, despite the large scatter in the data, which are in part related to the different environmental conditions of the studies.

In Chapter 3, I studied a long-term rainfed winter wheat mono-cropping system in Shanxi province in China, which is located at the Loess Plateau. The experimental site has a semi-arid climate with mean annual rainfall of around 500 mm. Monthly rainfall tends to be heavily concentrated in summer, and therefore is poorly synchronized with the growing season of winter wheat, which is the main staple food in this region. As a result, winter wheat heavily depends on the amount of soil water stored during the fallow season. The results indicated that a large proportion of rainwater initially stored in the soil was lost via evaporation. On average, about two-thirds of rainwater was lost by evaporation, i.e., 40% was evaporated during the growing season and 60% was evaporated during the fallow season. Only one-third of the available water was actually used by winter wheat for transpiration. Therefore, wheat yields, WUE and NUE were low and greatly differed between years. Wheat yield, WUE and NUE were positively related to water input level (Figure 4). The slight positive relationship between water input and WUE contrasts with the strong negative relationships between water input and WUE in Figure 2 and 3 based on the data of the meta-analysis study presented in Chapter 2.

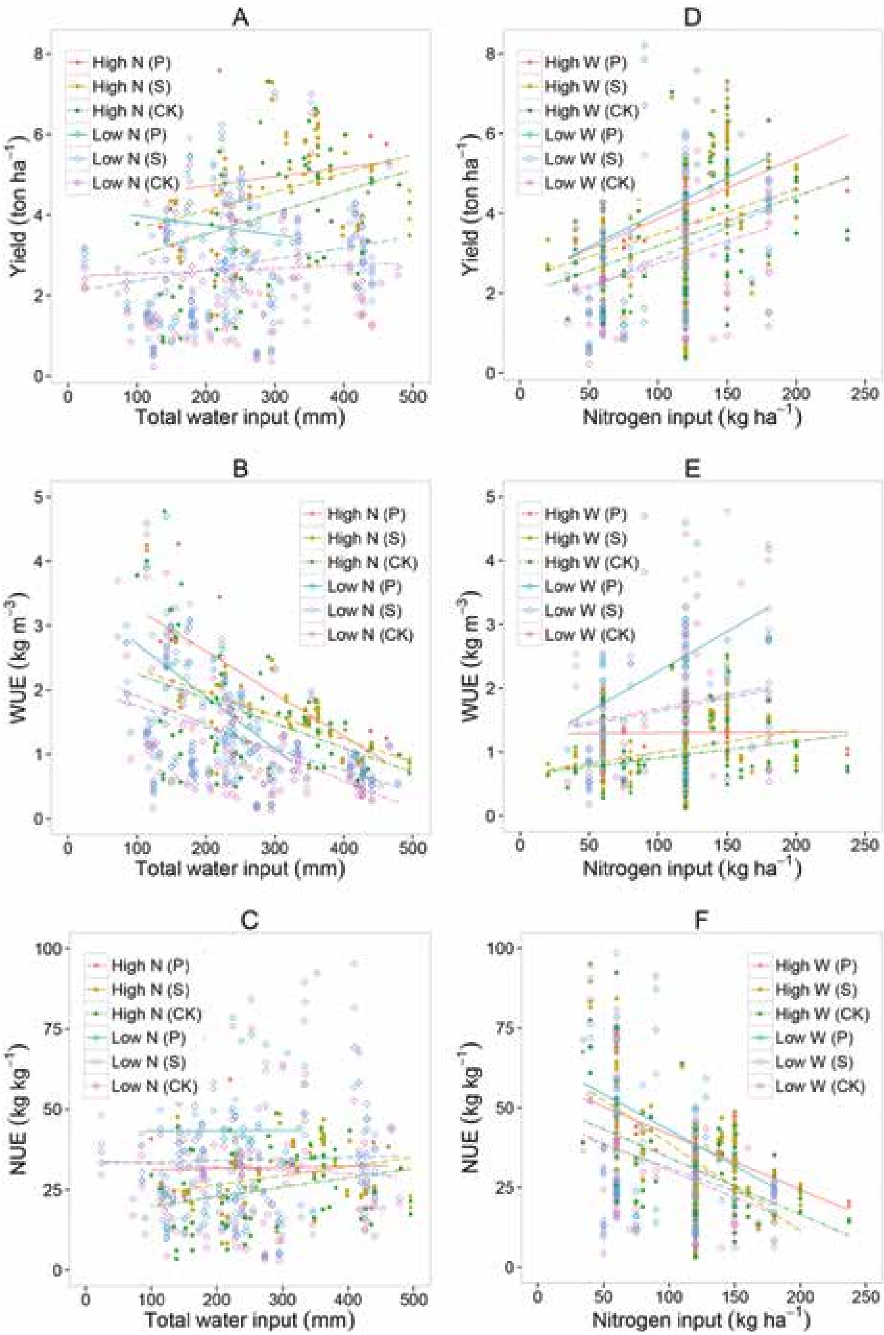


Figure 2. Relationships between water input and wheat yields, WUE and NUE (three panels on the left), and between N input and wheat yields, WUE and NUE (three panels on the right). Data were sub-grouped in high and low N (for A, B and C) and high and low water (for D, E and F) input levels, and in plastic cover (P), straw mulching (S) and no mulching (CK), respectively. Lines are the regressions of the data points, using ordinary least squares method. Data are derived from Chapter 2.

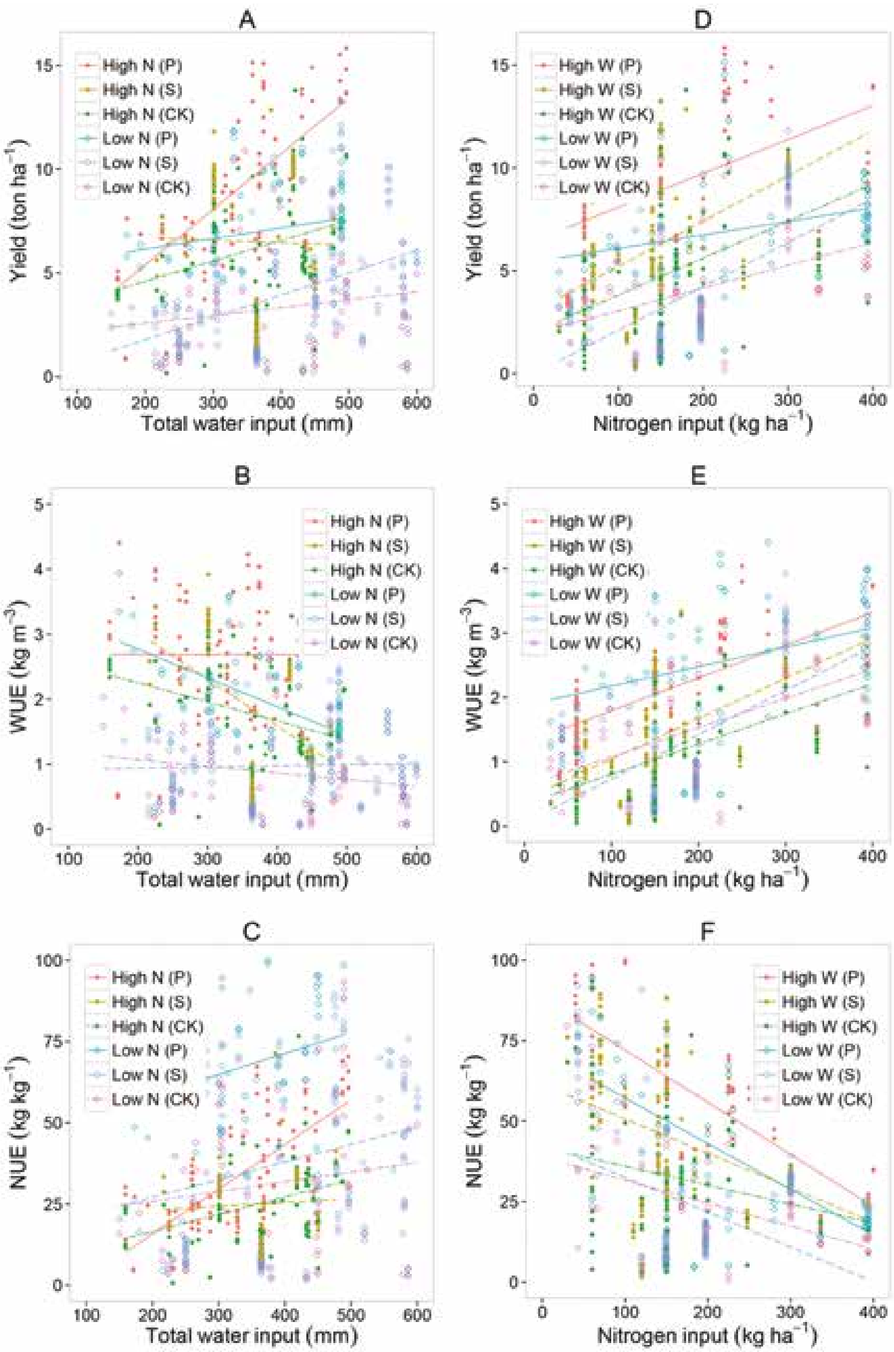
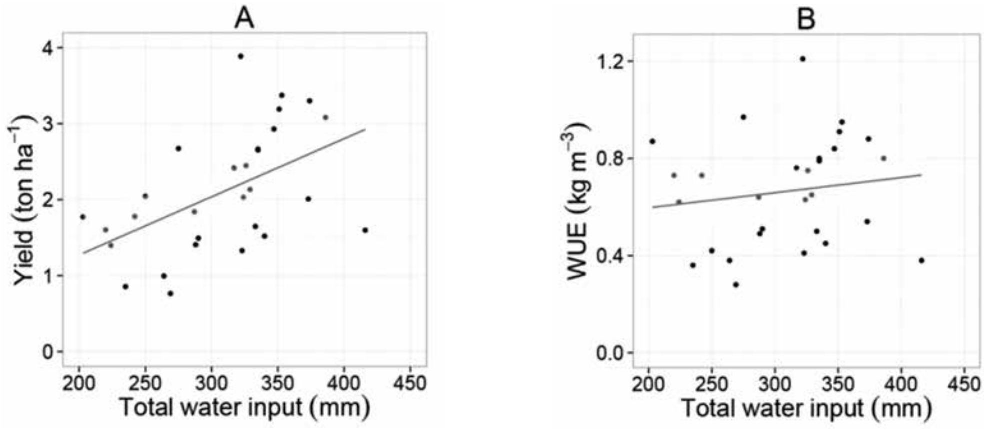


Figure 3. Relationships between water input and maize yields, WUE and NUE (three panels on the left), and between N input and maize yields, WUE and NUE (three panels on the right). Data were sub-grouped in high and low N (for A, B and C) and high and low water (for D, E and F) input levels, and in plastic cover (P), straw mulching (S) and no mulching (CK), respectively. Lines are the regressions of the data points, using ordinary least squares method. Data are derived from Chapter 2.



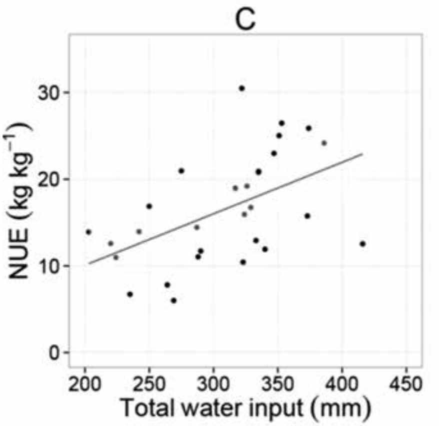


Figure 4. Relationships between water input (via rainfall) and wheat yields, WUE and NUE for the long-term monitoring study in Shanxi, China described in Chapter 3. The N input was 127.5 kg ha^{-1} in all 30 years. Lines are the regression of the data points, using ordinary least squares method. Data are derived from Chapter 3.

Evidently, the wheat yields were significantly limited by water availability and linearly related to ET. These findings were in line with several other studies conducted in the Loess Plateau (Huang et al., 2004; Kang et al., 2003b; Kang et al., 2002). Because of large water loss via soil evaporation, mean T/ET ratio was only about 60 % during the growing season, similar to that reported by Wang et al. (2012a) but about 10% lower than that reported by Liu et al. (2002) and Kang et al. (2003a). The higher T/ET ratio in the studies of Liu et al. (2002) and Kang et al. (2003a) was probably due to targeted irrigation. It is rather common that crop yield and WUE are higher in irrigated systems than in rainfed systems, especially in arid and semi-arid regions (Kang et al., 2002; Zhang and Oweis, 1999; Zhang et al., 2010).

To explore the effects of improved water management (via reducing E) on wheat yield, I calibrated and validated the FAO AquaCrop model (Steduto et al., 2012; Steduto et al., 2009). The long-term field experiment provided a good basis for model calibration and validation. Results of model experiments suggested that minimizing soil evaporation via straw mulch or plastic film covers could increase wheat yields by 15 to 25%, and

WUE by 30 to 90%, respectively. The estimations were largely in line with the results of the meta-analysis in Chapter 2, and also in line with some other review studies (Gan et al., 2013; Li et al., 2009). These results suggest that there are opportunities to increase wheat yield, WUE and NUE at the Loess Plateau by soil mulching.

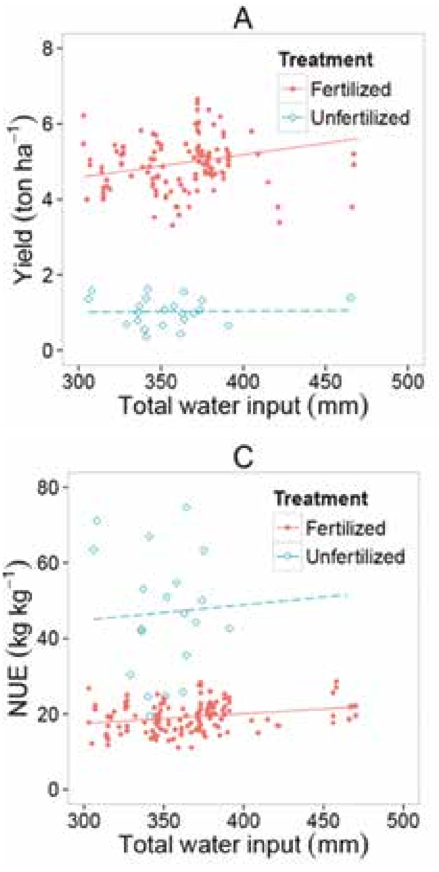
In Chapter 4, I studied a rain-fed winter wheat-soybean rotation system in Anhui province, at the southern fringe of the North China Plain. The North China Plain is responsible for ~50% of the total national wheat and maize production in China (Jeong et al., 2014; Liu et al., 2010). The experimental site has a monsoonal climate with a mean annual rainfall of 900 mm, which provides the possibility to grow two crops per year. Winter wheat-soybean and winter wheat-maize are common double crop production systems in this area. The productivity of these cropping systems is mainly related to the relatively poor soil physical and chemical conditions (a Vertisols with low soil organic matter content and poor drainage) and the variable rainfall. The long-term experiment was established in early 1980s with the aim to increase crop yields via improving chemical, physical and biological soil fertility through various combinations of fertilization and soil organic amendments (straw and animal manure).

Wheat and soybean yields were 5 and 2.5 times higher in the fertilized treatments than in the unfertilized control (CK), respectively. Among the fertilized treatments, NPK + manure was more effective in increasing yields than NPK alone or NPK + straw. The additional effect of manure is likely due to increased potassium (K) and/or micronutrients, and improved physical and biological soil fertility following by repeated applications of manure over time.

Manure applications greatly increased Olsen P values. In the treatment NPK fertilizer + manure, Olsen P values rapidly increased to around 75 mg kg^{-1} and then remained at this level during the course of the experiment, suggesting soil P saturation in the top soil and transport of P from the top soil to the subsoil. The optimal P Olsen level for cereals is normally in the range of 10 to 20 mg kg^{-1} (Bai et al., 2013). Olsen P remained within the recommended range of 10-20 mg kg^{-1} in the NPK fertilization treatments without animal manure, suggesting that the P inputs via NPK fertilizers and straw were adequate.

Long-term fertilization and addition of organic amendments significantly increased soil organic matter contents (SOC) over time (Hua et al., 2014), which may indirectly contribute to crop growth and development. Li et al. (2009) reported that long-term additions of animal manure increased soil moisture availability by 30 to 45 mm in a 2 meter deep soil profile. Contents of SOC increased significantly in the treatments with manure and straw. There were clear correlations between SOC content and crop yield, but the relationship between SOC and yield is highly nested to soil available N (soil N mineralization) and K.

Grain yields of the fertilized treatments were positively related to water input, but yields of the unfertilized treatments did not respond to water input (Figure 5). Grain yields of the fertilized treatments increased over time, and thereby WUE and NUE also increased over time. The steady increase in grain yields is likely the result of a combination of improved crop varieties, crop husbandry practices and soil fertility. Due to the steady increase in grain yields over time, yield became more water limited, suggesting that the need for soil mulching increased. Soil mulching with straw or plastic films are common measures to reduce evaporation and thereby to increase crop yields (and WUE and NUE) in Northwest China (Gan et al., 2013; Wang et al., 2012b), but has not been widely implemented in Anhui. Most of the straw is currently used as animal feed, burned or ploughed in the soil. In treatments of NPK fertilizers + straw, the straw was ploughed into the soil after harvest of the wheat. Model simulations indicated that straw mulching and plastic cover could increase mean wheat yield by 10-15%, and supplementary irrigation of 100 mm could increase mean wheat yields by 35%. Soybean yields did not respond to soil mulching and irrigation, because there was no water stress during the soybean growing seasons.



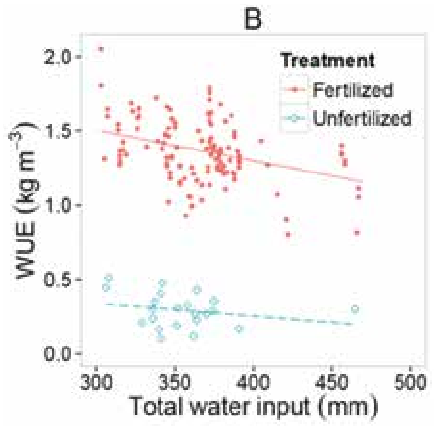


Figure 5. Relationships between water input and wheat yields, WUE and NUE for the long-term experimental field in Anhui, China, described in Chapter 4. The data points are distinguished as fertilized (solid dots) and unfertilized (open dots) treatments. Lines are the regressions of the data points, using ordinary least squares method. Data are derived from Chapter 4.

7

In chapter 5, I presented the results of a meta-analysis on water and N use efficiencies in orange production, using a dataset that consisted of 1009 yield observations collected from 55 studies and 11 countries. Most studies were factorial field experiments, comparing farmers' irrigation (≥100%ET), fertilization and/or fertigation practices with researchers' optimized practices. The dataset showed a large variation in orange yields, water and N input levels, WUE and NUE. Orange yields were positively related to both water and N inputs. WUE was negatively related to water input and NUE negatively to N input. Sub-optimal and over-optimal water and N management, with either a relative shortage or oversupply of water and N, respectively significantly reduced yield, WUE and NUE.

Figure 6 shows how orange yields, WUE and NUE were related to water and N inputs. Interactive effects between water input and high vs low N input in yield, WUE and NUE were relatively small; the slopes of the regression lines were nearly similar in the high N and low N input data-sets for the relationships between water input and yield, WUE and NUE. However, the slopes of the regression lines differed significantly in the high vs low water input data-sets for the relationships between N input and yield, WUE and NUE, i.e., N input increased WUE more at relatively low water input than at relatively high water input, and N input decreased NUE stronger at relatively high water input than at relatively low water input.

Phogat et al. (2013a) reported that, even under controlled water applications with fertigation system, plant water uptake was only 40% of applied water and drainage accounted for 49% of applied water. Large drainage was due to a combination of light soil texture and high rainfall during the experimental period. Accordingly, plant N recovery was only 42% and N leaching accounted for 50% of N supply. Effects of soil type and incidental rainfall events were not addressed in the meta-analysis, but likely played a role in the relationships between water and N inputs and yield, WUE and NUE.

Rainwater management has not received so much attention in orange studies as in cereal studies. In cereal production systems, rainwater harvesting technologies (e.g., building terraces, making furrow and ridges, and having it stored in the soil for later use) have been proven to be effective in reallocating water distribution during the growing season, thereby increasing yields, WUE and NUE (Li et al., 2008; Mavimbela and van Rensburg, 2012; Tian et al., 2003; Van Rensburg et al., 2012). Furthermore, soil mulching with straw and plastic covers can effectively reduce soil evaporation, re-direct soil water drainage and save water, and thereby increasing yield, WUE and NUE (Gan et al., 2013; Li et al., 2013b; Li et al., 2009). The scope for rainwater management and soil mulching in orange production should be explored further.

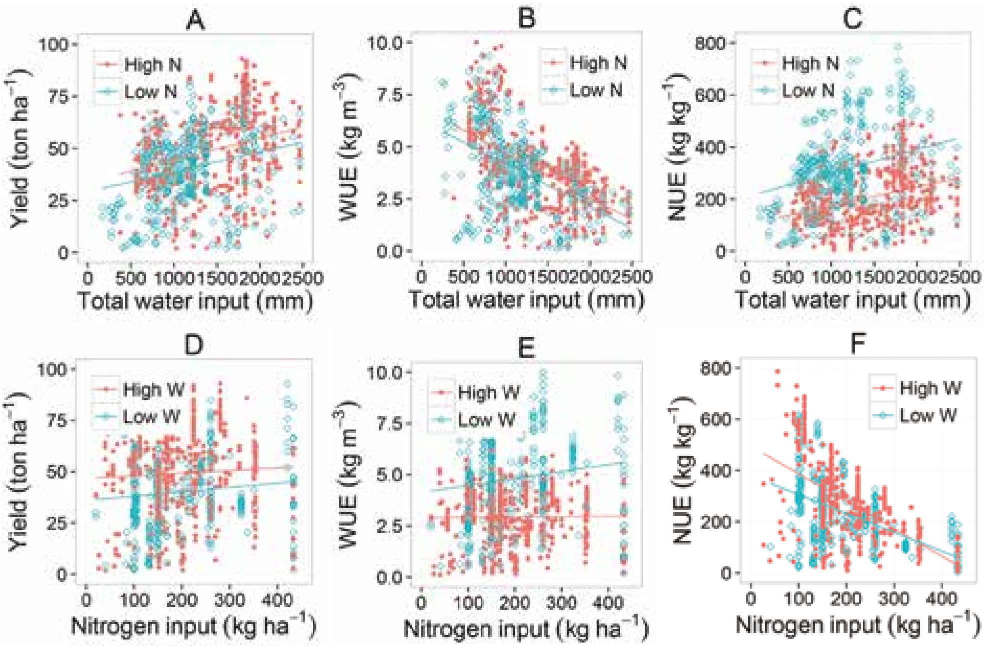


Figure 6. Relationships between water input and orange yields, WUE and NUE (three panels on the left), and between N input and maize yields, WUE and NUE (three panels on the right). Data were sub-grouped in high and low N (for A, B and C) and high and low water (for D, E and F) input levels, respectively. Lines are the regressions of the data points, using ordinary least squares method. Data are derived from Chapter 5.

In Chapter 6, I explored the simultaneous optimization of water and N use in orange production system, using coupled soil-crop models. My special interest was in the interactive effects of water and N inputs in yield, WUE and NUE, also because the interactive effects observed in the meta-analyses of Chapter 2 and 5 were not easily understood. In total 47 fertigation strategies were investigated, including 27 main scenarios (3x3x3 factorial design): 3 irrigation levels (80, 100 and 120% ET), 3 N supply levels (100, 200 and 300 kg N ha^{-1}) and 3 split applications (fractionations). In addition, 20 scenarios were tested to examine the effects of different soil type and rainfall scenarios, i.e., long-term average annual rainfall, and relatively dry and wet years. The results of simulations showed that orange yields were strongly influenced by N input, but not significantly affected by irrigation levels. Low N input of 100 kg ha^{-1} led to minimal low N losses via leaching and denitrification (12% of N input) but also resulted in lowest yield (32 ton ha^{-1}; equivalent to a yield reduction of 27%). High N input (300 kg ha^{-1}) produced the highest yield (44 ton ha^{-1}) but led to largest N losses (41% of N input). The optimal N input was 200 kg ha^{-1}, which equaled the set N demand. N fractionation strategies also had strong effects on yield and N losses, even within the same N input levels. Applying a relatively large fraction during the early half of the growing season gave a higher yield and lower N losses, than applying a steady portion throughout the growing season.

Figure 7 shows that orange yields and NUE were strongly related to N input but not to water input. Interactive effects between watwer input and N input in yield, WUE and NUE seemed relatively small; the slopes of the regression lines were similar in the high, optimal and low N input data-sets for the relationships between water input and yield, WUE and NUE (Figure 7A, B and C).

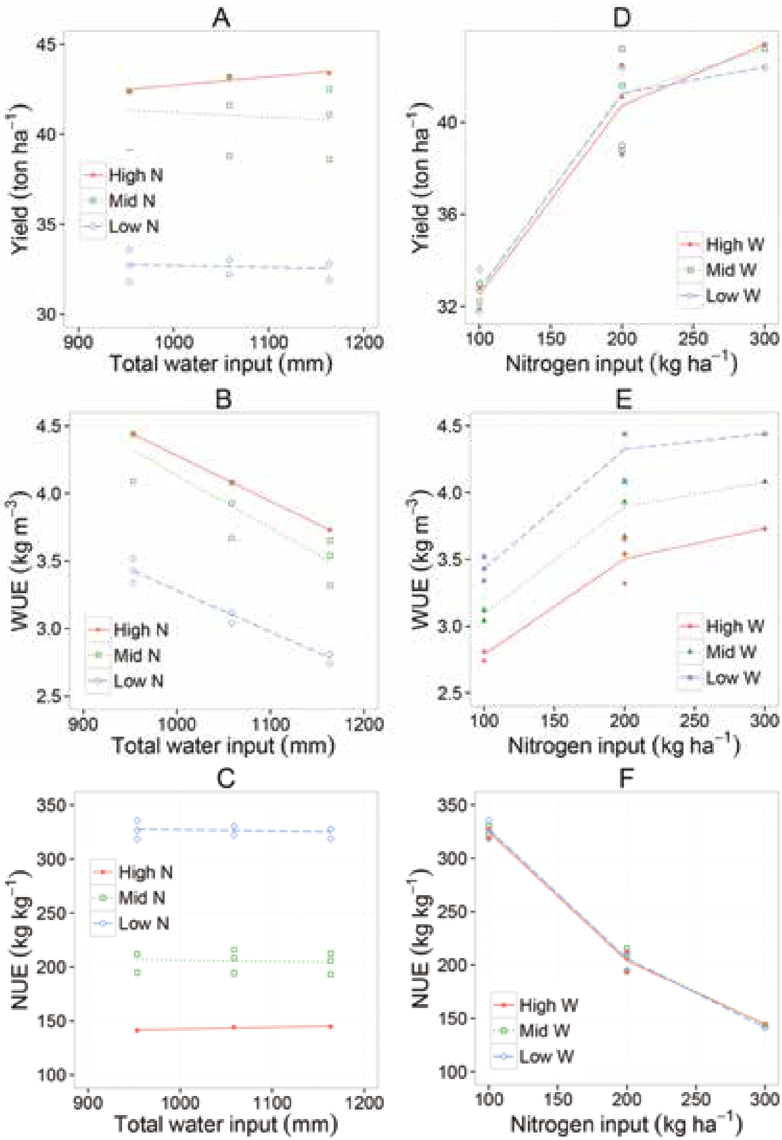


Figure 7. Relationships between water input and orange yields, WUE and NUE (three panels on the left), and between N input and maize yields, WUE and NUE (three panels on the right). Data were sub-grouped in high, middle and low N (for panel A, B and C) and water (for panel D, E and F) input levels, respectively. Lines are the regressions of the data points, using ordinary least squares method. For panel D, E and F, the data points were not linear therefore plotted with two slopes. Data are derived from Chapter 6.

7

The interactive effects were more clearly shown by distinguishing input levels of both water and N (Figure 7D, E and F); i.e., the slopes of the regression lines differed between different N inputs (stronger) and also between different water inputs. Evidently, the results presented in Figure 7 is the result of model calculations, including all the assumptions and simplifications made in the models, but based on general bio-physical theories.

7.2. Interactions between water and N inputs in yield, WUE and NUE

Interactions between water and N use in yield, WUE and NUE can be studied at different spatial scales (Spiertz, 2012, 2013). Firstly, at the plant level, where genetic traits (G) and environmental factors (E) determine crop yield, WUE, NUE and the ability to grow against stressful situations. Secondly, at the field level, where crop yield, WUE and NUE are determined by G and environmental factors (climate, soil, hydrology, E) and management (M). Thirdly, at the farm and regional levels, where in addition to G, E and M, policy (P) may have impact on water and N use and hence on WUE and NUE: hence, G x E x M x P.

At the plant level, the relationships between photosynthesis and availability of water and N are well documented. There is a positive relationship between photosynthesis and the leaf N content, in line with the functions of N and chlorophyll in photosynthesis, which is the basis for crop modelling. Similar relationship exist for water (Field et al., 1983). Further, there are diminishing returns, i.e., when the supply of water and N increase, the rate of photosynthesis tend to saturate and the effects of increased water and N input on WUE and NUE decrease, respectively. It has also been documented that increasing water supply may increase NUE, and increasing N may increase WUE, depending on the specific environmental conditions (Gong et al., 2011).

Interactions between water and N inputs in yield, WUE and NUE are therefore related to the interplay of G x E x M. For example, excessive water supply may lead to high losses of N and therefore shortages of N, but anaerobic condition may also induce the closure of stomata. This, in the end, may lead to a low N uptake and low NUE (Sojka and Stolzy, 1980). When N is limiting, photosynthesis will decrease which then leads to a low WUE. Excessive N may increase the susceptibility of plants to stress caused by frost, drought and pests (Field et al., 1983; Marschner, 1995). The relationships between photosynthesis and availability of water and N also differ between plant species and cultivars (Hetherington and Woodward, 2003; Lu et al., 1998).

At the field level, irrigation and fertilization directly influence yield, WUE and NUE, but other field management factors such as tillage, planting density, seed varieties, rotations and intercropping, weed and pest control also affect WUE and NUE (Hu et al., 2010; Li et al., 2007; Wang et al., 2011; Zhou et al., 2009). I studied interactions at the field level, using knowledge also from the plant level.

There were several similarities in the relationships and interactions between water and N input in crop yields, WUE and NUE, despite the differences in crop varieties and environmental conditions in the datasets analysed in the meta-analyses and long-term field experiments. Firstly, yield responded positively to water and N inputs, depending on water input levels, and there were often significant positive interactions in yields, especially at sub-optimal (short supply of) water and N input levels (Figures 2 and 3). Such sub-optimal water and N supplies are common for rainfed systems in arid and semi-arid regions with degraded soil fertility (Mueller et al., 2012; Rockstrom and Falkenmark, 2015; Vitousek et al., 2009). Positive interactions suggest that increasing both water and N availability increases yield more than increasing water input or N input alone. When water supply was near optimal or over-optimal, there may be negative interactions in yields, i.e., adding more water decreases yields because of increased N losses. Over-optimal water supply can be due to either excessive rainfall or over-supply of irrigation (Alva et al., 2006b; Ju et al., 2009). Secondly, water use efficiency (WUE) was negatively related to water input (Figures 2, 3, 5, 6, 7), with the exception of the long-term wheat experiment (Figure 4). Further, increases in N input increased WUE, because N increase plant root water uptake and plant transpiration (T) thereby yields and thereby reduced evaporation losses. Results from both the cereal and orange studies show consistently that the effects of N input were stronger at low water input than at high water input (Figures 2, 3, 6 and 7). Similarly, NUE was negatively related to N input and increases in water input tended to increase NUE more at relatively low N input. These results clearly indicate that the optimization of water and N inputs have to be done simultaneously.

7.3. Options for improving yield, WUE and NUE simultaneously

Soil mulching can effectively reduce water losses via soil evaporation and thereby increase crop yields, WUE and NUE by up to 60% in rainfed semi-arid areas. The effect of soil mulching on NUE has not been reported often, simply because most soil mulching studies focused on water use, yield and WUE only. Improved crop varieties, improved disease management and improved crop husbandry practices may also increase crop yield, WUE and NUE simultaneously (see for example Chapter 4), but was not the specific focus on my study. Land preparations such as building furrows, ridges and terraces can also prevent surface run-off and drainage (Gan et al., 2013). Reduced tillage and increasing soil organic matter content and quality may also contribute to conservation of soil water because of increased soil infiltration (Wang et al., 2011; Wang et al., 2012b). Manure application and straw return significantly increased soil organic matters and thereby soil fertility (Hua et al., 2014; Chapter 4). Legume and non-legume rotation can also bring benefits for increasing crop yields and improving soil quality (Giller et al., 2009). However, such rotations may not necessarily save water (Gao et al., 2014), and the increased N availability may not necessarily be utilized for the production of the main crops if water is relatively scarce.

Drip irrigation and fertigation are in theory highly effective water and N saving technologies in irrigated crop production. In practice though, there is a tendency of applying too much (chapter 5). The supply of water and N via fertigation is often derived from long-term mean rainfall data and average N uptake. Results of the meta-analysis indicated that orange yields, WUE and NUE may be increased by 20, 30 and 40%, respectively (Chapter 5), through optimization of water and N input via fertigation. Clearly, there is need for improvements in the automation and precision technologies in the fertigation systems, i.e., smart systems that can take into account changes in weather, soil and plant conditions, and automatically regulate and ensure optimal water and N supply to the plant. Such advanced technologies are available, but rather costly in terms of installation and maintenance, which limits their adoptions and implementations. Likely, smart fertigation systems will become more popularly when the technologies become much cheaper and more easy to use.

7.4. Strengths and weakness of my study

In this thesis, I used a combination of literature review, meta-analyses, long-term field experiments and soil-crop modeling to increase the understanding of possible interactions between water and N use in yield, WUE and NUE, and to explore options for increasing yield WUE and NUE in two contrasting crop production systems (i.e., annual cereals and perennial orange trees). These different approaches have contributed to a better understanding of the interactions of water and N use in yield, WUE and NUE in practice, but the mechanistic cause-effect relationships remained often unclear, simply because of lack of detailed information about G x E x M in the analyzed studies and long-term field experiments.

I studied interactions at the field level, using knowledge also from the plant level. Information about the management (M), environmental conditions (E), and the genetic traits (G) obtained from the literature studies and long-term field experiments was relatively poor, also because these studies were often set-up to optimize the input of either water or N.

7.4.1. Data (meta) analysis and data availability

Meta-analysis has been used widely in both natural and social sciences in the last few decades. However, use of meta-analysis in agricultural and environmental sciences, especially with the focus on crop yield and water and nutrient use efficiencies, are still at a relatively infant stage. There is still a lack of standardization of methods and protocols in conducting meta-analysis. For example, the metric (effect size) used in meta-analysis can be an absolute difference, (odd) ratios, or log response ratio (Hedges et al., 1999; Hungate et al., 2009; Rusinamhodzi et al., 2011). There are also different weighting methods for the calculated effect sizes (van Groenigen et al., 2014). The quality of meta-analysis also depend on the dataset and statistical tools; analyzing complex dataset often requires both in-depth understanding of the data structure and the complex statistical tools, such as mixed-effects models (Pinheiro et al., 2013). There is also a need for standardization of data documentation, to allow more efficient and accurate meta-analysis in the future, with bigger and complex data.

In the meta-analyses reported in chapters 2 and 5, it was implicitly assumed that the studies provide a realistic view of the studies carried out in practice, and that these studies reflect the range of conditions that actually occur in practice. This may not be the case when for example studies with small effects of negative effects are not published. It remains unclear to which extent this possible mechanism has biased my results presented in chapters 2 and 5. Publication policies of scientific journals indirectly affect the outcome of meta-analyses studies.

The compilations of datasets for meta-analysis are generally conducted manually, which is time-consuming, inefficient and it may introduce errors. There is need for developing advanced technologies in data collecting, storage and analysis in the field of agricultural and environmental sciences, to be able to deal with the emerging era of big data. The advanced (big data) technologies are mostly discussed and used in the fields of ICT and business (Hashem et al., 2015). Those technologies are in theory also applicable in the field of agricultural and environmental sciences.

Currently, there are online accessible databases for conducting large scale and global analyses (e.g., the FAO database). This does not hold for all databases; for example, several databases in China are not easy accessible, while the accuracy of some databases is also questionable (Yu and Abler, 2014). This relates also to data related to water and N use. The initial idea of my thesis research was to study the water and N use and their interactions at different spatial scales, and to include also the farm and regional levels where decisions can be made to better allocate water between agriculture, industry and households (at the system level), and where the irrigation supply may be limited. This turned out to be too complicated, mainly because of lack of data. Therefore, this research was focused on crop production systems at the field level.

7.4.2. Long-term versus short term experiments

Long-term field experiments are useful because of the temporal dimension; they provide insight in the annual variations in water and N demands by the crop and water supply by rainfall (Zhang et al., 2012; Zhang et al., 2006). Thereby, they provide the opportunity to better understand and unravel the effects of fluctuations in uncontrollable climate factors, increase the robustness of the analysis and avoid misinterpretations. Effects of some field practises, e.g., the effects of soil organic amendments with crop residue and/or animal manure in soil fertility and crop yields, can only be identified accurately in long-term experiments (Hua et al., 2014). Thereby, they provide the necessary data for calibration and validation of simulation models. The results of the two long-term field experiments discussed in chapters 3 and 4 clearly show the value of long-term monitoring. Results of a short-term experiment in Spain, planned to validate the model simulations described in chapter 6 came to late to be included in this thesis. However, the nature of the long-term experiments determines that they are not as flexible as short-term experiments. The objectives and the designs of the long-term experiments were established decades ago. Testing new hypotheses derived from the results of these long-term field experiments, therefore often requires conducting new field experiments, or a combination of literature research and simulation modelling.

7.4.3. Soil-crop modelling

Over the last five decades, there have been significant developments and improvements in soil-crop modelling (Sinclair and Seligman, 1996; Steduto et al., 2012). Soil-crop modelling has been proven useful, provided that the models are well calibrated and validated (Heinen et al., 2012; Hu et al., 2008b; Hu et al., 2010). Soil-crop modelling can be used as a tool for understanding the interactive effects between water and N use in yield, WUE and NUE, and for exploring new and improved management strategies.

In this thesis, I used the AquaCrop model because it is a water-driven crop model, which fits the needs and meets the constraints of my study. The model is particularly suited to address conditions where water is a key limiting factor in homogeneously cropped fields. One of the important aspects is that AquaCrop uses normalized water productivities for crops so that the application of AquaCrop is less sensitive to the variations in locations (Steduto et al., 2012; Steduto et al., 2009). Compared to other crop models, AquaCrop requires a relatively small number of parameters and input variables, and has a good balance of accuracy, simplicity and robustness. AquaCrop can separately calculate evaporation (E) from soil and transpiration (T) by plants, and can simulate the crop yield as a function of water use under pre-defined soil fertility levels.

However, AquaCrop simulates soil water dynamics in a simple one-dimensional manner and is therefore unable to simulate drip irrigated crop production (in three dimensions) appropriately. In drip irrigated crop production systems, such as in orange orchards, water moves into the soil in three dimensions from the point of application, leaving significant areas of the soil dry in between the drippers. Drip irrigation thereby reduces 'unproductive' water loss through evaporation. Such situations require models that are able to simulate water and solute transport in soil in three dimensions, such as in FUSSIM (Heinen, 2001). However, FUSSIM is unable to simulate crop growth and development. Therefore, coupling AquaCrop to FUSSIM results in a tool that allows exploring fertigation strategies of for example orange orchards in a simple way.

7.5. Conclusions

This thesis provides an analysis and synthesis of the effects of water and N use, and their interactions, in yield, WUE and NUE for two important and contrasting crop production systems (i.e., annual cereals and perennial orange orchards).

In arid and semi-arid regions, such as the Loess Plateau, I found that the water losses via soil evaporation was large, amounting to 60 to 70% of the total rainfall. Soil mulching is an effective strategy to reduce soil evaporation, and thereby to increase crop yields by up to 60%. Effects of soil mulching greatly depend on the local environmental conditions, indicating that site-specific recommendations have to be developed to guide farmers about the optimal soil mulching strategy.

When the productivity of rainfed wheat-soybean rotations is limited by soil fertility rather than by rainfall, yields, WUE and NUE are greatly influenced by fertilization and soil organic amendments. Combinations of mineral NPK fertilizers and animal manures increased yields more than mineral NPK fertilizer alone.

In advanced fertigated systems, a main challenge is to optimize water and N use for optimal yield while minimizing N losses. Fertigation provides opportunities to simultaneously optimize water and N use in orange production systems. Optimization of water and N supply is however complicated in practice due to erratic and uncontrollable rainfall, which may lead to large incidental losses. Improving water and N input can simultaneously increase orange yield, WUE and NUE (by 20, 30 and 40% respectively). The fractionation of the N supply over the growing season significantly affected crop yields, WUE, NUE, and N losses, at near optimal water and N input levels.

Based on the meta-analysis and long-term field experiments, I showed that crop yield (and WUE and NUE) in dryland agriculture can be increased by up to 60%, with currently available knowledge and soil mulching techniques. In many regions in the world, there is still a large gap between observed yield and attainable yield by best management. Given large potentials in low-performing agricultural systems, investments in knowledge and education, infrastructures and subsidies must be prioritized here.

References

Abedinpour, M., Sarangi, A., Rajput, T.B.S., Singh, M., Pathak, H., Ahmad, T., 2012. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. Agricultural Water Management 110, 55-66.

Abrisqueta, J.M., Mounzer, O., Álvarez, S., Conejero, W., García-Orellana, Y., Tapia, L.M., Vera, J., Abrisqueta, I., Ruiz-Sánchez, M.C., 2008. Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation. Agricultural Water Management 95, 959-967.

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat Geosci 5, 853-861.

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050. ESA Working Paper No. 12-03. Agricultural Development Economics Division, FAO.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998a. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper no.56, 300 pp.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998b. Crop evapotranspiration: guide-lines for computing crop water requirements. In: Irrigation and Drainage. PaperNo. 56. FAO, Rome.

Alva, A.K., Mattos Jr, D., Quaggio, J.A., 2008. Advances in nitrogen fertigation of citrus. J. Crop Improv. 22, 121-146.

Alva, A.K., Paramasivam, S., Fares, A., Obreza, T.A., Schumann, A.W., 2006a. Nitrogen best management practice for citrus trees. II. Nitrogen fate, transport, and components of N budget. Scientia Horticulturae 109, 223-233.

Alva, A.K., Paramasivam, S., Graham, W.D., Wheaton, T.A., 2003. Best nitrogen and irrigation management practices for citrus production in sandy soils. Water Air and Soil Pollution 143, 139-154.

Alva, A.K., Paramasivam, S., Obreza, T.A., Schumann, A.W., 2006b. Nitrogen best management practice for citrus trees - I. Fruit yield, quality, and leaf nutritional status. Scientia Horticulturae 107, 233-244.

Andarzian, B., Bannayan, M., Steduto, P., Mazraeh, H., Barati, M.E., Barati, M.A., Rahnama, A., 2011. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. Agricultural Water Management 100, 1-8.

Araya, A., Habtu, S., Hadgu, K.M., Kebede, A., Dejene, T., 2010a. Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (Hordeum vulgare), Agricultural Water Management, pp. 1838-1846.

Araya, A., Keesstra, S.D., Stroosnijder, L., 2010b. Simulating yield response to water of Teff (Eragrostis tef) with FAO's AquaCrop model. Field Crops Research 116, 196-204.

Bai, Z.H., Li, H.G., Yang, X.Y., Zhou, B.K., Shi, X.J., Wang, B.R., Li, D.C., Shen, J.B., Chen, Q., Qin, W., Oenema, O., Zhang, F.S., 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant and Soil 372, 27-37.

Bai, Z.H., Ma, L., Qin, W., Chen, Q., Oenema, O., Zhang, F.S., 2014. Changes in Pig Production in China and Their Effects on Nitrogen and Phosphorus Use and Losses. Environmental Science & Technology 48, 12742-12749.

Ballester, C., Castel, J., Intrigliolo, D.S., Castel, J.R., 2011. Response of Clementina de Nules citrus trees to summer deficit irrigation. Yield components and fruit composition. Agricultural Water Management 98, 1027-1032.

Ballester, C., Castel, J., Intrigliolo, D.S., Castel, J.R., 2013. Response of Navel Lane Late citrus trees to regulated deficit irrigation: yield components and fruit composition. Irrigation Science 31, 333-341.

Bar-Yosef, B., 1999. Advances in fertigation. Advances in Agronomy, Vol 65 65, 1-77.

Bates, D., Maechler, M., Bolker, B.M., Walker, S., 2014. Lme4: Linear mixed-effects models using Eigen and S4. J Stat Softw.

Belder, P., Bouman, B.A.M., Cabangon, R., Lu, G., Quilang, E.J.P., Li, Y.H., Spiertz, J.H.J., Tuong, T.P., 2004. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. Agricultural Water Management 65, 193-210.

Bernacchi, C.J., VanLoocke, A., 2015. Terrestrial Ecosystems in a Changing Environment: A Dominant Role for Water. Annu Rev Plant Biol.

Black, C.A., 1965. Methods of soil analysis. Part 2. Chemical and microbiological properties. Madison, Wisc: ASA.

Bouman, B., 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. Agricultural Systems 93, 43-60.

Bu, L.D., Liu, J.L., Zhu, L., Luo, S.S., Chen, X.P., Li, S.Q., Hill, R.L., Zhao, Y., 2013. The effects of mulching on maize growth, yield and water use in a semi-arid region. Agricultural Water Management 123, 71-78.

Carter, M.R., 2002. Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. Agronomy Journal 94, 38-47.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., Singh, U., 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Research 56, 7-39.

Castellanos, M.T., Tarquis, A.M., Ribas, F., Cabello, M.J., Arce, A., Cartagena, M.C., 2013. Nitrogen fertigation: An integrated agronomic and environmental study. Agricultural Water Management 120, 46-55.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2004. Intensification of agriculture in the south-eastern Pampas - I. Capture and efficiency in the use of water and radiation in double-cropped wheat-soybean. Field Crops Research 87, 117-129.

Celano, G., Dumontet, S., Xiloyannis, C., Nuzzo, V., Dichio, B., Arcieri, M., 1998. Green manure plant biomass evaluation and total mineral nitrogen in the soil of a peach orchard system. . Acta Hort. 465: 579-586.

Cerda, A., Jurgensen, M.F., 2008. The influence of ants on soil and water losses from an orange orchard in eastern Spain. Journal of Applied Entomology 132, 306-314.

Chakraborty, D., Garg, R.N., Tomar, R.K., Singh, R., Sharma, S.K., Singh, R.K., Trivedi, S.M., Mittal, R.B., Sharma, P.K., Kamble, K.H., 2010. Synthetic and organic mulching and nitrogen effect on winter wheat (Triticum aestivum L.) in a semi-arid environment. Agricultural Water Management 97, 738-748.

Chakraboyty, D., Nagarajan, S., Aggarwal, P., Gupta, V.K., Tomar, R.K., Garg, R.N., Sahoo, R.N., Sarkar, A., Chopra, U.K., Sarma, K.S.S., Kalra, N., 2008. Effect of mulching on soil and plant water status, and the growth and yield of wheat (Triticum aestivum L.) in a semi-arid environment. Agricultural Water Management 95, 1323-1334.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. In: Value of Water: Research Report Series no. 16. UNESCO-IHE, Delft, the Netherlands.

Chaves, M.M., Pereira, J.S., Maroco, J., Rodrigues, M.L., Ricardo, C.P.P., Osorio, M.L., Carvalho, I., Faria, T., Pinheiro, C., 2002. How plants cope with water stress in the field. Photosynthesis and growth. Annals of Botany 89, 907-916.

Chen, S.Y., Zhang, X.Y., Pei, D., Sun, H.Y., Chen, S.L., 2007. Effects of straw mulching on soil temperature, evaporation and yield of winter wheat: field experiments on the North China Plain. Annals of Applied Biology 150, 261-268.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F., 2014. Producing more grain with lower environmental costs. Nature 514, 486-489.

Consoli, S., Stagno, F., Roccuzzo, G., Cirelli, G.L., Intrigliolo, F., 2014. Sustainable management of limited water resources in a young orange orchard. Agricultural Water Management 132, 60-68.

Corbeels, M., Hofman, G., Van Cleemput, O., 1998. Analysis of water use by wheat grown on a cracking clay soil in a semi-arid Mediterranean environment: weather and nitrogen effects. Agricultural Water Management 38, 147-167.

Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J., Thorburn, P.J., 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. Irrigation Science 22, 143-156.

Coulibaly, Y.N., Mulia, R., Sanou, J., Zombre, G., Bayala, J., Kalinganire, A., van Noordwijk, M., 2014. Crop production under different rainfall and management conditions in agroforestry parkland systems in Burkina Faso: observations and simulation with WaNuLCAS model. Agroforestry Systems 88, 13-28.

Daniels, M.B., Scott, H.D., 1991. Water-Use Efficiency of Double-Cropped Wheat and Soybean. Agronomy Journal 83, 564-570.

Darilek, J.L., Huang, B.A., Wang, Z.G., Qi, Y.B., Zhao, Y.C., Sun, W.X., Gu, Z.Q., Shi, X.Z., 2009. Changes in soil fertility parameters and the environmental effects in a rapidly developing region of China. Agriculture Ecosystems & Environment 129, 286-292.

de Willigen, P., van Noordwijk, M., 1987. Roots, plant production, and nutrient use efficiency. PhD Thesis, Wageningen Agricultural University, The Netherlands, 270 p. Available at: http://edepot.wur.nl/202228.

de Willigen, P., van Noordwijk, M., 1994. Mass-Flow and Diffusion of Nutrients to a Root with Constant or Zero-Sink Uptake .2. Zero-Sink Uptake. Soil Science 157, 171-175.

de Wit, C.T., 1958. Transpiration and crop yields. Verslag Landbouwkundig Onderzoek, Wageningen, Netherlands: Wageningen University.

de Wit, C.T., Vankeulen, H., 1987. Modeling Production of Field Crops and Its Requirements. Geoderma 40, 253-265.

Deng, X.P., Shan, L., Zhang, H.P., Turner, N.C., 2006. Improving agricultural water use efficiency in and and semiarid areas of China. Agricultural Water Management 80, 23-40.

Dobermann, A., 2007. Nutrient use efficiency – measurement and management. In IFA, Fertilizer Best Management Practices, Brussels, Belgium.7–9 Mar. 2007. Int. Fertilizer Industry Assoc., Paris., 1-28.

Dobermann, A., Cassman, K.G., 2005. Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. Science in China Series C-Life Sciences 48, 745-758.

Dobermann, A., Cassman, K.G., Mamaril, C.P., Sheehy, J.E., 1998. Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. Field Crops Research 56, 113-138.

Dominguez, A., Tarjuelo, J.M., de Juan, I.A., Lopez-Mata, E., Breidy, J., Karam, F., 2011. Deficit irrigation under water stress and salinity conditions: The MOPECO-Salt Model. Agricultural Water Management 98, 1451-1461.

Downton, W.J.S., Loveys, B.R., Grant, W.J.R., 1988a. Non-Uniform Stomatal Closure Induced by Water-Stress Causes Putative Non-Stomatal Inhibition of Photosynthesis. New Phytologist 110, 503-509.

Downton, W.J.S., Loveys, B.R., Grant, W.J.R., 1988b. Stomatal Closure Fully Accounts for the Inhibition of Photosynthesis by Abscisic-Acid. New Phytologist 108, 263-266.

Evenson, R.E., Gollin, D., 2003. Assessing the impact of the Green Revolution, 1960 to 2000. Science 300, 758-762.

Fagerstrom, M.H.H., Nilsson, S.I., van Noordwijk, M., Phien, T., Olsson, M., Hansson, A., Svensson, C., 2002. Does Tephrosia candida as fallow species, hedgerow or mulch improve nutrient cycling and prevent nutrient losses by erosion on slopes in northern Viet Nam? Agriculture Ecosystems & Environment 90, 291-304.

FAO, 2009. How to Feed the World in 2050 - High-Level Expert Forum http://www.fao.org/wsfs/forum2050/wsfs-forum/en/.

FAO, 2012. FAO Agriculture and Trade Policy Background Note http://www.fao.org/fileadmin/templates/est/meetings/wto_comm/Trade_policy_brief_China_final.pdf.

FAO, 2014a. AQUASTAT, FAO. http://www.fao.org/nr/water/aquastat/water_use/index.stm.

FAO, 2014b. FAO database. Food and Agriculture Organization, Rome. http://faostat.fao.org/.

FAO, 2015a. Crop Water Information: Wheat http://www.fao.org/nr/water/cropinfo_wheat.html.

FAO, 2015b. FAO Cereal Supply and Demand Brief http://www.fao.org/worldfoodsituation/csdb/en/

Farahani, H.J., Izzi, G., Oweis, T.Y., 2009. Parameterization and Evaluation of the AquaCrop Model for Full and Deficit Irrigated Cotton. Agronomy Journal 101, 469-476.

Fernández, J.E., Moreno, F., 1999. Water use by the olive tree. Journal of Crop Production 2: 101-162. Also appeared in M.B. Kirkham (ed.), Water Use in Crop Production, pp. 101-162. Food Products Press, an imprint of The Haworth Press, Inc.

Field, C., Merino, J., Mooney, H.A., 1983. Compromises between Water-Use Efficiency and Nitrogen-Use Efficiency in 5 Species of California Evergreens. Oecologia 60, 384-389.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337-342.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B., Galloway, J.N., Vitousek, P., Leach, A., Bouwman, A.F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., Voss, M., 2013. The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society B-Biological Sciences 368.

Gan, Y.T., Siddique, K.H.M., Turner, N.C., Li, X.G., Niu, J.Y., Yang, C., Liu, L.P., Chai, Q., 2013. Ridge-Furrow Mulching Systems-An Innovative Technique for Boosting Crop Productivity in Semiarid Rain-Fed Environments. Advances in Agronomy, Vol 118 118, 429-476.

Gao, B., Ju, X.T., Su, F., Meng, Q.F., Oenema, O., Christie, P., Chen, X.P., Zhang, F.S., 2014. Nitrous oxide and methane emissions from optimized and alternative cereal cropping systems on the North China Plain: A two-year field study. Science of the Total Environment 472, 112-124.

Gao, Y.J., Li, Y., Zhang, J.C., Liu, W.G., Dang, Z.P., Cao, W.X., Qiang, Q., 2009. Effects of mulch, N fertilizer, and plant density on wheat yield, wheat nitrogen uptake, and residual soil nitrate in a dryland area of China. Nutrient Cycling in Agroecosystems 85, 109-121.

Gärdenäs, A.I., Hopmans, J.W., Hanson, B.R., Simunek, J., 2005. Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. Agricultural Water Management 74, 219-242.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable Intensification in Agriculture: Premises and Policies. Science 341, 33-34.

Geerts, S., Raes, D., Garcia, M., Miranda, R., Cusicanqui, J.A., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., Condori, O., Mamani, J., Morales, B., Osco, V., Steduto, P., 2009a. Simulating Yield Response of Quinoa to Water Availability with AquaCrop. Agronomy Journal 101, 499-508.

Geerts, S., Raes, D., Garcia, M., Taboada, C., Miranda, R., Cusicanqui, J., Mhizha, T., Vacher, J., 2009b. Modeling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altiplano. Agricultural Water Management 96, 1652-1658.

Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Tittonell, P., 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field Crops Research 124, 468-472.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Research 114, 23-34.

Girona, J., Mata, M., del Campo, J., Arbones, A., Bartra, E., Marsal, J., 2006. The use of midday leaf water potential for scheduling deficit irrigation in vineyards. Irrigation Science 24, 115-127.

Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812-818.

Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. Philosophical Transactions of the Royal Society B-Biological Sciences 369.

Godfray, H.C.J., Pretty, J., Thomas, S.M., Warham, E.J., Beddington, J.R., 2011. Linking Policy on Climate and Food. Science 331, 1013-1014.

Goldhamer, D.A., Intrigliolo, D.S., Castel, J.R., Fereres, E., 2012. Citrus. In: Steduto, P., Th.C. Hsiao, E. Fereres, and D. Raes. 2012. Crop yield response to water. FAO Irrigation and Drainage Paper No. 66, pp. 316-345, FAO, Rome, Italy.

Gong, X.Y., Chen, Q., Lin, S., Brueck, H., Dittert, K., Taube, F., Schnyder, H., 2011. Tradeoffs between nitrogen- and water-use efficiency in dominant species of the semiarid steppe of Inner Mongolia. Plant and Soil 340, 227-238.

Gonzalez-Altozano, P., Castel, J.R., 1999. Regulated deficit irrigation in 'Clementina de Nules' citrus trees. I. Yield and fruit quality effects. Journal of Horticultural Science & Biotechnology 74, 706-713.

Green, T.R., Yu, Q.A., Ma, L.W., Wang, T.D., 2010. Crop water use efficiency at multiple scales Preface. Agricultural Water Management 97, 1099-1101.

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant Acidification in Major Chinese Croplands. Science 327, 1008-1010.

Hammami, A., Rezgui, S., Hellali, R., 2010. Leaf nitrogen and potassium concentrations for optimum fruit production, quality and biomass tree growth in Clementine mandarin under Mediterranean. Journal of Horticulture and Forestry Vol. 2(7), pp. 161-170.

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35, 365-377.

Hanson, B.R., Simunek, J., Hopmans, J.W., 2006. Evaluation of urea-ammonium-nitrate fertigation with drip irrigation using numerical modeling. Agricultural Water Management 86, 102-113.

Hashem, I.A.T., Yaqoob, I., Anuar, N.B., Mokhtar, S., Gani, A., Khan, S.U., 2015. The rise of "big data" on cloud computing: Review and open research issues. Inform Syst 47, 98-115.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutrient Cycling in Agroecosystems 51, 123-137.

He, Y., Hou, L.L., Wang, H., Hu, K., McConkey, B., 2014. A modelling approach to evaluate the long-term effect of soil texture on spring wheat productivity under a rain-fed condition. Scientific reports 4.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150-1156.

Heinen, M., 1997. Dynamics of water and nutrients in closed, recirculating cropping systems in glasshouse horticulture. With special attention to lettuce grown in irrigated sand beds. . PhD Thesis, Wageningen Agricultural University, The Netherlands. Available at: http://edepot.wur.nl/210124.

Heinen, M., 2001. FUSSIM2: brief description of the simulation model and application to fertigation scenarios. Agronomie 21, 285-296.

Heinen, M., 2006. Simplified denitrification models: Overview and properties. Geoderma 133, 444-463.

Heinen, M., 2014. Compensation in Root Water Uptake Models Combined with Three-Dimensional Root Length Density Distribution. Vadose Zone Journal 13.

Heinen, M., de Willigen, P., 1998. FUSSIM2 A two-dimensional simulation model for water flow, solute transport and root uptake of water and nutrients in partly unsaturated porous media, Quantitative Approaches in Systems Analysis No. 20. DLO Research Institute for Agrobiology and Soil Fertility and the C.T. de Wit Graduate School for Production Ecology, Wageningen, The Netherlands, 140 p. Available at: http://edepot.wur.nl/4408.

Heinen, M., Noij, I.G.A.M., Heesmans, H.I.M., van Groenigen, J.W., Groenendijk, P., Thissen, J.T.N.M., 2012. A novel method to determine buffer strip effectiveness on deep soils. Journal of Environmental Quality 41, 334-347.

Hetherington, A.M., Woodward, F.I., 2003. The role of stomata in sensing and driving environmental change. Nature 424, 901-908.

Hoa, N.M., Janssen, B.H., Oenema, O., Dobermann, A., 2006. Comparison of partial and complete soil K budgets under intensive rice cropping in the Mekong Delta, Vietnam. Agriculture Ecosystems & Environment 116, 121-131.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proceedings of the National Academy of Sciences of the United States of America 109, 3232-3237.

Hoekstra, A.Y., Wiedmann, T.O., 2014. Humanity's unsustainable environmental footprint. Science 344, 1114-1117.

Hou, X.Q., Li, R., Jia, Z.K., Han, Q.F., Wang, W., Yang, B.P., 2012. Effects of rotational tillage practices on soil properties, winter wheat yields and water-use efficiency in semi-arid areas of north-west China. Field Crops Research 129, 7-13.

Hou, Y., Velthof, G.L., Oenema, O., 2014. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Glob Chang Biol.

Hsiao, T.C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., Fereres, E., 2009. AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. Agronomy Journal 101, 448-459.

Hu, K., Li, B., Chen, D., Zhang, Y., Edis, R., 2008a. Simulation of nitrate leaching under irrigated maize on sandy soil in desert oasis in Inner Mongolia, China. Agricultural Water Management 95, 1180-1188.

Hu, K.L., Li, B.G., Chen, D.L., Zhanq, Y.P., Edis, R., 2008b. Simulation of nitrate leaching under irrigated maize on sandy soil in desert oasis in Inner Mongolia, China. Agricultural Water Management 95, 1180-1188.

Hu, K.L., Li, Y., Chen, W.P., Chen, D.L., Wei, Y.P., Edis, R., Li, B.G., Huang, Y.F., Zhang, Y.P., 2010. Modeling Nitrate Leaching and Optimizing Water and Nitrogen Management under Irrigated Maize in Desert Oases in Northwestern China. Journal of Environmental Quality 39, 667-677.

Hua, K.K., Wang, D.Z., Guo, X.S., Guo, Z.B., 2014. Carbon Sequestration Efficiency of Organic Amendments in a Long-Term Experiment on a Vertisol in Huang-Huai-Hai Plain, China. Plos One 9.

Huang, M.B., Gallichand, J., Zhong, L.P., 2004. Water-yield relationships and optimal water management for winter wheat in the Loess Plateau of China. Irrigation Science 23, 47-54.

Hudson, B.D., 1994. Soil Organic-Matter and Available Water Capacity. J Soil Water Conserv 49, 189-194.

Hungate, B.A., van Groenigen, K.J., Six, J., Jastrow, J.D., Luo, Y.Q., de Graaff, M.A., van Kessel, C., Osenberg, C.W., 2009. Assessing the effect of elevated carbon dioxide on soil carbon: a comparison of four meta-analyses. Global Change Biology 15, 2020-2034.

IPCC, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the International Panel of Climate Change. Cambridge Univ. Press, UK.

IPNI, 2012. 4R Plant Nutrition: A Manual for Improving the Management of Plant Nutrition. International Plant Nutrition Institute. Norcross, Georgia, USA. ISBN 978-0-9834988-1-0.

ISS-CAS, 2012. China Soil Scientific Database Website. Institute of Soil Science, Chinese Academy of Science (ISS-CAS), China. Available: http://www.soil.csdb.cn/. Accessed 2012 Oct 1.

IUSS, 2006. World reference base for soil resources 2006. A framework for international classification, correlation and communication, 2nd edition. World Soil Resources Reports No. 103. FAO, Rome.

Jeong, S.J., Ho, C.H., Piao, S.L., Kim, J., Ciais, P., Lee, Y.B., Jhun, J.G., Park, S.K., 2014. Effects of double cropping on summer climate of the North China Plain and neighbouring regions. Nat Clim Change 4, 615-619.

Jin, L., Hu, K.L., Deelstra, J., Li, B.G., Wei, D., Wang, H.Y., 2014. Evaluation of nitrogen fate, water and nitrogen use efficiencies of winter wheat in North China Plain based on model approach. Acta Agriculturae Scandinavica Section B-Soil and Plant Science 63, 127-138.

Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proceedings of the National Academy of Sciences of the United States of America 106, 3041-3046.

Kang, S., Evett, S.R., Robinson, C.A., Stewart, B.A., Payne, W.A., 2009. Simulation of winter wheat evapotranspiration in Texas and Henan using three models of differing complexity. Agricultural Water Management 96, 167-178.

Kang, S.Z., Gu, B.J., Du, T.S., Zhang, J.H., 2003a. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. Agricultural Water Management 59, 239-254.

Kang, S.Z., Zhang, L., Liang, Y.L., Dawes, W., 2003b. Simulation of winter wheat yield and water use efficiency in the Loess Plateau of China using WAVES. Agricultural Systems 78, 355-367.

Kang, S.Z., Zhang, L., Liang, Y.L., Hu, X.T., Cai, H.J., Gu, B.J., 2002. Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. Agricultural Water Management 55, 203-216.

Key, T.J., Allen, N.E., Spencer, E.A., Travis, R.C., 2002. The effect of diet on risk of cancer. Lancet 360, 861-868.

Koenker, R., 2013. Comment on “Local quantile regression”. Journal of Statistical Planning and Inference 143, 1134-1135.

Koenker, R., Hallock, K.F., 2001. Quantile regression. J Econ Perspect 15, 143-156.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Research Letters 9.

Legaz, F., Primo-Millo, E., 2000. Guidelines for Citrus fertilization under located drip irrigation. In: J.M.V. Giner and S.L. Phytoma-España (eds.), Fertirrigation in Citrus. Polytechnic University of València. Department of the Agriculture, Fish and Food of the Valencian Government, Valencia, 137–155 (in Spanish).

Li, H., Parent, L.E., Karam, A., Tremblay, C., 2004. Potential of Sphagnum peat for improving soil organic matter, water holding capacity, bulk density and potato yield in a sandy soil. Plant and Soil 265, 355-365.

Li, L., Li, S.M., Sun, J.H., Zhou, L.L., Bao, X.G., Zhang, H.G., Zhang, F.S., 2007. Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. Proceedings of the National Academy of Sciences of the United States of America 104, 11192-11196.

Li, R., Hou, X.Q., Jia, Z.K., Han, Q.F., Ren, X.L., Yang, B.P., 2013a. Effects on soil temperature, moisture, and maize yield of cultivation with ridge and furrow mulching in the rainfed area of the Loess Plateau, China. Agricultural Water Management 116, 101-109.

Li, S.X., Wang, Z.H., Li, S.Q., Gao, Y., Tian, X.H., 2013b. Effect of plastic sheet mulch, wheat straw mulch, and maize growth on water loss by evaporation in dryland areas of China. Agricultural Water Management 116, 39-49.

Li, S.X., Wang, Z.H., Malhi, S.S., Li, S.Q., Gao, Y.J., Tian, X.H., 2009. Nutrient and Water Management Effects on Crop Production, and Nutrient and Water Use Efficiency in Dryland Areas of China. Advances in Agronomy, Vol 102 102, 223-265.

Li, X.Y., Zhao, W.W., Song, Y.X., Wang, W., Zhang, X.Y., 2008. Rainfall harvesting on slopes using contour furrows with plastic-covered transverse ridges for growing Caragana korshinskii in the semiarid region of China. Agricultural Water Management 95, 539-544.

Lidon, A., Ramos, C., Ginestar, D., Contreras, W., 2013. Assessment of LEACHN and a simple compartmental model to simulate nitrogen dynamics in citrus orchards. Agricultural Water Management 121, 42-53.

Liu, C.M., Yu, J.J., Kendy, E., 2001. Groundwater exploitation and its impact on the environment in the North China Plain. Water International 26, 265-272.

Liu, C.M., Zhang, X.Y., Zhang, Y.Q., 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agricultural and Forest Meteorology 111, 109-120.

Liu, E.K., He, W.Q., Yan, C.R., 2014a. ‘White revolution’ to ‘white pollution’-agricultural plastic film mulch in China. Environmental Research Letters 9.

Liu, J., Yang, H., Savenije, H.H.G., 2008. China’s move to higher-meat diet hits water security. Nature 454, 397.

Liu, J.G., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94, 478-493.

Liu, J.L., Bu, L.D., Zhu, L., Luo, S.S., Chen, X.P., Li, S.Q., 2014b. Optimizing Plant Density and Plastic Film Mulch to Increase Maize Productivity and Water-Use Efficiency in Semiarid Areas. Agronomy Journal 106, 1138-1146.

Liu, X., Ju, X., Zhang, F., Pan, J., Christie, P., 2003. Nitrogen dynamics and budgets in a winter wheat-maize cropping system in the North China Plain. Field Crops Research 83, 111-124.

Liu, X.J., Zhang, Y., Han, W.X., Tang, A.H., Shen, J.L., Cui, Z.L., Vitousek, P., Erisman, J.W., Goulding, K., Christie, P., Fangmeier, A., Zhang, F.S., 2013. Enhanced nitrogen deposition over China. Nature 494, 459-462.

Liu, Y., Wang, E.L., Yang, X.G., Wang, J., 2010. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Global Change Biology 16, 2287-2299.

Long, S.P., Zhu, X.G., Naidu, S.L., Ort, D.R., 2006. Can improvement in photosynthesis increase crop yields? Plant Cell and Environment 29, 315-330.

Lopez-Bellido, R.J., Lopez-Bellido, L., Benitez-Vega, J., Lopez-Bellido, F.J., 2007. Tillage system, preceding crop, and nitrogen fertilizer in wheat crop: I. Soil water content. Agronomy Journal 99, 59-65.

Lu, R.K., 2000. Analytical methods of soil agricultural chemistry. China Agricultural Science and Technology Press, Beijing.

Lu, Z.M., Percy, R.G., Qualset, C.O., Zeiger, E., 1998. Stomatal conductance predicts yields in irrigated Pima cotton and bread wheat grown at high temperatures. Journal of Experimental Botany 49, 453-460.

Ma, L., Wang, F.H., Zhang, W.F., Ma, W.Q., Velthof, G., Qin, W., Oenema, O., Zhang, F.S., 2013. Environmental Assessment of Management Options for Nutrient Flows in the Food Chain in China. Environmental Science & Technology 47, 7260-7268.

Marris, E., 2008. Water: More crop per drop. Nature 452, 273-277.

Marschner, H., 1995. Mineral Nutrition of Higher Plants. Academic Press, San Diego: 889 pp.

Martínez-Alcántara, B., Quiñones, A., Legaz, F., Primo-Millo, E., 2012. Nitrogen-use efficiency of young citrus trees as influenced by the timing of fertilizer application. J Plant Nutr Soil Sc 175, 282-292.

Mavimbela, S.S.W., van Rensburg, L.D., 2012. Integrating Micro-Flood Irrigation with in-Field Rainwater Harvesting: Maize Yield and Water Use Efficiency. Irrigation and Drainage 61, 70-81.

Meng, Q.F., Sun, Q.P., Chen, X.P., Cui, Z.L., Yue, S.C., Zhang, F.S., Romheld, V., 2012. Alternative cropping systems for sustainable water and nitrogen use in the North China Plain. Agriculture Ecosystems & Environment 146, 93-102.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Climate change - Stationarity is dead: Whither water management? Science 319, 573-574.

Mkhabela, M.S., Bullock, P.R., 2012. Performance of the FAO AquaCrop model for wheat grain yield and soil moisture simulation in Western Canada. Agricultural Water Management 110, 16-24.

Molden, D., 2007. Water for food, Water for life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan/IWMI.

Morgan, K.T., Zotarelli, L., Dukes, M.D., 2010. Use of Irrigation Technologies for Citrus Trees in Florida. Horttechnology 20, 74-81.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12: 513-522.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature.

Perez-Perez, J.G., Romero, P., Navarro, J.M., Botia, P., 2008a. Response of sweet orange cv ‘Lane late’ to deficit-irrigation strategy in two rootstocks. II: Flowering, fruit growth, yield and fruit quality. Irrigation Science 26, 519-529.

Perez-Perez, J.G., Romero, P., Navarro, J.M., Botia, P., 2008b. Response of sweet orange cv ‘Lane late’ to deficit irrigation in two rootstocks. I: water relations, leaf gas exchange and vegetative growth. Irrigation Science 26, 415-425.

Phogat, V., Skewes, M.A., Cox, J.W., Alam, J., Grigson, G., Simunek, J., 2013a. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. Agricultural Water Management 127, 74-84.
Phogat, V., Skewes, M.A., Cox, J.W., Alam, J., Grigson, G., Šimůnek, J., 2013b. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. Agricultural Water Management 127, 74-84.
Phogat, V., Skewes, M.A., Mahadevan, M., Cox, J.W., 2013c. Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. Agricultural Water Management 118, 1-11.
Piao, S.L., Ciais, P., Huang, Y., Shen, Z.H., Peng, S.S., Li, J.S., Zhou, L.P., Liu, H.Y., Ma, Y.C., Ding, Y.H., Friedlingstein, P., Liu, C.Z., Tan, K., Yu, Y.Q., Zhang, T.Y., Fang, J.Y., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43-51.
Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., the R Development Core Team, 2013. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-111.
Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2014. Productivity limits and potentials of the principles of conservation agriculture. Nature.
Qin, W., Chi, B.L., Oenema, O., 2013. Long-Term Monitoring of Rainfed Wheat Yield and Soil Water at the Loess Plateau Reveals Low Water Use Efficiency. Plos One 8.
Quemada, M., Baranski, M., Nobel-de Lange, M.N.J., Vallejo, A., Cooper, J.M., 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agriculture Ecosystems & Environment 174, 1-10.
Quiñones, A., Banuls, J., Millo, E.P., Legaz, F., 2003. Effects of N-15 application frequency on nitrogen uptake efficiency in Citrus trees. Journal of Plant Physiology 160, 1429-1434.
Quiñones, A., Martinez-Alcantara, B., Legaz, F., 2007. Influence of irrigation system and fertilization management on seasonal distribution of N in the soil profile and on N-uptake by citrus trees. Agriculture Ecosystems & Environment 122, 399-409.
R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria URL http://www.R-project.org/.
Raes, D., Steduto, P., Hsiao, T.C., Fereres, E., 2009. AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. Agronomy Journal 101, 438-447.
Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield Trends Are Insufficient to Double Global Crop Production by 2050. Plos One 8.
Rigby, D., Caceres, D., 2001. Organic farming and the sustainability of agricultural systems. Agricultural Systems 68, 21-40.
Robert, P.C., 2002. Precision agriculture: a challenge for crop nutrition management. Plant and Soil 247, 143-149.
Rockstrom, J., Falkenmark, M., 2015. Increase water harvesting in Africa. Nature 519, 283-285.
Rockstrom, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture-The need for a paradigm shift. Agricultural Water Management 97, 543-550.
Rockstrom, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences of the United States of America 104, 6253-6260.
Romero, C.C., Dukes, M.D., Baigorria, G.A., Cohen, R., 2009. Comparing theoretical irrigation requirement and actual irrigation for citrus in Florida. Agricultural Water Management 96, 473-483.
Rosegrant, M.W., Cline, S.A., 2003. Global food security: Challenges and policies. Science 302, 1917-1919.
Ruiz-Canales, A., Franco, J.A., Plana, V., Abrisqueta, J.M., 2006. Root Distribution in Apricot Orchard (Prunus armeniaca L. 'Búlida') under Trickle Irrigation. Acta Horticulturae 717: 307-311.

Ruiz-Sánchez, M.C., Plana, V., Ortuno, M.F., Tapia, L.M., Abrisqueta, J.M., 2005. Spatial root distribution of apricot trees in different soil tillage practices. Plant and Soil 272, 211-221.

Rusinamhodzi, L., Corbeels, M., van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy for Sustainable Development 31, 657-673.

Sachs, J.D., 2008. Common Wealth. Economics for a Crowded Planet. The Penguin Press, New York, 386 pp.

Salemi, H., Soom, M.A.M., Lee, T.S., Mousavi, S.F., Ganji, A., KamilYusoff, M., 2011. Application of AquaCrop model in deficit irrigation management of Winter wheat in arid region. African Journal of Agricultural Research 6, 2204-2215.

Salvagiotti, F., Cassman, K.G., Specht, J.E., Walters, D.T., Weiss, A., Dobermann, A., 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Research 108, 1-13.

Sanchez, P.A., 2010. Tripling crop yields in tropical africa. Nat Geosci 3, 299-300.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kogel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49-56.

Scholberg, J.M.S., Parsons, L.R., Wheaton, T.A., McNeal, B.L., Morgan, K.T., 2002. Soil temperature, nitrogen concentration, and residence time affect nitrogen uptake efficiency in citrus, Journal of Environmental Quality, pp. 759-768.

Schröder, J.J., Neeteson, J.J., Oenema, O., Struik, P.C., 2000. Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Research 66, 151-164.

Setiyono, T.D., Walters, D.T., Cassman, K.G., Witt, C., Dobermann, A., 2010. Estimating maize nutrient uptake requirements. Field Crops Research 118, 158-168.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229-U113.

Siahpoosh, M.R., Dehghanian, E., 2012. Water Use Efficiency, Transpiration Efficiency, and Uptake Efficiency of Wheat during Drought. Agronomy Journal 104, 1238-1243.

Sinclair, T.R., Seligman, N.G., 1996. Crop modeling: From infancy to maturity. Agronomy Journal 88, 698-704.

Singh, R., Singh, K., Bhandarkar, D.M., 2014. Estimation of water requirement for soybean (Glycine max) and wheat (Triticum aestivum) under vertisols of Madhya Pradesh. Indian Journal of Agricultural Sciences 84, 190-197.

Smil, V., 2000. Feeding the world. A challenge for the twenty-first century. MIT Press, Cambridge, Massachusetts, USA.

Sojka, R.E., Stolzy, L.H., 1980. Soil-Oxygen Effects on Stomatal Response. Soil Science 130, 350-358.

Spiertz, H., 2012. Avenues to meet food security. The role of agronomy on solving complexity in food production and resource use. European Journal of Agronomy 43, 1-8.

Spiertz, H., 2013. Challenges for Crop Production Research in Improving Land Use, Productivity and Sustainability. Sustainability-Basel 5, 1632-1644.

Srivastava, A.K., 2012. Advances in citrus nutrition.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. FAO Irrigation and drainage paper 66, Crop yield response to water, Food and Agriculture Organization of the United Nations

Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2009. AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. Agronomy Journal 101, 426-437.

Stricevic, R., Cosic, M., Djurovic, N., Pejic, B., Maksimovic, L., 2011. Assessment of the FAO AquaCrop model in the simulation of rainfed and supplementally irrigated maize, sugar beet and sunflower, Agricultural Water Management, pp. 1615-1621.

Sutton, M.A., Bleeker, A., 2013. ENVIRONMENTAL SCIENCE The shape of nitrogen to come. Nature 494, 435-437.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S., 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Sutton, M.A., Oenema, O., Erisman, J.W., Leip, A., van Grinsven, H., Winiwarter, W., 2011. Too much of a good thing. Nature 472, 159-161.

Tian, Y., Li, F.M., Liu, P.H., 2003. Economic analysis of rainwater harvesting and irrigation methods, with an example from China. Agricultural Water Management 60, 217-226.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108, 20260-20264.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671-677.

Todorovic, M., Albrizio, R., Zivotic, L., Saab, M.T.A., Stockle, C., Steduto, P., 2009. Assessment of AquaCrop, CropSyst, and WOFOST Models in the Simulation of Sunflower Growth under Different Water Regimes. Agronomy Journal 101, 509-521.

Treeby, M., Falivene, S., Phogat, V., Skewes, M., 2012. Knowledge and tools to manage fertigation technologies in highly productive citrus orchards for minimal environmental footprint. Final Report to National Program for Sustainable Irrigation.

UNESCO, 2009. The United Nations World Water Development Report 3: Water in a Changing World. Paris: UNESCO, and London: Earthscan.

van Genuchten, M.T., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. . Soil Sci. Soc. Am. J. 44: 892-898.

van Groenigen, J.W., Lubbers, I.M., Vos, H.M.J., Brown, G.G., De Deyn, G.B., van Groenigen, K.J., 2014. Earthworms increase plant production: a meta-analysis. Scientific reports 4.

van Groenigen, K.J., Six, J., Hungate, B.A., de Graaff, M.A., van Breemen, N., van Kessel, C., 2006. Element interactions limit soil carbon storage. Proceedings of the National Academy of Sciences of the United States of America 103, 6571-6574.

Van Rensburg, L.D., Botha, J.J., Anderson, J.J., Hensley, M., 2012. The Nature and Function of the in-Field Rainwater Harvesting System to Improve Agronomic Sustainability. Irrigation and Drainage 61, 34-40.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277, 494-499.

Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L.E., Holland, E., Johnes, P.J., Katzenberger, J., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D., Palm, C.A., Robertson, G.P., Sanchez, P.A., Townsend, A.R., Zhang, F.S., 2009. Nutrient Imbalances in Agricultural Development. Science 324, 1519-1520.

Walkley, A., Black, I.A., 1934. An examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37: 29-38.

Wang, P., Song, X.F., Han, D.M., Zhang, Y.H., Zhang, B., 2012a. Determination of evaporation, transpiration and deep percolation of summer corn and winter wheat after irrigation. Agricultural Water Management 105, 32-37.

Wang, X.B., Cai, D.X., Hoogmoed, W.B., Oenema, O., Perdok, U.D., 2007. Developments in conservation tillage in rainfed regions of North China. Soil & Tillage Research 93, 239-250.

Wang, X.B., Dai, K.A., Zhang, D.C., Zhang, X.M., Wang, Y., Zhao, Q.S., Cai, D.X., Hoogmoed, W.B., Oenema, O., 2011. Dryland maize yields and water use efficiency in response to tillage/crop stubble and nutrient management practices in China. Field Crops Research 120, 47-57.

Wang, X.B., Wu, H.J., Dai, K., Zhang, D.C., Feng, Z.H., Zhao, Q.S., Wu, X.P., Jin, K., Cai, D.X., Oenema, O., Hoogmoed, W.B., 2012b. Tillage and crop residue effects on rainfed wheat and maize production in northern China. Field Crops Research 132, 106-116.

Wang, X.Y., Tong, Y.N., Gao, Y.M., Gao, P.C., Liu, F., Zhao, Z.P., Pang, Y., 2014. Spatial and Temporal Variations of Crop Fertilization and Soil Fertility in the Loess Plateau in China from the 1970s to the 2000s. Plos One 9.

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O., 2014. Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Global Environmental Change-Human and Policy Dimensions 26, 196-205.

Whisler, F.D., Acock, B., Baker, D.N., Fye, R.E., Hodges, H.F., Lambert, J.R., Lemmon, H.E., Mckinion, J.M., Reddy, V.R., 1986. Crop Simulation-Models in Agronomic Systems. Advances in Agronomy 40, 141-208.

Willmott, C.J., 1982. Some Comments on the Evaluation of Model Performance. Bulletin of the American Meteorological Society 63, 1309-1313.

Willmott, C.J., Matsuura, K., 2005. Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. Climate Research 30, 79-82.

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90, 169-185.

Xie, W.Y., Zhou, H.P., Guan, C.L., Zhang, J.J., Yan, X.Y., Wang, S.w., 2011. Spatial Distribution of Soil Active Nutrients in Farmland in Shanxi Province. Journal of Shanxi Agricultural Sciences.

Yang, N., Wang, Z.H., Gao, Y.J., Zhao, H.B., Li, K.Y., Li, F.C., Malhi, S.S., 2014. Effects of planting soybean in summer fallow on wheat grain yield, total N and Zn in grain and available N and Zn in soil on the Loess Plateau of China. European Journal of Agronomy 58, 63-72.

Yu, X., Abler, D., 2014. Where have all the pigs gone? Inconsistencies in pork statistics in China. China Economic Review 30, 469-484.

Zhang, F., Cui, Z., Chen, X., Ju, X., Shen, J., Chen, Q., Liu, X., Zhang, W., Mi, G., Fan, M., Jiang, R., 2012. Integrated Nutrient Management for Food Security and Environmental Quality in China, Advances in Agronomy, pp. 1-40.

Zhang, H., Wang, X., You, M., Liu, C., 1999. Water-yield relations and water-use efficiency of winter wheat in the North China Plain. Irrigation Science 19, 37-45.

Zhang, H.P., Oweis, T., 1999. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agricultural Water Management 38, 195-211.

Zhang, X.Y., Chen, S.Y., Sun, H.Y., Shao, L.W., Wang, Y.Z., 2011. Changes in evapotranspiration over irrigated winter wheat and maize in North China Plain over three decades. Agricultural Water Management 98, 1097-1104.

Zhang, X.Y., Chen, S.Y., Sun, H.Y., Wang, Y.M., Shao, L.W., 2010. Water use efficiency and associated traits in winter wheat cultivars in the North China Plain. Agricultural Water Management 97, 1117-1125.

Zhang, X.Y., Pei, D., Chen, S.Y., Sun, H.Y., Yang, Y.H., 2006. Performance of double-cropped winter wheat-summer maize under minimum irrigation in the North China Plain. Agronomy Journal 98, 1620-1626.

Zhou, L.-M., Li, F.-M., Jin, S.-L., Song, Y., 2009. How two ridges and the furrow mulched with plastic film affect soil water, soil temperature and yield of maize on the semiarid Loess Plateau of China. Field Crops Research 113, 41-47.

Zwart, S.J., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69, 115-133.

Zwart, S.J., Bastiaanssen, W.G.M., de Fraiture, C., Molden, D.J., 2010. A global benchmark map of water productivity for rainfed and irrigated wheat. Agricultural Water Management 97, 1617-1627.

Summary

Water and nitrogen (N) are two key limiting factors in global crop production. However, the optimization of water and N use is often studied separately, and the interactions between water and N use in crop production are often neglected. Lack of systematic and quantitative understanding of the interactions between water and N use may lead to misleading and/or biased recommendations. The main objective of this thesis research was 'to increase the understanding of interactions between water and N use in crop production'. The specific objectives were (i) to analyse water and N use and their interactions in crop yields and in water and N use efficiencies (WUE and NUE), and (ii) to explore options for increasing crop yields and water and N use efficiencies simultaneously.

Two main and contrasting crop production systems were chosen; i.e., an annual cereal-based production system and a perennial orange production system. Cereal production systems were chosen because of their importance in ensuring global food, feed and fuel supply. Special attention was given to rainfed wheat and maize systems because their yields are significantly limited by water and N availability, especially in arid and semi-arid regions. Fertigated orange production systems were considered because of their increasing importance in the global fruit market and in human diets. Rapid development in orange production is also because of the improvements in technologies and facilities, such as drip irrigation/fertigation, logistics and food processing.

The main research questions were:

- What are the effects of soil mulching on yields, WUE and NUE?
- What are the options for increasing yield, WUE and NUE in rainfed dryland system?
- What are the effects of long-term applications of soil organic amendments and mineral fertilizers on crop yields, WUE and NUE in rain fed dryland system?
- What are the potentials of increasing yields, WUE and NUE in orange production?
- What are the possible fertigation strategies for increasing yields, WUE and NUE in orange production?

In this thesis, I combined the use of literature review and meta-analysis, long-term field experiments and soil-crop modelling to quantify relationships between water and N use and their interactions in crop yields, WUE and NUE, and to explore options for improving the productivity and sustainability of two important crop systems (i.e., annual cereal and perennial orange systems).

In Chapter 2, I conducted a meta-analysis on the effects of soil mulching on wheat and maize yields, WUE and NUE, using 1310 yield observations from 74 studies conducted in 19 countries. Soil mulching (with plastic film cover and/or straw mulching) reduces evaporation, modifies soil temperature and thereby affects crop yields, WUE and NUE. The results indicated that soil mulching significantly increased crop yields, WUE and NUE, by 20 to 60%, compared with the no-mulching treatment. Effects of plastic covers were two times higher for maize than for wheat. Interestingly, plastic film performed better at relatively low temperature than at relatively high temperature, while straw mulching showed the opposite trend. Effects of mulching tended to decrease with increasing water and N inputs. Soil mulches also changed the relationships between water input level and crop yield, WUE and NUE, as well as the relationship between N input and crop yield, WUE and NUE.

In Chapter 3, I analysed the relationships between water input and yields, WUE and NUE of a rainfed winter wheat system in the Loess Plateau, using data of a long-term (>30 years) monitoring field experiment in Shanxi province, China. The loess Plateau is an arid and semi-arid region with limited annual rainfall (<500 mm), which is often the main limiting factor for crop yields. The results showed that, on average, about two-third of the rainwater was lost by evaporation, i.e., 40% was evaporated during the growing season and 60% was evaporated during the fallow season. Only one-third of the available water was actually used by winter wheat for transpiration. Wheat yield, WUE and NUE were positively related to evapotranspiration (ET), confirming a water limiting situation. Therefore, wheat yields, WUE and NUE were low and greatly differed between years.

To explore the effects of improved water management (via reducing evaporation) on wheat yield, I calibrated and validated the FAO AquaCrop model. Results of model experiments suggested that minimizing evaporation via straw mulch or plastic film covers could increase wheat yields by 15 to 25%, and WUE by 30 to 90%, respectively. The estimations were largely in line with the results of the meta-analysis in Chapter 2. These results suggest that there is a room for significant increase in wheat yield, WUE and NUE at the Loess Plateau by soil mulching.

In chapter 4, I analysed the productivity and sustainability of a rainfed wheat-soybean system in the North China Plain, using data of a long-term (> 30 years) field experiment conducted in Anhui province. In this chapter, I investigated the effects of a series of field management practices (i.e., recommended fertilization, and the same fertilization with additions of straw and animal manure as soil organic amendments) on crop yield, WUE and NUE over time. Wheat and soybean yields were 5 and 2.5 times higher in the fertilized treatments than in the unfertilized control, respectively. Among the fertilized treatments, NPK + manure was more effective in increasing yields than

NPK alone or NPK + straw. The additional effect of manure is likely due to increased potassium (K) and/or micronutrients, and improved physical and biological soil fertility following repeated applications of manure over time.

Manure applications greatly increased P Olsen values. In the treatment NPK fertilizer + manure, P Olsen values rapidly increased to around 75 mg kg^{-1} and then remained at this level during the course of the experiment, suggesting soil P saturation in the top soil and transport of P from the top soil to the subsoil. The optimal P Olsen level for cereals is normally in the range of 10 to 20 mg kg^{-1}. P Olsen remained within the recommended range of 10-20 mg kg^{-1} in the NPK fertilization treatments without animal manure, suggesting that the P inputs via NPK fertilizers and straw were adequate.

Long-term fertilization and addition of organic amendments significantly increased soil organic matter contents (SOC) over time, which may indirectly contribute to crop growth and development. Contents of SOC increased significantly in the treatments with manure and straw. There were clear correlations between SOC content and crop yield, but the relationship between SOC and yield is highly nested to soil available N (soil N mineralization) and K.

Grain yields of the fertilized treatments were positively related to water input, but yields of the unfertilized treatments did not respond to water input. Grain yields of the fertilized treatments increased over time, and thereby WUE and NUE also increased over time. The steady increase in grain yields is likely the result of a combination of improved crop varieties, crop husbandry practices and soil fertility. Due to the steady increase in grain yields over time, yield became more water limited, suggesting that the need for soil mulching increased. Soil mulching with straw or plastic films are common measures to reduce evaporation and thereby to increase crop yields (and WUE and NUE) in Northwest China, but has not been widely implemented in Anhui. Model simulations indicated that straw mulching and plastic cover could increase mean wheat yield by 10-15%, and supplementary irrigation of 100 mm could increase mean wheat yields by 35%. However, soybean yields did not respond to soil mulching and irrigation, because there was no water stress during the soybean growing seasons.

In chapter 5, I conducted a meta-analysis on orange production systems in the world, using 1009 yield observations from 55 studies conducted in 11 countries. Orange trees mainly grow in subtropical and tropical regions, and require relatively large amounts of water and N. In this chapter, relationships between water input and orange yield, WUE and NUE, and between N input and yield, WUE and NUE were analysed. Also, effects of sub- and over-optimal water and N supply on yield, WUE and NUE were quantified and water and N saving potential of each region were estimated.

Median orange yields ranged from 30 to 60 ton ha-1, which were in between average global yields (range 10-30 ton ha^{-1}) and attainable yields (range 60-90 ton ha^{-1}). Median WUE ranged from 2.5 to 5 kg m^{-3} and median NUE from 150 to 350 kg kg^{-1}. Orange yields were related to water and N inputs and tree age. Relationships between water and N inputs and yield, WUE and NUE were also analysed for sub-datasets and quantiles, to examine the relationships near the frontiers.

There were statistical significant interactions between water and N inputs in yield and NUE, but not in WUE. This indicates that studies aimed at the optimization of water and N inputs must consider interactions and must optimize water and N inputs simultaneously. Based on our analyses, I estimated that reducing over-optimal irrigation to optimal irrigation may increase orange yield by 20%, WUE by 30% and NUE by 15%. Similarly, reducing over-optimal N fertilization to optimal N fertilization may increase yield by 10%, WUE by 15% and NUE by 40%. The results suggested that there is room for a significant increase in yield, WUE and NUE through the simultaneous optimization of water and fertilizer N inputs via precision fertigation.

In chapter 6, I explored the simultaneous optimization of water and N use for orange production in the Mediterranean region, using a coupled soil-crop model, i.e., coupling the soil hydrological model FUSSIM-3D and the water-driven crop model AquaCrop. In total, 47 fertigation strategies were investigated, which included 27 main scenarios (3 x 3 x 3 factorial design): 3 irrigation levels (80,100 and 120% *ET*), 3 N supply levels (100, 200 and 300 kg N ha^{-1}) and 3 split applications (N fractionation). 20 additional scenarios were run to investigate the effects of rainfall, soil type and fine-tuning fertigation strategies.

The results of the simulations showed that orange yields were strongly influenced by N input levels but not by water input levels. Increasing water and N input levels led to increased N losses (via leaching and denitrification); there are significant positive interactions between water and N inputs in N losses. On average, low N input (100 kg ha^{-1}) led to relatively low N losses (16 kg ha^{-1}, 16% of N input) but resulted in low yield (33 ton ha^{-1}, 25% yield reduction). High N input (300 kg ha^{-1}) produced a high yield (43 ton ha^{-1}) but led to large N losses (104 kg ha^{-1}, 35% of N input). Optimal N input (200 kg ha^{-1}) significantly reduced N losses (45 kg ha^{1}) without yield reduction. Importantly, with optimal N input, improving N fractionation significantly increased yield by 13% and reduced N losses by 40%.

The statistical significant interactions between water and N inputs and N fractionation regime in yield, WUE, NUE and N losses indicate that the optimization of fertigation strategies must consider these three key variables simultaneously. Our results clearly showed that over-optimal water and N inputs lead to high water and N losses. Reduced irrigation (80% *ET*) and N input (200 kg ha^{-1}) can significantly reduce N

losses (43%) without yield reduction. N fractionation strategy should be adjusted to the N demand by the crop during the growing season.

In summary, this thesis provides a systematic and quantitative analysis and synthesis of water and N use and their interactions in yield, WUE and NUE for two important and contrasting crop production systems (i.e., annual cereals and perennial orange tree).

In arid and semi-arid regions, such as the Loess Plateau, I found that the water loss via soil evaporation was large; as much as 60 to 70% of total rainfall was lost and thereby significantly limited wheat yields. Soil mulching can effectively reduce soil evaporation thereby increasing crop yields by up to 60%. In sub-humid regions, the productivity and sustainability of rainfed wheat-soybean rotation systems can be constrained by soil fertility and other factors besides water and nutrient management. Fertilization and soil organic amendments greatly increased wheat yield and WUE, but decreased NUE.

In advanced fertigated orange production systems, a main challenge is to optimize water and N use for optimal yield while minimizing environmental pollution. Fertigation provides opportunities to simultaneously optimize water and N use in orange production systems. Optimization of water and N supply is, however, complicated in practice due to erratic and uncontrollable rainfall, which may lead to large incidental losses. Improving water and N input can significantly and simultaneously increase orange yield, WUE and NUE (by 20, 30 and 40% respectively). Importantly, even with optimal water and N input levels, fractionation (split) strategies can significantly increase orange yield and reduce N losses.

In conclusion, rainfed cereal crop yields, WUE and NUE in dryland agriculture can be increased by up to 60%, with currently available knowledge and soil mulching techniques. In many regions in the world, there is still a large gap between observed crop yields and attainable yield by best management. Given large potentials in low-performing agricultural systems, investments in knowledge and education, infrastructures and subsidies should also be prioritized for these regions. Potentially, this will significantly contribute to local and global food security.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor and promoter, Prof. Oene Oenema, for his continuous support on my PhD study, for his patience, encouragement and immense knowledge. His curiosity and questions intrigued me to learn and think more, to provide underpinnings and to find better solutions. His guidance helped me in all the time of research and the completion of this thesis. During my PhD study, we also travelled together in China for several times, amazingly, he could easily communicate with local people although he did not speak the language, and his questions always surprised us because no one could explicitly answer and explain. Also because of that, he knows China better than me, and I often joke that he is a half Chinese, but I am just one-third Dutch (given the time that I have stayed in the Netherlands). In today's Dutch custom, we are more colleagues than supervisor and student; but in Chinese philosophy, even if he taught/supervised me for one day, he shall be respected as my father for my entire life. It has been a great honor and a big fortune for me to have him as my supervisor; his questions, openness, humor and encouragement will continue inspiring me in pursuing the beauty of science and life.

Secondly, I would like to thank my co-promoter, Prof. Hu Chunsheng, for his great support and supervision from home. Interestingly, the first time that we met each other was in Wageningen but not in China. At that time, He was a visiting scholar in Wageningen. We sat in the same office in the Atlas building. We often had lunch and dinner together after work. He likes eating noodles because he was born in Shanxi Province where people can cook noodles in many different ways. To welcome him, we also made noodles by ourselves, which turned out to be good. He was very happy about the noodles that we made in Wageningen. After he went back to China, he kindly invited us to visit his institute and the long-term field experiments. He also introduced me to many excellent scientists which provided me the opportunities to collaborate with them. I am very grateful for his thoughtful arrangements for many fields' visits in China during my PhD study, which formed a robust basis of this thesis.

Next, I would like to thank my co-promoter, Dr. Marius Heinen, for having me participated in the EFFIDRIP project, which was funded by the 7th Framework Programme of the European Union (EU FP7-SME-2011, grant 286807). The work in the EFFIDRIP project formed an important component of this thesis. During these collaborations, I have learned enormous amount of knowledge on both modelling and writing. He is very open-minded for having various discussions, and he was always supportive and helpful when I encountered problems. He contributed significantly to the writing and completing of this thesis.

Besides my promoter and co-promoters, I would like to thank many important people who helped and supported me in pursuing my PhD. I would like to thank Prof. Zhang Fusuo for introducing me to Prof. Oene Oenema, so that I could start my PhD in Wageningen. I would like to thank Dr. Gerard Velthof for his supervision and encouragement at the early stage of my PhD study. I would like to thank Prof. Lijbert Brussaard for his great support and encouragement of my PhD study, and I thank Department of Soil Quality of Wageningen University for the financial support for my PhD study.

Further, I would like to thank many important collaborators of this thesis, Prof. Chi Baoliang, Prof. Guo Xisheng, Dr. Wang Daozhong and Ir. Assinck Falentijn. They conducted the long-term field experiments and the model simulations, which formed the basis of this thesis. I would also like to thank many other excellent collaborators, Prof. Ma Lin, Dr. Li Haigang, Dr. Bai Zhaohai, Dr. Fan Liangxin, Dr. Qin Shuping, Dr. Wei Sha, and Ir. Zhang Jianjie who have me involved in their work, which greatly motivated me to widen my research from various perspectives.

I would like to thank many fellow PhDs, Yu Yang, Wang Xinxin, Yao Mingtian, Yan Dan, Wang Jingmeng, Liu Qian, Hou Yong, for the stimulating discussions. I would like to thanks all the friends in Wageningen and in China, for their great accompanies and encouragement, which made my PhD study an extraordinary journey :)

In the end, I would like to thank my parents for supporting me throughout my PhD and my life in general. I would like to thank Chunxu Song, my girlfriend, for her continuous encouragement, support and love :)

Curriculum vitae

Wei Qin was born on 14th of January, 1980 in Donglan County, Guangxi Zhuang Autonomous Region, China. He grew up in a remote mountainous village where agriculture was dominated by subsistence farming. His grandparents were also subsistence farmers who grew maize in the scattered and narrow terraces. Maize is an important crop in local regions, providing food and fuel for the households. Wei Qin spent his early life in such rural setting, so he had a dream of increasing the productivity and profitability of agricultural systems from his childhood. To pursue his dream, he completed his BSc in Soil Science and Plant Nutrition at China Agricultural University in 2002, MSc in International Land and Water Management at Wageningen University in 2005 and had defended his PhD thesis entitled “Exploring options for increasing water and nitrogen use efficiency in crop production systems” at Wageningen University on 6 Nov 2015.

Besides scientific training, he also played many important social roles in Wageningen. In the campaign of 2004, he was elected as a Board Member of the Student Council of Wageningen University. After that, he co-founded a company in the Netherlands in 2005, with the vision of linking business opportunities between Europe and China. He worked as Managing Director of the company from 2005-2008. Then, he returned to Wageningen University and worked as Junior Researcher at Department of Soil Quality, before pursuing a PhD at Wageningen University. From 2010-2011, he was the Chairman of Chinese Association of Students and Scholars in Wageningen (CASSW). At the same time, he was also the first international ambassador of Wageningen Alumni Network (KLV).

Publications

Qin, W., Hu, C., and Oenema, O. (Submitted). Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis.

Qin, W., Chi, B., and Oenema, O. 2013. Long-term monitoring of rainfed wheat yield and soil water at the Loess Plateau reveals low water use efficiency. Plos One.

Qin, W., Wang, D., Guo, X., Yang, T., and Oenema, O. (Submitted). Productivity and sustainability of a rainfed wheat-soybean cropping system in the North China Plain.

Qin, W., Assinck, F. B. T., Heinen, M., and Oenema, O. (Submitted). Water and nitrogen interactions in orange production: A meta-analysis.

Qin, W., Heinen, M., Assinck, F. B. T., and Oenema, O. (Submitted). Exploring optimal fertigation strategies for orange production, using combined soil-crop modelling.

Qin, W., Ma, L., Zhang, F. S., and Oenema, O. 2012. Urbanization affects water and nitrogen use in the food chain in China. Agro Environ 2012, Wageningen.

Bai, Z.H., Li, H.G., Yang, X.Y., Zhou, B.K., Shi, X.J., Wang, B.R., Li, D.C., Shen, J.B., Chen, Q., **Qin, W.**, Oenema, O., Zhang, F.S., 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant Soil 372, 27-37.

Bai, Z.H., Ma, L., **Qin, W.**, Chen, Q., Oenema, O., Zhang, F.S., 2014. Changes in Pig Production in China and Their Effects on Nitrogen and Phosphorus Use and Losses. Environ Sci Technol 48, 12742-12749.

Bai, Z.H., Ma, L., **Qin, W.**, Chen, Q., Oenema, O., Zhang, F.S., 2015. Changes in phosphorus use and losses in the food chain of China during 1950-2010 and forecasts for 2030. Nutrient Cycling in Agroecosystems.

Fan, L.X., Wang, F., Liu, G.B., Yang, X.M., **Qin, W.**, 2014. Public Perception of Water Consumption and Its Effects on Water Conservation Behavior. Water-Sui 6, 1771-1784.

Fan, L.X., Niu, H., Yang, X., **Qin, W.**, Bento, C., Ritsema, C., Geissen, V. 2015 Factors affecting farmers' behaviour in pesticide use: Insights from a field study in northern China. Science of The Total Environment 08/2015; 537:360-368.

Ma, L., Ma, W.Q., Velthof, G.L., Wang, F.H., **Qin, W.**, Zhang, F.S., Oenema, O., 2010. Modeling Nutrient Flows in the Food Chain of China. J Environ Qual 39, 1279-1289.

Ma, L., Velthof, G.L., Wang, F.H., **Qin, W.**, Zhang, W.F., Liu, Z., Zhang, Y., Wei, J., Lesschen, J.P., Ma, W.Q., Oenema, O., Zhang, F.S., 2012. Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005. Sci Total Environ 434, 51-61.

Ma, L., Wang, F.H., Zhang, W.F., Ma, W.Q., Velthof, G., **Qin, W.**, Oenema, O., Zhang, F.S., 2013. Environmental Assessment of Management Options for Nutrient Flows in the Food Chain in China. Environ Sci Technol 47, 7260-7268.

Ma., L., **Qin, W.**, Garnett, T, Zhang, F.S., (Submitted). Review on drivers, trends and emerging issues of the food wastes and losses in China. Frontiers of Agricultural Science and Engineering.

Qin, S., Wang, W., Zhao, Z., Clough, T., Luo, J., Li, S., Hu, C., Ma, L., Zhang, Y., **Qin, W.** (Submitted). Key management, meteorological, and soil parameters for direct N2O emissions: a meta-analysis.

Wei, S., Bai, Z., **Qin, W.**, Xia, L., Oenema, O., Jiang, R., Ma, L. (Submitted). Assessment of the sustainability of peri-urban pig production in Beijing.

Wei, S., Bai, Z., **Qin, W.**, Xia, L., Oenema, O., Jiang, R., Ma, L. (in preparation). Trade-offs analysis of farming system in peri-urban area in Beijing.

Xiang Y.J., Wang F.H., **Qin W.**, Ma L., et al. 2011. The enlightenment of United State nutrient management regulations to China (in Chinese), World agriculture, 383(3): 51-55.

Zhang J.J., Guo,C.X., **Qin, W.**, Zhang, Q. 2015 Spatiotemporal Analysis of Livestock and Poultry Production and Its Manure Nutrients in Shanxi Province during 1978-2012 (in Chinese). Chinese Journal of Applied Ecology.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Soil mulching significantly enhances yields and water nitrogen use efficiencies of maize and wheat: a meta-analysis (2015)

Writing of project proposal (4.5 ECTS)

- Exploring options for improving water and nitrogen use efficiency in crop production system

Post-graduate courses (4.6 ECTS)

- Soil ecology: taking global issues underground; WUR (2010)
- Introduction to R for statistical analysis; WUR (2013)
- Nutrients management workshop; China Agricultural University (2013)

Laboratory training and working visits (2 ECTS)

- High yield and high resources use efficiency; Shanxi and Anhui Academy of Agricultural Sciences (2013)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Agriculture, Ecosystems and Environment: long-term impacts of wheat fertilization on water and nitrogen interactions in a semi-arid profile (2010)

Deficiency, refresh, brush-up courses (6 ECTS)

- Ecological models and data in R (2013)

Competence strengthening / skills courses (4.5 ECTS)

- Project and time management; WUR (2011)
- Presentation skill – voice matters; WUR (2011)
- Scientific writing; WUR (2012)
- Writing grant proposals; WUR (2012)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Weekend (2011)
- PE&RC Day (2011)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- Workshop: managing livestock manure for sustainable agriculture; Wageningen (2010)
- Plant-soil interactions; Wageningen (2011)
- R users group; Wageningen (2013)

International symposia, workshops and conferences (4.5 ECTS)

- International symposium on P Dynamics in the plant-soil continuum; Beijing, China (2010)
- International workshop: Agro Environ; Wageningen, the Netherlands (2012)
- International workshop: 18^{th} N workshop; Lisbon, Portugal (2014)

Lecturing / supervision of practical's / tutorials (1.5 ECTS)

- Ecological models and data in R (2013)

The research described in this thesis was financially supported by Department of Soil Quality of Wageningen University, and by the EFFIDRIP project funded by the 7th Framework Programme of the European Union; EU FP7-SME-2011, grant 286807.

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Cover & Layout design: Agilecolor Design Studio/Atelier || www.agilecolor.com
Printed by: GVO drukkers & vormgevers B.V. || www.gvo.nl