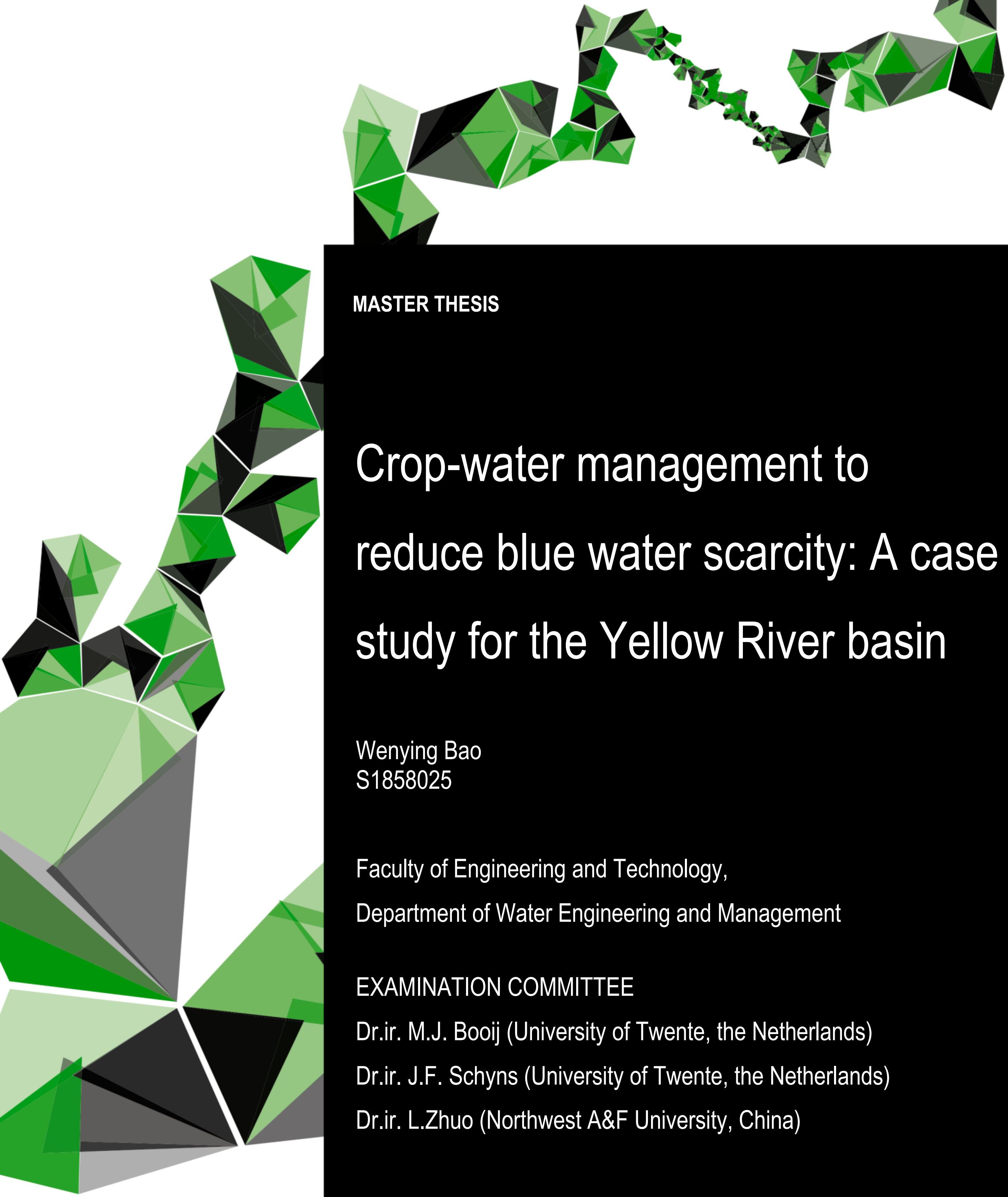

MASTER THESIS

Crop-water management to reduce blue water scarcity: A case study for the Yellow River basin

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Summary

Water scarcity in crop-intensive basins has raised wide attention as it threatens food security to meet the increasing global population demand. The Yellow River basin (YRB) is one of these basins that serve as a major food production basin but face severe blue water scarcity. Agriculture is the primary section for water use in the basin. Researchers have explored the reduction in the blue WF of crop production. But it is not clear how much contribution reducing the blue WF of crop production makes to alleviate the water scarcity in the YRB. This study aims to assess the blue water scarcity in the YRB and its alleviation by crop-water management.

The study is carried out in four steps. Firstly, we analyzed the reference blue water scarcity following the 'water footprint assessment' framework. The blue WFs of 17 crops in YRB is calculated in a 5*5 arcmin resolution at the dry (2006), the wet (2007), and the average year (2009). The generation of evapotranspiration (ET) and yield are through AquaCrop plug-in modeling. The blue ET is further separated from the AquaCrop output for blue WF calculation. Adding the blue water use from domestic and industrial sectors to the crop blue WF, the total blue WF is obtained. Then, the total blue WF is compared to the maximum available water in order to evaluate the blue water scarcity. The blue water scarcity is analyzed temporally (yearly and monthly) and spatially (grid cell) to have a comprehensive perspective of the blue water scarcity in the YRB. Secondly, two strategies that can best reduce the crop blue WF are formed. One strategy is to limit the irrigation water while maintaining stable yield by deficit irrigation and mulching. The other is to close the yield gap (the difference between observed yield and attainable yield in the region) by assuming the biophysical factors such as fertilizer, pesticides, and weed control to be optimized. Further, an additional scenario of each strategy is designed to adjust production to the reference level with proportional cropping area change. This additional scenario compensates for the change in total production brought by the two strategies and compares the blue WFs (m3) to the reference at the same level of production. Thus, the four scenarios in this study is formed as:

i) Strategy 1, area as the reference (S1).
ii) Strategy 1, area adjusted (S1AA).
iii) Strategy 2, area as the reference (S2).
iv) Strategy 2, area decreased (S2A-).

Thirdly, the blue water scarcity of the scenarios are then compared to the reference temporally (yearly and monthly) and spatially (grid cell). The effect of crop-water management on the blue water scarcity in the YRB is then assessed.

Results show that the yearly blue water scarcity in YRB is 47%, 47%, and 39% to the maximum available blue water in 2006 (dry year), 2007 (wet year), and 2009 (average year) respectively. It means that the YRB has severe blue water scarcity for 2006 and 2007, and significant blue water scarcity for 2009. The monthly blue water scarcity in YRB is severe from February to June in all three years. There are three months of the phase lag of available water to the total blue WF due to the mismatch of precipitation season and the cropping season. Spatially, half of the basin suffers from severe blue water scarcity throughout the whole year, and 70% of the area experiences different levels of blue water scarcity during the cropping season (from March to June). Winter wheat and maize, which cover 50% of the total blue WF from March to August, is noticeable. After applying scenarios to the crops in YRB, the blue WFs of crops are effectively reduced. In general, an average of 41%-44% of blue water (m^3) is saved over three years by applying S1, and 56%-58% of blue water (m^3) is saved by S2A-. The potential of water-saving aligns with the precipitation distribution temporally and spatially in scenario S1 and S1AA, and ranges from 0 to 80%. The potential of water-saving in S2A- is between 60% - 80% in most of the middle basin. The annual blue water scarcity is relieved by scenarios but cannot be solved entirely. S1 and S1AA can bring down the annual blue water scarcity one level down in all three years, and S2A- can bring down the annual blue water scarcity two levels down in 2006 and 2007, one level down in 2009. Scenarios flatten the peak water demand for cropping from March to June in all three years. Scenarios can also relieve 4-5 months (out of all the months in three years) from the level of water scarcity in which the total blue WF is more than 500% of the maximum available water. However, there are still five months each year that suffer from severe blue water scarcity under any of the scenarios, and these months align with the growing season. Scenarios relieve the water scarcity in the north and middle Inner Mongolia, middle Shaanxi province, and west of Qinghai province. Moreover, the month (October) with the lowest blue water scarcity under these scenarios shows a bimodal distribution. We can deduce that any blue water use can cause tremendous blue water scarcity in some areas due to the blue water's uneven spatial distribution.

There are many limitations to the study. For example, the choice of environmental water flow standard varies; the effect of reservoirs is not considered; the monthly blue water use data in industrial and domestic sectors are not available. However, this study is the first to assess the blue water scarcity in a finer resolution by bringing down the crop blue WF in the YRB. The results can be fundamental to understand where the blue water scarcity still needs to be improved and the direction of improvement.

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B	Biomass
CC	Canopy cover
CC_0	Canopy cover after sowing
CC_x	Maximum canopy cover
CCpot	Potential canopy cover
CDC	Canopy decline coefficient
CGC	Canopy growth coefficient
D	Soil water depletion
E	Evaporation
ET	Evapotranspiration
ET_0	Reference evapotranspiration
FC	Field capacity
f_m	Parameter for mulch material
HI	Harvest Index
HI_0	Reference harvest index
$Kc_{,Tr}$	Crop transpiration coefficient
K_e	Soil evaporation coefficient
K_s	Stress coefficient
K_{sat}	Hydraulic conductivity at saturation
Ks_{sto}	Water stress which can strike stomatal closure
PWP	Permanent wilting point
RDI	Regulated deficit irrigation
TAW	Total available water
T_r	Transpiration
$\sum T_r$	Cumulative amount of crop transpiration
WP^*	Normalized biomass water productivity
Y	Yield

1. Introduction

1.1 Background and the research gap

Water scarcity is the result of unbalanced water demand and supply. Water supply variability in time and space is mainly determined by the nature of precipitation and runoff (Postel et al., 1996). Climate change from the supply side is considered to have an overall negative impact on water availability (Kundzewicz et al., 2007). While some areas will receive more rainfall, most of the current water-scarce area will become drier and warmer. Meanwhile, more factors from the demand side, such as population growth and economic development, are becoming more dependent on water. Finite but fluctuating water resources versus increasing consumption result in increased water scarcity, and it is becoming a threat to the sustainability of humanity (Mekonnen & Hoekstra, 2016). Among all the water consumption, 92% relates to agriculture (Hoekstra & Mekonnen, 2012). As estimated by the Food and Agriculture Organization of the United Nation (FAO), the current agricultural production is expected to increase by more than 60% to feed the growing population by 2050 (Sadras et al., 2015). This emphasized the need to relieve the tension between agricultural water use and water availability. There are two ways to address the problem: one is to limit water consumption growth; another is to increase the efficiency of water use (Hoekstra, 2013). Limiting agricultural water may seem hard to practice with the ever-increasing food demand. Thus, the call for increasing the efficiency of crop water use, which is to decrease the water footprint (WF) of crop production, is of great importance to guarantee future food security and address the complication caused by climate change (Steduto et al., 2012).

Hoekstra (2014) pointed out that it is necessary to sustain an adequate amount of blue water for ecosystem development from the sustainability perspective. There should be a certain amount of water available in a river basin for environmental and ecological use. This part of the water is called environmental water flow requirements (EFRs). The maximum available blue water that humans can withdraw from a river basin is the natural runoff from the basin minus the environmental flow requirements (EFRs). When the blue water requirement of the basin exceeds the maximum available blue water, the river basin will start to face blue water scarcity.

Yellow River Basin (YRB) (Figure 1) is one of the river basins of the world that face water scarcity problems. YRB is the second-longest river in China, which has a total basin area of 795,000 m2. It holds only 3% of the world's water resources and has to feed a population of over 60 million. The irrigation area in YRB increased three-fold in 50 years, and agricultural water use 2.5 times (YRCC, 2019). The demand for water for industrial and domestic use increased even more rapidly from a lower basis. However, the Chinese government is concerned about food security for all time which is reflected by the agricultural policy. The government target to remain at least 95% food self-sufficiency as a part of the medium-to-long-term policy even when the demand for food continues to grow, and urbanization continues to swallow cultivated land. The growing competition for water resources in the basin is clear in the future (Cai & Rosegrant, 2004). According to Hoekstra et al. (2012), YRB faces blue water scarcity for 6-7 months a year during 1996-2005. This indicates that the exacerbated conflict between water availability and water consumption is inevitable in the basin.

There have been studies on assessing the blue water scarcity of the YRB (Zhuo et al., 2016, b; Xie et al., 2020). There have also been many studies on reducing the water use in crop production: deficit irrigation to increase the crop productivity (Chai et al., 2016); different combinations of irrigation strategy, irrigation techniques, and mulching to reduce the blue WF (Chukalla et al., 2015); partially changing cropping pattern to match the local condition in order to reduce the WF. But there are rare studies to assess the blue water scarcity after reducing the WF of a basin. Nouri et al. (2019) quantified the blue WF reduction by deficit irrigation plus mulching, and assessed the water scarcity alleviation temporally (yearly and monthly). Any similar assessment of the blue water scarcity alleviation has not yet been done to the YRB. Furthermore, there are rare studies which analyze the water scarcity change at a higher spatial resolution. Thus, this study aims to fill the research gap of assessing the blue water scarcity change of the YRB by reducing the blue WF in crop production. Compared to the previous water scarcity study, this study is performed temporally (yearly and monthly) and spatially at a high resolution. Since we focus on the water scarcity change, only the blue portion of the WF is considered. Green water is not relevant to address water scarcity.

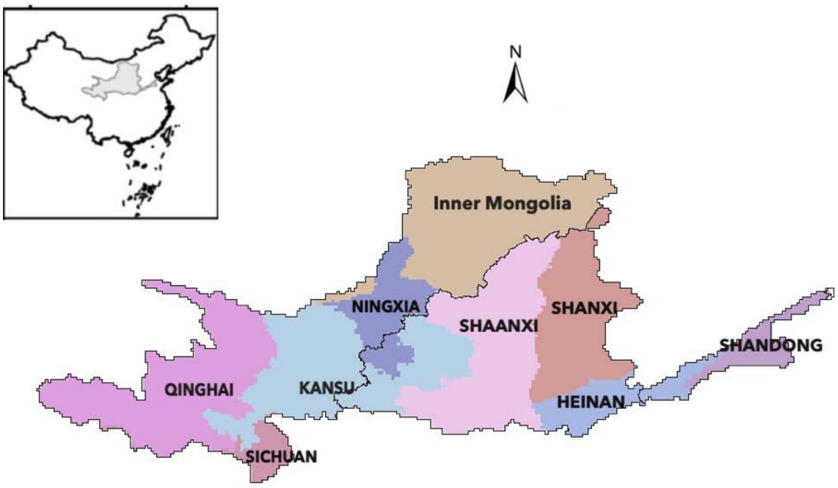


Figure 1: The Yellow River basin and its provincial districts, sub-basins, and location in China.

1.2 Research scope and objectives

The blue WF calculation is performed on major crops (17 crops) in YRB within 3 typical climate year (the dry year 2006, the wet year 2007, and the average year 2009). The crop blue WF is estimated through the AquaCrop model on daily basis at a resolution of a 5×5 arcmin. The current situation in 2006, 2007 and 2009 is defined as reference case.

Blue WF (m^3/t) is the crop water use divided by the yield. Reducing the WF can be attained by 'less drop per crop' or 'more crop per drop' (Blum, 2009). "Less drop per crop' refers to decreasing the crop water use while maintaining a relatively stable yield, while 'more crop per drop' is closing the yield gap while maintaining a constant crop water use. This study develops two strategies that fit in the range of 'less drop per crop' and 'more crop per drop' correspondingly.

Less drop per crop. Possibilities to decrease crop water consumption varies widely, including drip irrigation, deficit irrigation, changing irrigation techniques or irrigation strategies (Chukalla et al., 2015), breeding drought resistance crop (Hu & Xiong, 2014), etc. We focus on bringing down the WF with the current crops and the original planting date, limiting the options to field management, such as irrigation strategies, irrigation techniques, and mulching. Irrigation strategies are to make an irrigation plan, including when to irrigate and how much to irrigate (full irrigation, deficit irrigation, supplementary irrigation, or no irrigation). Irrigation techniques are how the water is applied to the field (furrow, drip, or sprinkler). Clemmens and Dedrick (1994) argued that all irrigation techniques could attain approximately the same level of water use. Despite this argument, the design of the irrigation system that serves the irrigation technique highly depends on the external circumstances of different regions such as the topography, soil characteristic, and financial approval. The uncertainty and specificity of designing the irrigation system over a large region are too high to consider. Deficit irrigation has been described as a crucial water-saving technology in agriculture (Chai et al., 2014). According to Chukalla et al. (2015), deficit irrigation has a larger potential to reduce the blue WF than other irrigation strategies like supplementary irrigation and full irrigation. Therefore, this study applies deficit irrigation as the irrigation strategy to bring down the blue WF in crop production. Mulching is field management that can reduce the soil evaporation, keep the soil fertility, preserve the soil temperature at the early sowing stages and therefore increase the crop yield (Shaxson & Barber, 2003). The increase in yield by mulching can offset the decrease in yield caused by deficit irrigation. Organic mulching is chosen together with the deficit irrigation as a strategy in order to bring down the crop water use while stabilizing the yield change.

More crop per drop. Integrative measures including the improvement of soil fertilization, pesticide control, land improvement can be considered to increase WP by increasing the crop yield (Pradhan et al., 2015). The yield gap is the difference between the maximum yield a crop can reach and the real yield of that crop in the field. Researchers pointed out that the global yield variability mainly results from differences in irrigation management, climate, and fertilizer use. The yield gap closing to 100% attainable yield is possible (Mueller et al., 2012). It is reasonable to assume that the potential yield can be obtained by applying a certain amount of fertilizer and pesticides. Therefore, the closing yield gap is chosen as a strategy to reduce the blue WF in crop production.

In summary, we designed two strategies in order to bring down the blue WF in crop production. They are: Strategy 1 (deficit irrigation + organic mulching); Strategy 2 (closing the yield gap). Two strategies are expected to influence yield, therefore increasing or decreasing the total production of each crop. The objective of this study is to assess at a higher resolution, whether bringing down the blue WF of crop production by crop-water management can solve the temporal and spatial blue water scarcity problem in YRB. The research question is then formed as:

To what extent can crop-water management relieve the water scarcity inter-annually and spatially in YRB?

Sub-questions:

⇒ How is the blue water scarcity temporally and spatially at the reference case?

⇒ What are the effects of the crop-water management strategies to the blue WF (in m^3/t and m^3)?

⇒ How will blue water scarcity change temporally and spatially to the crop-water management strategies?

1.3 Outline of the thesis

A brief explanation of the methodology and the data used is given in Chapter 2. This Chapter includes the general knowledge of AquaCrop, the blue WF calculation, the blue water scarcity indicator, and the set-up of the strategies. Chapter 3 presents the results of the reference blue water scarcity, the effect of crop-water management on the blue WF, and the changed of blue water scarcity by applying crop-water management strategies. In Chapter 4, a discussion of the results is given. Chapter 5 presents the conclusion of the study and the recommendations for possible directions related to this study.

2. Method and Data

2.1 Simulating evapotranspiration, blue WF, and yield with AquaCrop

The dynamic crop-growth model AquaCrop is developed to simulate the crop yield (Y) response to water (Steduto et al., 2012). As AquaCrop simulates ET and Y, WFs can be calculated with the output. The model runs daily, and the origins of the final ET can be traced back by examining the output data of crop growth and soil water balance. Meanwhile, the model has great advantages among crop growth models due to its simplicity, accuracy, and robustness (Steduto et al., 2009).

AquaCrop generates outputs for one growing season at a specific location every time it runs, and with the help of AquaCrop plug-in, AquaGIS or AquaData, scaled-up simulations are therefore feasible (Lorite et al., 2013). For this study, the plug-in version is implemented to simulate a wider spatial and temporal scale. In this section, a study of the AquaCrop model is present with the dynamic of soil water balance (Section 2.1.1), the crop growth simulation (Section 2.2.2), and the crop response to root zoon depletion (Section 2.1.3). After obtaining the evapotranspiration (ET) and yield from AquaCrop, the blue ET are separated. The blue WF is calculated based on the blue ET and yield (Section 2.1.4).

2.1.1 Soil Water Balance

The crop root zone in AquaCrop can be considered as a reservoir (Figure 2). AquaCrop calculates the amount of water stored in the root zone system by keeping track of the incoming water (rainfall, irrigation, and capillary rise) and outgoing water (evapotranspiration, deep percolation, and runoff) within its boundary, and the amount of water stored in the root zone at any moment can be quantified using soil water balance (Raes et al., 2009). AquaCrop performs a daily water balance within the root zoon system. To model the movement of water added to the soil layer and the water subtracted from the soil layer, AquaCrop uses parameters like drainage coefficient and hydraulic conductivity at saturation (K_{sat}) within the boundary of permanent wilting point (PWP) or the lower limit of water holding point, and field capacity (FC) or the upper limit of water holding capacity. The maximum amount of water that can infiltrate into the soil is limited by the hydraulic conductivity of the topsoil layer (Raes et al., 2012). Excess water is lost as surface runoff and is estimated by the curve number method developed by the US Soil Conservation Service (USDA, 1964).

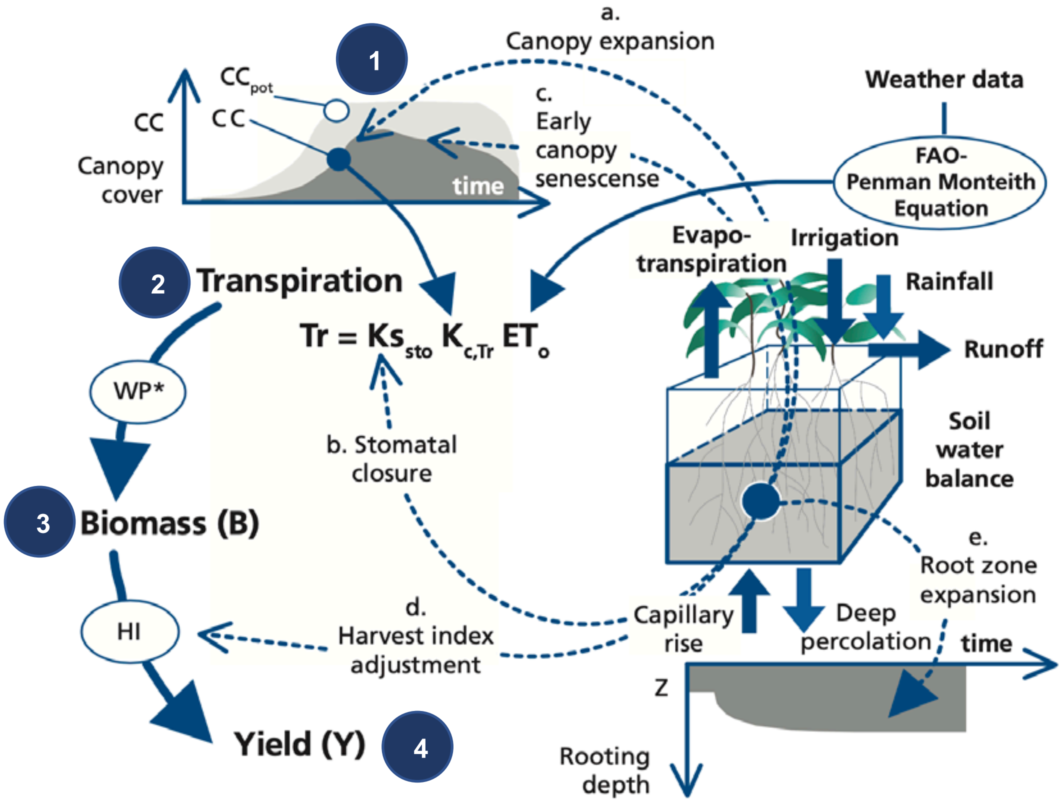


Figure 2: Crop growth scheme simulated in AquaCrop showing the root zoon as a reservoir with water inflowing and outflowing, the crop growth in four steps, and the process (dotted lines) affected by water stress (a-e). CC is the canopy cover, CC_{pot} is the potential canopy cover, ET_0 is the reference evapotranspiration, Ks_{sto} is the water stress which can strike stomatal closure and $Kc_{,Tr}$ is the crop transpiration coefficient (influenced by CC), Source: Steduto et al. (2012)

2.1.2 Crop Growth Simulation

The crop growth engine AquaCrop simulates the crop growth in four steps (Figure 2).

1) First, AquaCrop simulates crop development through canopy cover (CC) expansion. CC is the fraction of soil surface covered by crop canopy. The value of CC varies from its original sowing density to the maximum canopy that covers the soil (almost 100% depending on crop type). The canopy development without limiting conditions (CC_{pot} in Figure 2) is modeled by the initial canopy cover after sowing (CC_0), the canopy growth coefficient (CGC), and the maximum canopy cover reached (CC_x). After the crop starts senescence, the canopy decline coefficient (CDC) will be applied to the simulation. Therefore, the water stress coefficient K_s, if existing, acts on CGC when canopy develops, and on CDC when canopy declines.

2) The second step of the crop growth engine is to simulate the crop transpiration. AquaCrop separates the actual evapotranspiration (ET) into soil evaporation (E) which is the non-productive water flux and crop transpiration (T_r) which is the productive water flux. Crop transpiration without stress limitation is proportional to the canopy cover and corrected by interrow microadvection and sheltering effect from partial canopy cover. When water stress and waterlogging induce stomatal closure, parameters will be applied further to adjust the crop transpiration. The separation of ET avoids the role of nonproductive use of water (which is the

evaporation to the environment) at the core procedure of crop growth simulation: the simulation of above-ground biomass (B).

The soil evaporation (E) is calculated by multiplying ET_0 with factors: the evaporation reduction coefficient related to water stress, and the soil evaporation coefficient K_e which is proportional to the soil surface that is not covered by the canopy. The moisture at the soil surface not covered by canopy determines the soil evaporation in two stages: energy limiting stage (stage I) and falling rate stage (stage II) (Ritchie, 1972). At stage I, the soil surface layer is wet when rainfall occurs, or water is supplied by irrigation. The evaporation rate is only affected by the energy available for soil evaporation as long as readily available water (RAW) remains in the surface layer. RAW then represents the maximum total depth of water that can be evaporated during the stage I (Allen et al., 1998). After all the RAW is evaporated, the soil evaporation will switch to stage II. At this stage, the evaporation rate is determined simultaneously by the available energy and hydraulic properties of the soil. Evaporation stops when total available water (TAW) from the topsoil is depleted.

The soil evaporation coefficient K_e is also adjusted further by the withered canopy, mulches, and partial wetting by irrigation. AquaCrop can simulate the effect of mulching on evaporation by a correction factor which is determined by two variables: soil surface covered by mulch (from 0% to 100%) and the mulching material (f_m). The parameter f_m varies between 0.5 to 1 from organic mulching material to plastic mulching material (Allen et al., 1998). During the modeling process, these two variables can be specified in the field management section and hence correct the calculation of evaporation by mulching. It also enables researchers to study the evaporation reduction by mulching and water savings under various mulching conditions.

3) Above-ground B at the end of the season is obtained by multiplying the normalized biomass water productivity (WP*) to the cumulative amount of crop transpiration (ΣT_r). Water productivity (WP) tends to be constant at a given climatic condition and a given crop species after normalization (Hanks, 1983; Tanner and Sinclair, 1983). Normalization of biomass water productivity accounts for the evaporative demand of the atmosphere which is also known as ET_0 and air carbon dioxide concentration ($[CO_2]$).

4) Crop yield (Y) is then derived by partitioning the B into a yield part (Y) using Harvest Index (HI). The HI is obtained by adjusting the reference harvest index (HI_0) with an adjustment factor of all types of stresses combined. HI_0 is a portion of B that is harvestable and should be specified by cultivators and researchers according to the crop species in the local field.

2.1.3 Crop Response to Root Zoon Depletion

There exist many stresses that can influence the crop growth in AquaCrop, for example, the air temperature stress on crop transpiration and pollination, water stress as a-e in Figure 2., soil fertility or salinity on CGC, etc. Among all the stresses, water stress and its impact on crop growth is our greatest concern, since the research tests will be developed base on the crop responses to water stress. Three processes are happening to have an impact on crop growing period: water stress that can restrict canopy expansion, water stress that can cause early senescence, and water stress that can induce stomatal closure. Water stress related to the canopy expansion rate happens mostly during the initial and development growing stage, stomatal closure happens throughout the life cycle, and senescence acceleration happens at the later development stage.

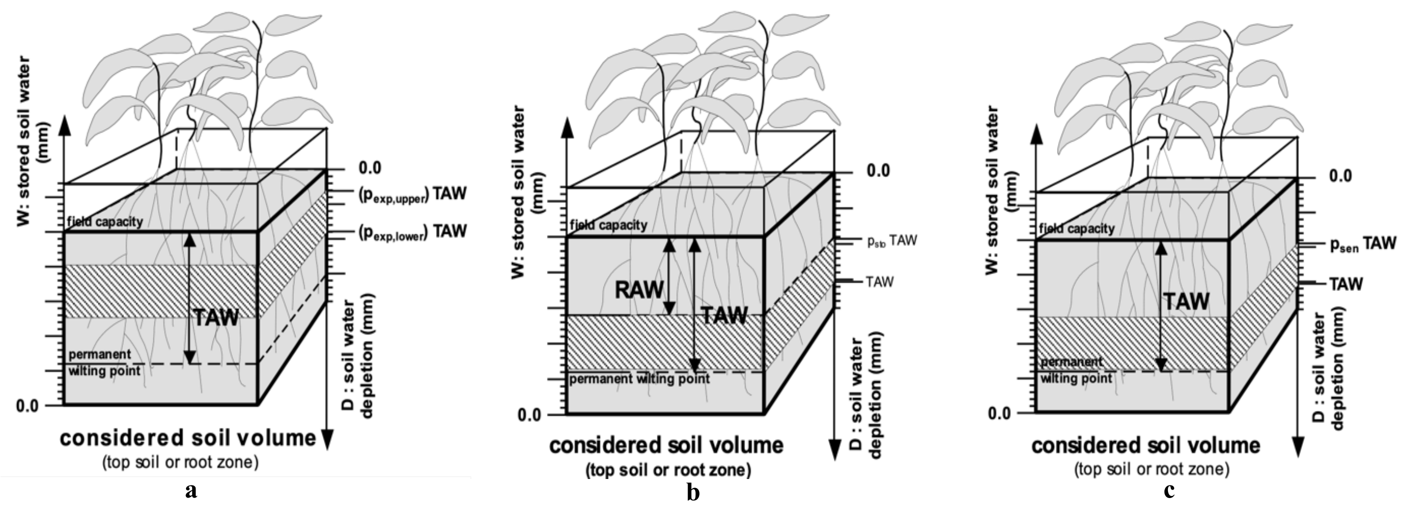


Figure 3: Upper and lower limit of root zoon depletion affecting (a) canopy expansion rate, (b) stomatal closure and (c) early senescence due to water stress. Source: Raes et al. (2012).

The indicator of water stress is the soil water depletion (D)(mm) in the root zone. Soil water depletion refers to the amount of water that is required to bring the soil water content back to FC in the considered soil volume. As we explained in section 2.1.1, root can be simplified as a reservoir, the upper boundary and lower boundary to store soil water are FC and PWP. The amount of water a crop can theoretically extract from the considered volume of soil is the water stored between FC and PWP, which is also known as total available water (TAW). But when root depletes to a certain level which is expressed as a fraction to TAW in AquaCrop, crop growth will respond correspondingly to the depletion. Figure 3 shows the depletion thresholds of the three processes in the simplified root zoon system. Water stress starts to affect the processes when the root zoon depletion reaches the upper limit of the depletion threshold and at its full strength when reaching the lower limit of the depletion threshold. The canopy expands at the maximum rate when there is no water limitation during the crop growing period. The expansion rate begins to fall below the maximum rate when root zoon depletion triggers the upper threshold of limiting crop expansion, which is ($p_{exp,upper}$)TAW, and the expansion stops completely when the root zoon depletion meets the lower threshold, ($p_{exp,lower}$)TAW (Figure 3a). Water stress yet prevents the maximum canopy cover (CC_x) to be reached and results in a smaller size of final CC. In AquaCrop, further depletion beyond the lower threshold has no additional effect on the previous basis of limiting crop growth. Early canopy senescence will occur as root zoon depletion in the considered soil volume exceeds the upper threshold, (p_{sen}) TAW (Figure 3c). Once the depletion reaches the lower limit which is the PWP for this process, the canopy decline is at full speed. Water stress, therefore, accelerates the canopy senescence process and reduces the crop cycle. Root zoon depletion can affect crop transpiration and root deepening by triggering stomatal closure, and in AquaCrop this process begins when root zoon depletion exceeds (p_{sto})TAW. The stomata are completely closed, and the crop transpiration is terminated when soil water content reaches its lower limit, PWP (Figure 3b). Transpiration is the main mechanism to form biomass, and hence water stress can result in less biomass by provoking the stomatal closure. Studies show that the process that is the most sensitive to water stress is canopy expansion, the least sensitive is stomatal conductance. And the sensitivity of senescence is slightly less than stomatal conductance depending on the species (Bradford & Hsiao, 1982). The effect of water stress on the crop is described by stress coefficients (K_s) accordingly when root zoon D reaches the upper limit and K_s acts as a modifier on current model parameters.

Users can implement various water supply options from rainfed to irrigation with different application methods (furrow, drip, or sprinkler) in AquaCrop. By irrigation, users can specify the date and depth of each application or let the program generate its irrigation schedule by setting some criteria. The criteria of the date can be a fixed interval or a period that allows soil water level to deplete to a certain value (mm) or a certain percentage of total available water; the criteria of depth can be a fixed depth (mm) or a recovery to field capacity. Hence, the program allows users to test deficit irrigation by applying certain amounts of irrigation water to the crop and develop an optimized irrigation plan at different stages of the crop growing cycle.

2.1.4 Post-processing of AquaCrop output to obtain blue WFs

Separating the blue component. The AquaCrop output is further processed to separate the blue water component from the incoming and outgoing water fluxes and the soil water content. As explained in section 2.2.1, the root zoon is simplified as a reservoir, and the daily incoming and outgoing water fluxes are tracked:

$$S_{(n)} = S_{(n-1)}+P_{(n)} + I_{(n)} + CR_{(n)} - ET_{(n)} - RO_{(n)} - DP_{(n)} \quad (1)$$

where $S_{(n)}$ is the soil water content at the end of day n and S_{n-1} is the soil water content at the end of the previous day. $P_{(n)}$ (mm) is the precipitation during the day and it adds to the green soil stock, $I_{(n)}$ (mm) is the irrigation on that day and it adds to blue soil water stock, $CR_{(n)}$ (mm) is the capillary rise from the groundwater and it adds to the blue soil water. $CR_{(n)}$ is assumed to be 0 in this case since the groundwater table is considered much larger than 1m (Allen et al., 1998). $ET_{(n)}$ (mm) represents the actual evapotranspiration during the day and $DP_{(n)}$ (mm) represents the deep percolation. The partition of the blue component of ET and DP is decided by the fraction of blue soil water content to the total soil water content at the end of the previous day. $RO_{(n)}$ (mm) refers to the surface runoff which is generated from irrigation or rainfall due to soil saturation. The blue component of RO_n is proportional to the amount of irrigation segment in the total amount of rainfall and irrigation. Thus, the blue soil component is derived from revising equation (1) as follow:

$$S_{blue(n)} = S_{blue(n-1)} + I_{(n)} - RO_{(n)} \times \frac{I_{(n)}}{I_{(n)}+P_{(n)}} - (DP_{(n)} + ET_{(n)}) \times \frac{S_{blue(n-1)}}{S_{(n-1)}} \quad (2)$$

where $S_{blue(n)}$ is the blue soil water content at the end of the day and the $S_{blue(n-1)}$ is the blue soil water content at the end of the previous day.

Calculating the WF. After separating the blue ET, blue WF can be computed. This is done with the water footprint accounting framework described by Hoekstra et al. (2011). Per grid cell per crop, the blue water footprint (WF_{blue}, m^3/t) is calculated as the blue crop water use per area (m^3/ha) during the growing period divided by crop yield (Y, t/ha) within the grid cell. The blue crop water use per area is calculated by accumulating the daily blue evapotranspiration (ET_{blue}, mm/day) over the growing period:

$$WF_{blue} = \frac{10000m^2 \times \sum_{d=1}^{lgp} ET_{blue}/1000}{Y} \ (m^3/t) \quad (3)$$

in which 1ha = 10000 m^2. The blue crop water use (CWU_{blue}, m^3) per crop within one grid cell is determined as the accumulated ET_{blue} (m^3/ha) multiplied with the corresponding harvest area (H, ha) of the crop within the grid cell:

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET \times H \ (m^3) \quad (4)$$

Therefore, the blue water footprint is finally separated and calculated for the growing season.

Initializing soil water content. Soil water content is initialized to make the simulation results more valid. The initial soil water content is determined following the settings and assumptions from Zhuo et al. (2016, b) which is also quoted from Siebert et al. (2010). The initial soil water content is derived from running the software two years before the actual sewing date with a maximum soil water content at the beginning under fallow condition. The initial soil water content is assumed to be green water at the start of the initializing run.

2.2 Blue water scarcity

Blue water scarcity is defined as the ratio of total blue WF (m^3) to the maximum available blue WF(m^3) in the catchment during a certain period. The maximum available blue WF is the water volume that can be used in one basin for human activities. The maximum available blue WF in a river basin can be translated as the natural runoff(m^3) minus the environmental flow requirement which is the water required to maintain a sustainable environment (Hoekstra et al., 2012):

$$BWF_{max} = R_{nat,m} - EFR_m \tag{5}$$

where $R_{nat,m}$ represents the monthly natural runoff of the river basin and EFR_m is the monthly environmental flow requirement. The EFR_m can be conservatively estimated as 80% of the $R_{nat,m}$ according to Richter et al. (2012). There are also discussions on the decision of EFR_m which we will discuss in Section 4.1. The maximum available blue WF is thus around 20% of the natural runoff of the grid cell plus the natural runoff from upstream grid cells minus the blue WFs of upstream grid cells. Total blue WF consists of agricultural water, industrial water, and domestic water. The blue water scarcity indicator as a value can illustrate water sustainability in a basin. The blue water scarcity values are classified into four levels to clarify the water scarcity levels (Hoekstra et al., 2012):

- Low: the blue WF is smaller than 100% of the maximum available blue WF.
- Moderate: the blue WF is between 100%-150% of the maximum sustainable blue WF.
- Significant: the blue WF is between 150%-200% of the maximum sustainable blue WF.
- Severe: the blue WF is larger than 200% of the maximum sustainable blue WF.

The monthly blue WF availability is calculated at a 5×5 arc min grid in this study. Monthly natural runoff of the YRB can be extracted from the hydrological model PCR-GLOBWB (Beek et al., 2011; Wada & Bierkens, 2014; Wada et al., 2011) at 6×6 arcmin resolution, and is resampled to 5×5 arc min resolution. The total blue WF of YRB is estimated by summing the blue WFs from agriculture and the blue WFs from industrial sectors and domestic use. The annual agricultural water consumption in 2006 accounts for 73.9% of the total water consumption from the YRB. Industrial and domestic water consumption occupied around 15% of the total yearly water consumption. Here, we assume little monthly variation in water consumption of industrial and domestic use, and the annual data is evenly distributed to 12 months. This is also similar to the approach used by Zhuo et al. (2016, b). The annual blue water consumption of industrial and domestic use in YRB is available from YRCC (2019).

2.3 Formation of the two strategies and four scenarios

With the AquaCrop modeling and the WF calculation study, we perform the blue WF simulations and the blue water scarcity assessment with the reference case and reduction strategies. The reference case is calculated based on the current agricultural situation in 2006, 2007, and 2009 in YRB. The formation of the two strategies is explained in Section 2.3.1. Strategy 1 is to irrigate less while maintaining a stable yield. Strategy 2 is to close the yield gap by assuming optimized field management in fertilizer use, pesticide use, and weed control. We expect the yield change by applying two strategies. The blue WF saving (m^3) of strategy 1 might be at the cost of total production loss. And for strategy 2, the same amount of blue water is applied to reach increased production. In order to compare the blue WF (m^3) of the reference and two strategies in the same production level, an additional scenario is developed to compensate for the production change by enlarging or narrowing down the total cropping area. Therefore, four scenarios which including the two strategies, are developed (Section 2.3.2). Figure 4 illustrates the simulation settings of the two strategies and four scenarios.

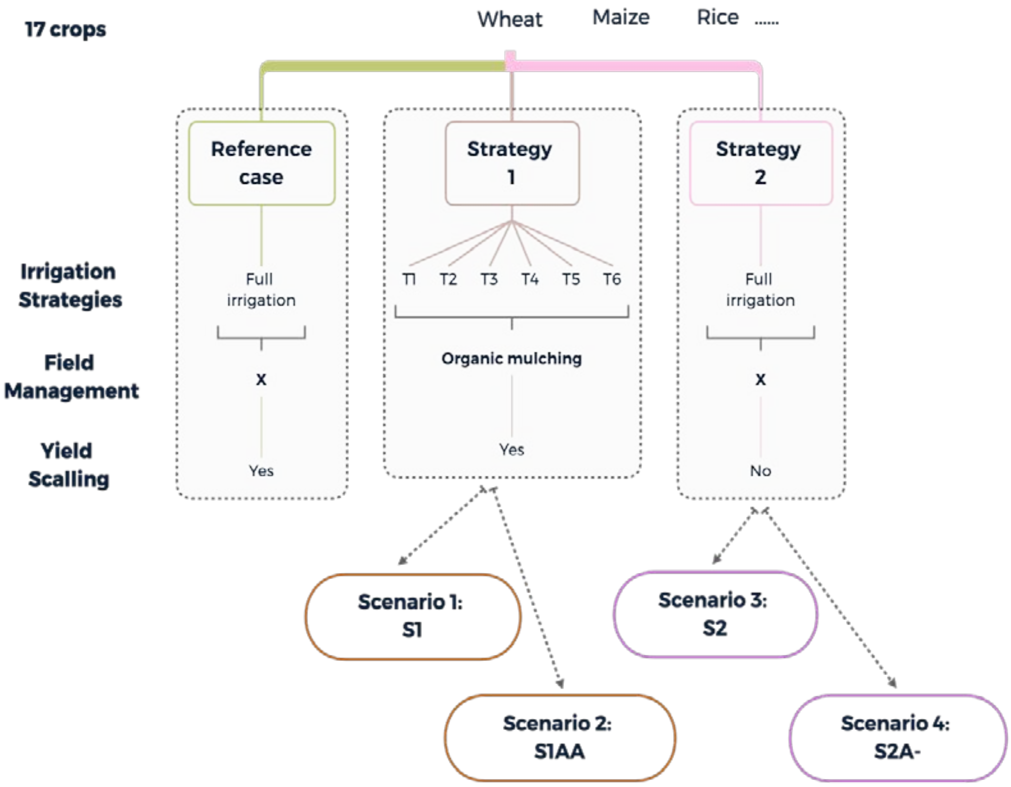


Figure 4: Structure visualizing how strategies and scenarios are set up. T1, T2, T3, T4, T5, T6 represent the irrigation strategy tests applied on strategy 1. X means no field management applied. S1 means strategy 1, S1AA means strategy 1 with area adjustment, S2 means strategy 2, S2A- means strategy 2 with area reduction.

2.3.1 Formation of the two strategies

Reference case: WF of actual circumstances in YRB

The reference case is the crop growth situation in the YRB each year. For the same crop species, no irrigation (rain-fed) is used in some of the areas in YRB, but irrigation is applied to the other parts. Therefore, for each species, the simulation of the rain-fed and the irrigated crop are separated. The irrigated crop in the reference case is simulated under full irrigation. Field management is not considered in the reference case. AquaCrop is proven to simulate reasonable final yield under different irrigation strategies (from deficit irrigation to full irrigation) (Linker et al., 2016). The yield is scaled up to match the actual yield. This compensates for not considering other stresses like soil salinity and nutrient stress during the simulation. The scaling method is described in section 2.5.

Strategy 1: WF reduction through deficit irrigation together with field management

Similar to the reference case, the rain-fed part and irrigated part from one crop species are simulated separately. By applying deficit irrigation, a significant reduction in water consumption and less yield loss are expected compare to the reference case. Making irrigation plans are to answer the question of how much and when to irrigate.

How much to irrigate. The key to applying deficit irrigation is to irrigate below the ET requirements without harming the crop development or in other words, not to trigger the early senescence (Playán & Mateos, 2006). Yet the crop sensitivity to water stress differs at different growing stages. An optimized deficit irrigation schedule that considers the sensitivity of different crop growth stages and various crop types helps the crops to be exposed to reasonable levels of water stresses without decreasing much on the yield. This is titled as regulated deficit irrigation (RDI). For crops, limiting the reproductive and vegetative stage of crop growth has less effect on final yield formation. To operate RDI as such, the precise knowledge of crop response to drought at each growing stage is required (Kirda et al., 1999). Therefore, the drought sensitivity of 17 crops in the YRB is studied. The crop growth stages responding to water stress in this study are defined as drought-sensitive phase and drought-tolerant phase. The drought-sensitive phase and drought-tolerant phase at four distinct growth stages are selected from previous literature and the information is summarized in *Table 1*. Crop growing stages are roughly divided in to four stages: the initial stage, the developing stage, the middle-season stage and the late-season stage following.

Table 1: Summary of drought-sensitive phase and drought-tolerant phase of 17 crops from YRB at four growth stages. L_{ini}, L_{dev}, L_{mid} and L_{late} represents the initial stage, the developing stage, the middle-season stage and the late season stage separately.

🟥 Drought-sensitive 🟩 Drought-tolerant

Crop	**Relative Crop Growing Stage**				**References**
	L_{ini}	L_{dev}	L_{mid}	L_{late}	
Rice	🟩	🟩	🟥	🟩	Sarvestani et al. (2008)
Spring Wheat	🟩	🟥	🟩	🟩	Zhang et al. (2006)
Winter Wheat	🟩	🟥	🟩	🟩	Zhang et al. (2004); Sun et al. (2006)
Maize	🟩	🟥	🟥	🟩	Huang et al. (2002)
Millet	🟩	🟩	🟥	🟩	Fazel et al. (2010)
Sorghum	🟩	🟩	🟥	🟩	
Barley	🟩	🟩	🟥	🟩	
Soybeans	🟩	🟩	🟥	🟩	Kirda et al. (1999)
Potato	🟩	🟩	🟩	🟥	Iqbal et al. (1999)
Sweet Potato	🟩	🟩	🟩	🟥	
Peanuts	🟩	🟩	🟥	🟩	Ahmad (1999)
Rapeseed	🟩	🟩	🟥	🟥	Champolivier and Merrien (1996)
Sunflower	🟩	🟥	🟥	🟩	Karam et al. (2007)
Cotton	🟩	🟩	🟥	🟩	Kanber et al. (2006); Kirda et al. (1999)
Sugarcane	🟩	🟩	🟥	🟩	Pene (1995)
Tomato	🟩	🟩	🟥	🟥	Marouelli and Silva (2007)
Apple	🟩	🟩	🟩	🟥	

When to irrigate. As explained in 2.1.3, AquaCrop can develop its irrigation scheme by setting the irrigation appliance date as the soil water level is depleted to a certain value (mm). When soil water depletes to a certain level, canopy growth and crop transpiration will start to be affected. With water going away from the soil, first the depletion level reaches the upper threshold of slowing down the canopy growth, then induces the upper threshold of stomatal closure. At the later development stage, water stress will finally trigger the threshold of early canopy senescence. In this study, the upper thresholds of these responses are determined based on the thresholds of several default crops and the corresponding soil texture in AquaCrop: for net irrigation, the water that is allowed to be depleted in the root zone is set to 50% of RAW as in default; the depletions that affect the leaf expansion range between 20% to 60% of RAW; the depletions that induces the stomatal closure are set at 100% RAW; the depletions that cause early canopy senescence mostly range from 80%-130% except for wheat which the upper threshold can reach 170% of RAW. Applying RDI is to irrigate less at drought-tolerance stages which may reduce normal plant growth but cause minimum yield loss. To determine a better combination of how much depletion at the drought-sensitive stage and how much depletion at the drought-tolerant stage throughout the growing season, a series of tests are designed. Irrigation applied at the drought-sensitive stage is when 80% or 100% of RAW is depleted. Delay of irrigation may result in stomatal close and affect yield formation at this stage (Geerts & Raes, 2009). Irrigation applied at the drought-tolerant stage is when 100%, 120%, or 140% of RAW is depleted and early canopy senescence can be avoided at this stage for most of the crops. Each irrigation application restores the soil water content to FC. Therefore, the best irrigation strategy for each crop is to decide from the results of the 6 experimental tests (Table 2).

Mulching. Mulches can be organic or synthetic. Organic mulches are made from degradable organic materials. Synthetic materials consist of plastic sheets or other materials. According to Chukalla et al. (2015), organic mulching reduces the blue WF considerably, and synthetic mulching further. Choices of organic or synthetic mulch are personalized, but using organic mulch means using materials available in the field (Ranjan et al., 2017). Compared to synthetic mulching, the sustainability of organic mulching on the environment is higher since the degraded and broken-down organics help with soil fertilization. Here in this study, organic mulching is adopted as field management for all 17 crops to reduce the soil water loss. In AquaCrop simulation, the variables of organic mulching are settled as that 80% of the soil is covered and 50% of soil evaporation is reduced by organic mulching.

Table 2: Six experimental tests designed for strategy 1 to decide the best irrigation strategy.

Tests	**Soil water depletion when irrigation applies**	
	Drought-sensitive phase	Drought-tolerant phase
T1	80% RAW	100% RAW
T2	80% RAW	120%RAW
T3	80% RAW	140%RAW
T4	100% RAW	100% RAW
T5	100% RAW	120%RAW
T6	100% RAW	140%RAW

The yield is scaled up by the scaling factor (section 2.4) obtained from the reference case. Therefore, 6 experimental tests as irrigation strategies, organic mulching as field management, and yield scaling are operated per crop. The best-practice is therefore defined as the combination that results in the lowest blue WF.

Strategy 2: WF reduction through removing non-water stress

Default settings in AquaCrop assume no other stresses occurring if no constraints are provided and thus the yield AquaCrop estimated is the optimized yield without stress interfere. We only considered water stress in estimating the reference blue WF before scaling up to the actual yield. The yield from AquaCrop direct output of the reference case is thus the practice we are looking for strategy 2 (Figure 4), since the simulate yield is only water-stress related and other stresses are considered optimized (temperature stress exist but remain stable for all reference and the strategies). Similar to strategy 1, the test is operated at the dry (2006), the average (2009), and the wet year (2007).

2.3.2 Formation of the four scenarios

In this section, the formation of 4 scenarios will be explained. The scenarios are the extension from the strategies. Scenario 1 and scenario 2 are developed based on strategy 1. Scenario 3 and scenario 4 are developed based on strategy 2 (Figure 4). An overview of the 4 scenarios is given in Table 3.

Table 3: Overview of the settings of 4 scenarios and their abbreviations.

Scenarios	**Related strategy**	**Land Control**	**Abbreviations**
Reference	Reference case	Area harvested unchanged	
Scenario1	Strategy 1	Area harvested unchanged	S1
Scenario2		Area harvested adjusted to match the reference production	S1AA
Scenario3	Strategy 2	Area harvested unchanged	S2
Scenario4		Area harvested decreased to match the reference production	S2A-

Applying RDI to crops is expected to bring production loss for strategy 1, and optimizing non-water related stresses are expected to increase production for strategy 2. Scenario 1 is the original strategy 1 with the expected production loss. We mention scenario 1 as S1 in the following text as it is strategy 1. The percentage of production lost or gained by scenario 1 compared to the reference case is compensated by enlarging or narrowing the cropping area to reach the reference production level. The crop on the expanded or narrowed land is assumed to have the average yield and average crop water use of the crop. Therefore scenario 2 is strategy 1 with cropping area adjusted, written in the following text as S1AA. Scenario 3 is originally strategy 2 with the expected yield gain, written as S2. The formation of scenario 4 is similar to the formation of scenario 2. The percentage of production which is larger than the reference case is reduced by cutting back a certain extent of the cropping area to meet the same production. Therefore, in scenario 4, producing the same amount of food requires less land as in reference and thus further saves the blue water that is required to irrigate the land. Scenario 4 is represented by S2A- which means it is strategy 2 with area reduction. The four scenarios are then formed as S1, S1AA, S2, S2A-.

2.4 Data

A GIS polygon of the YRB and drainage direction is extracted from HydroSHEDS at 30×30 arcsec (Lehner et al., 2008). Precipitation, temperature, and reference ET_0 data are obtained at 30 arcmins from CRU-TS-3.100.01 (Harris et al., 2014) on a monthly basis, and the interpolation method is used to downscale the monthly data to daily data regarding the weight of ET_0 and temperature at the previous month. According to YRCC (2019), the average groundwater table depth in YRB at the end of the year is 2m minimum. Therefore, the capillary rise is assumed to be 0 in this study (Allen et al., 1998). Soil texture is gathered at $10km^2$ scale from ISRIC Soil and Terrain Database for China (Dijkshoorn et al., 2008). Indicative values by AquaCrop for soil hydraulic characteristics are used. The spatial distribution of soil water capacity at 5arcminn is collected from Batjes (2012). The irrigated area and the rain-fed area of each crop spatially are obtained from Monfreda et al. (2008) and Portmann et al. (2010). Irrigated and rain-fed data is provided in only 2000, so the data required for 2006, 2007, and 2009 are deducted corresponding by scaling up the harvest area from Chinese Agriculture Yearbook (2000). Yearly areas and yields are also scaled up to match the provincial yearly statistic from NBSC (2018), yet yearly areas and yields for tomatoes are obtained from FAOSTAT (FAO, 2014). Table 4 shows a summary of the data used by this study.

Crop growing stages, HI_0, and max. rooting depth. Researchers (Vanuytrecht et al., 2014) found that the simulated yield of AquaCrop is sensitive to root and soil parameters. Therefore, to achieve better accuracy in running the simulations, parameters that are highly related to local geographical conditions are selected carefully from various sources as Zhuo et al. (2016, b) did. Planting date and crop growing stages differ with location, climate, and crop gene type. Zhuo et al. (2016, b) studied the green, blue, and grey WF of major crops in YRB over 1961- 2009 with AquaCrop. The same parameters of planting date, length of crop growth stages, HI_0, and maximum rooting depth can be used in this study. The parameters and values are listed in Appendix I.

Table 4: A summary of data types and resources for this study.

Dataset		**Description**	**Source**	**Resolution**
Geographical Information	Grid of YRB	Information		5 arcmin
Land	Irrigation and rain-fed area	Distribution	Portmann et al. (2010); Monfreda et al. (2008)	5 arcmin
Climate	Reference ET0	Distribution	CRUTS-3.10.01, Harris et al. (2014)	30 arcmin Monthly
	Precipitation			
	Max. & Min. Temperature			
Soil	Soil texture	Distribution	Dijkshoorn et al. (2008)	$10km^2$
	Groundwater table depth	Information	YRCC (2019); Allen et al. (1998)	
Crop	Area	Numerical distribution	Agriculture Yearbook (2000); NBSC (2018)	National Annual
	Max. rooting depth	Parameters	Allen et al. (1998); Chapagain & Hoekstra (2004)	
	Sowing date		Chen et al. (1995)	
	Growing cycle		Allen et al. (1998); Chapagain & Hoekstra (2004)	
	Harvest Index		Xie et al. (2011); Zhang and Zhu (1990)	
Initial Condition	Soil water capacity	Distribution	Batjes (2012)	5 arcmin
Calibration	Yield	Numerical distribution	Agriculture Yearbook (2000), NBSC (2018)	National Annual

Max. sustainable WF	Natural runoff	Hydrological model	Beek et al. (2011)	6 arcmin
			Wada and Bierkens (2014)	
			Wada et al. (2011)	
Blue WF of industrial and domestic	The blue water consumption of domestic and industrial	Numerical	YRCC (2019)	

Dry weight to fresh weight and yield calibration. The yield generated by AquaCrop is calculated as the dry weight of the crop. Dry weight means that the water content in the crop is not considered. However, we often use fresh weight when calculating the statistical yield. The dry weight has to be converted to the fresh weight by a conversion factor. The actual yield of crops can be much higher than the AquaCrop simulated yield, especially for fruit and vegetables. Thus, the conversion from dry weight to fresh weight is essential. The conversion factors from fresh weight to dry weight are chosen from Fischer et al. (2012) and the values are listed in Appendix II. The converted yield is then scaled up by the provincial statistic from NBSC (2018) for the reference case. For each province in each year, a scaling factor S_f is given as:

$$Y_{n\_cal} = Y_{n\_sim} \times S_f \tag{6}$$

$$S_f = \frac{Y_{statistic}}{Y_{Simulated}} \tag{7}$$

where Y_{n_cal} is the calibrated yield at *n*th grid of a crop and Y_{n_sim} is AquaCrop simulated yield at *n*th grid. $Y_{statistic}$ is the provincial statistical yield from NBCS (2018) and $Y_{Simulated}$ is the sum of the AquaCrop yield of the grids belong to this province.

3. Results

3.1 Blue water scarcity of the reference case

3.1.1 The yearly blue water scarcity

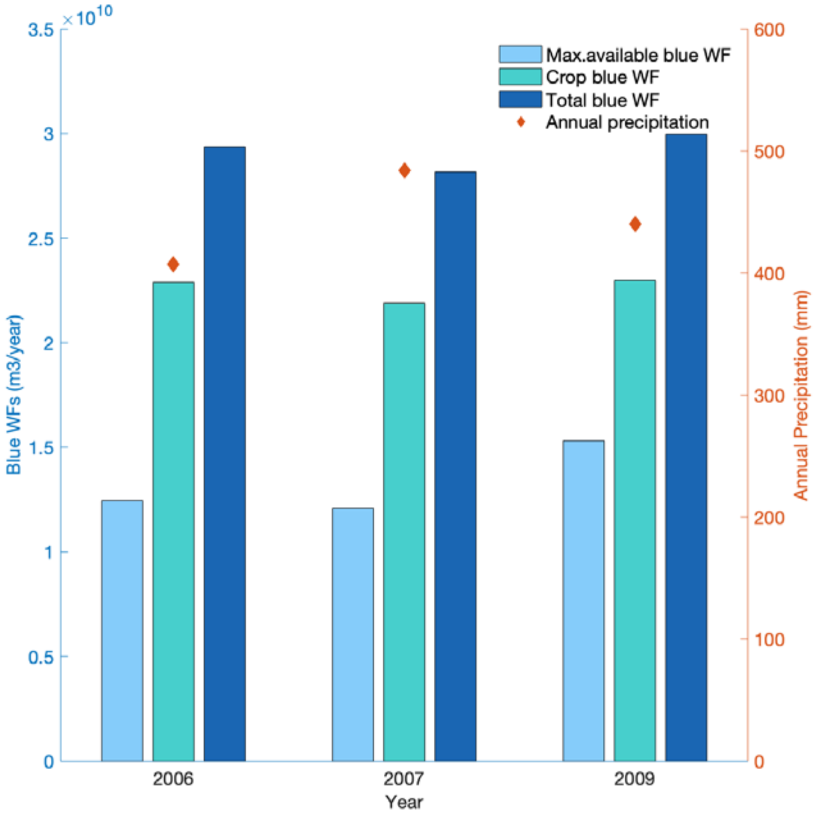


Figure 5: The total annual blue WF, the annual crop blue WF, the maximum available blue WF and the annual precipitation in 2006 (dry year), 2007 (wet year) and 2009 (average year).

Figure 5 visualized the blue WF of crop production, the total blue WF to the maximum sustainable blue WF, and the precipitation over the study years every year. The annual crop blue WF within YRB represents 78%, 78%, and 77% of total blue WF (adding agricultural, domestic, and industrial sectors) in 2006 (dry year), 2007 (wet year), and 2009 (average year). Agriculture is the largest sector in total blue WF from a yearly perspective. The ratios of the annual total blue WF within the basin to the maximum available blue WF in 2006, 2007, and 2009 are 235.82%, 233.08%, and 195.68%, which represent severe blue water scarcity in 2006 and 2007, significant blue WF in 2009 (Section 2.2). The annual blue WF doubled the maximum available blue WF each year. Less precipitation at dry and average year leads to larger blue WF and further enlarges the water scarcity.

3.1.2 The monthly blue water scarcity

Figure 6 displays the monthly blue WF (total), the maximum sustainable blue WF, and the monthly natural runoff of the whole YRB for 2006 (dry year), 2007 (wet year), and 2009 (average year). The effect of the reservoirs to the natural runoff is not involved in this figure, and the effect of reservoir will be discussed in section 4.1. The crest of the blue WF happens from March to July which is in line with the crop growing season of major crops in YRB, while the crest of the natural runoff occurs in the monsoon season which is from June to September. The arrival of the natural runoff crest is almost three months later than the arrival of the blue WF crest, which lead to the extreme water shortage in March, April, and May. The blue WF in May is more than six times the maximum available blue WF in all three years. The volume of blue water that is required is more than the total water volume the river can provide from March to May of the dry year (2006) and the average year (2009). The fluctuation of runoff in the YRB aggravates the blue water shortage in the basin. The excessive but concentrated rainfall at monsoon season will result in a short time but intensive runoff in the river, and the low natural runoff, which can be one-fifth of the peak runoff from November to February, further intensify the water shortage in the non-cropping season due to the water requirement of domestic and industrial use in these months.

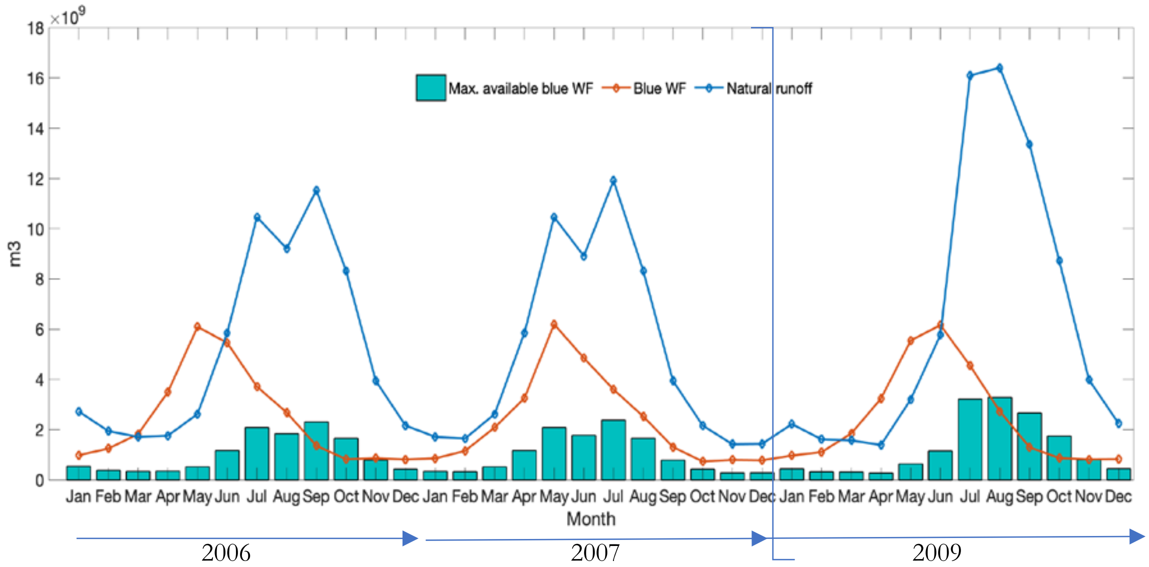


Figure 6 : The monthly blue WF (total), natural runoff and maximum available blue WF of the whole YRB in 2006 (dry year), 2007 (wet year) and 2009 (average year).

Table 5: Number of months in 2006 (dry year), 2007 (wet year) and 2009 (average year) that experience low, moderate, significant, severe water scarcity and complete depletion (blue WF larger than 500% of maximum available blue WF) in the reference case.

	2006	2007	2009
Low water scarcity (blue WF<100% max. available blue WF)	2 (Sep, Oct)	0	3 (Aug, Sep, Oct)
Moderate water scarcity (blue WF is between 100%-150% max. available blue WF)	2 (Aug, Nov)	0	2 (Jul, Nov)
Significant water scarcity (blue WF is between 150%-200% max. available blue WF)	3 (Jan, Jul, Dec)	4 (Jul, Aug, Sep, Oct))	1 (Dec)
Severe water scarcity (blue WF>200% max. available blue WF)	5 (Feb, March, Apr, May, Jun)	8 (Jan, Feb, Mar, May, Jun, Nov, Dec)	6 (Jan, Feb, Mar, Apr, May, Jun)
Complete depletion (blue WF>500% max. available blue WF)	3 (March, Apr, May)	0	4 (March, Apr, May, Jun)

While the blue WFs vary from month to month depending on the intensity of irrigation and precipitation over the months, each month's blue water scarcity within a year also differs a lot. YRB experienced 10 months that maximum available blue WF was exceeded during the dry year (2006), and 9 months during the average year (2009). However, all the months in 2007 (the wet year) have exceeded the maximum available blue WF. For the number of months that the blue WF exceeds the maximum available blue WF, 2007 as a wet year seems to have worse water scarcity than the dry and average year. Nevertheless, when we look into the water scarcity values of each month in detail, we found that the water scarcity values of each month vary largely. The most widely used water scarcity indicator (Hoekstra et al., 2011) defined severe water scarcity as when the blue WF larger than 200% of the maximum available blue WF. However, the monthly blue WF in the YRB can be larger than 500% of the maximum available blue WF in some of the months. Blue WF larger than 500% of the maximum available blue WF means that the blue WF of the month is larger than the natural runoff of the month. We use 'complete depletion' as a further indicator when blue WFs is equal to or larger than 500% of the maximum available WF. Table 5 lists the number of months in each year where the blue WFs exceed the maximum sustainable blue WFs and the number of months facing low, moderate, significant, severe blue water scarcity and complete depletion. The YRB experienced severe water scarcity in the dry year and the average year for 5 and 6 months, out of which two-thirds are under the range of complete depletion. Although the wet year, 2007, suffered more months of severe water scarcity (8 months) than the other two years, it has 0 months of complete depletion in the river basin. From this perspective, we can understand in which months water scarcity happens and how the scarcity levels are. The number of months experiencing water scarcity in a year does not reflect the entire situation of monthly water scarcity in the year.

3.1.3 The spatial blue water scarcity

Monthly blue water scarcity also shows a spatial variability within YRB. Figure 8 present the spatial distribution of the blue water scarcity in January (low blue WFs and low max. available blue WF), April (blue WFs increase while max. available blue WF is still low), July (blue WFs decrease while max. available blue WF goes up), and October (low blue WFs while max. available blue WF falls) in each study year. The western part of the upper basin, northeast part of the middle basin, and middle and western part of the lower basin suffered the highest level of water scarcity (complete depletion) throughout the year and in all three years. The area which suffered the highest level of blue water scarcity is more than 50% of the total area of the basin. In April and July of all three years, 70% of the basin has a blue WF larger than 500% of the maximum available blue WF. The water scarcity level is relieved till January when fewer areas in YRB suffer the complete depletion. There is less water scarcity happening at Qinghai, west of Kansu, and the part of Sichuan province in the YRB throughout the year and all three years, since firstly the cropping area is relatively restricted due to the climate and the topography. Secondly, population density in the area is low which means less domestic and industrial water is required. Some parts of the area with smaller cropping areas, for example, the southern part of Inner Mongolia, suffer the highest level of water scarcity throughout the year. The occurrence of water scarcity in such areas is the interaction of less precipitation and the demand for blue water from domestic and industrial sectors.

In the average year 2009, the YRB goes through 4 months (March, April, May, and June) of the highest level of water scarcity where blue WF exceeds 500% of the maximum blue water scarcity (Table 5). Figure 8 shows the spatial distribution of crops which have the largest share of the crop blue WF from March to June in 2009. Table 6 shows the contribution of main crops to the total blue WF from March to June in 2009. Rapeseed took the largest share of crop blue WF over almost half the area of YRB throughout this period (Figure 8). However, in terms of the total blue WF, the contribution of rapeseed in each grid cell is not more than 25%, and the contribution of rapeseed of all grid cells is less than 5% each month during these four months (Table 6). This is because, in some of the grid cells, industrial and domestic blue WFs are the main source of the total blue WF. In addition to rapeseed, winter wheat covers the most area with the largest share in crop blue WF from March to May (Figure 7). Maize replaces winter wheat in June since the cropping season of winter wheat finishes in May. For half a year (March to August), the blue WF of winter wheat plus maize cover over 50% of the total blue WF, and this ratio is over 60% in April and May (Table 6) which are also the months who experienced the highest level of water scarcity in the year. So, this means if the blue WF of winter wheat and maize are brought down by any means, the total blue WF will be relieved to a large extent during the water-scarce months (March to June).

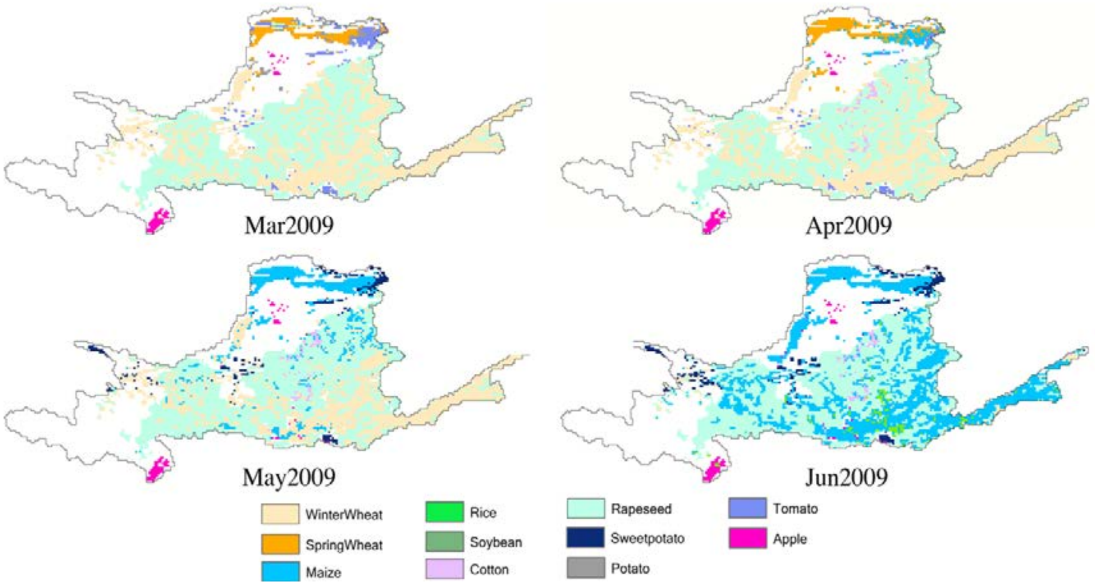
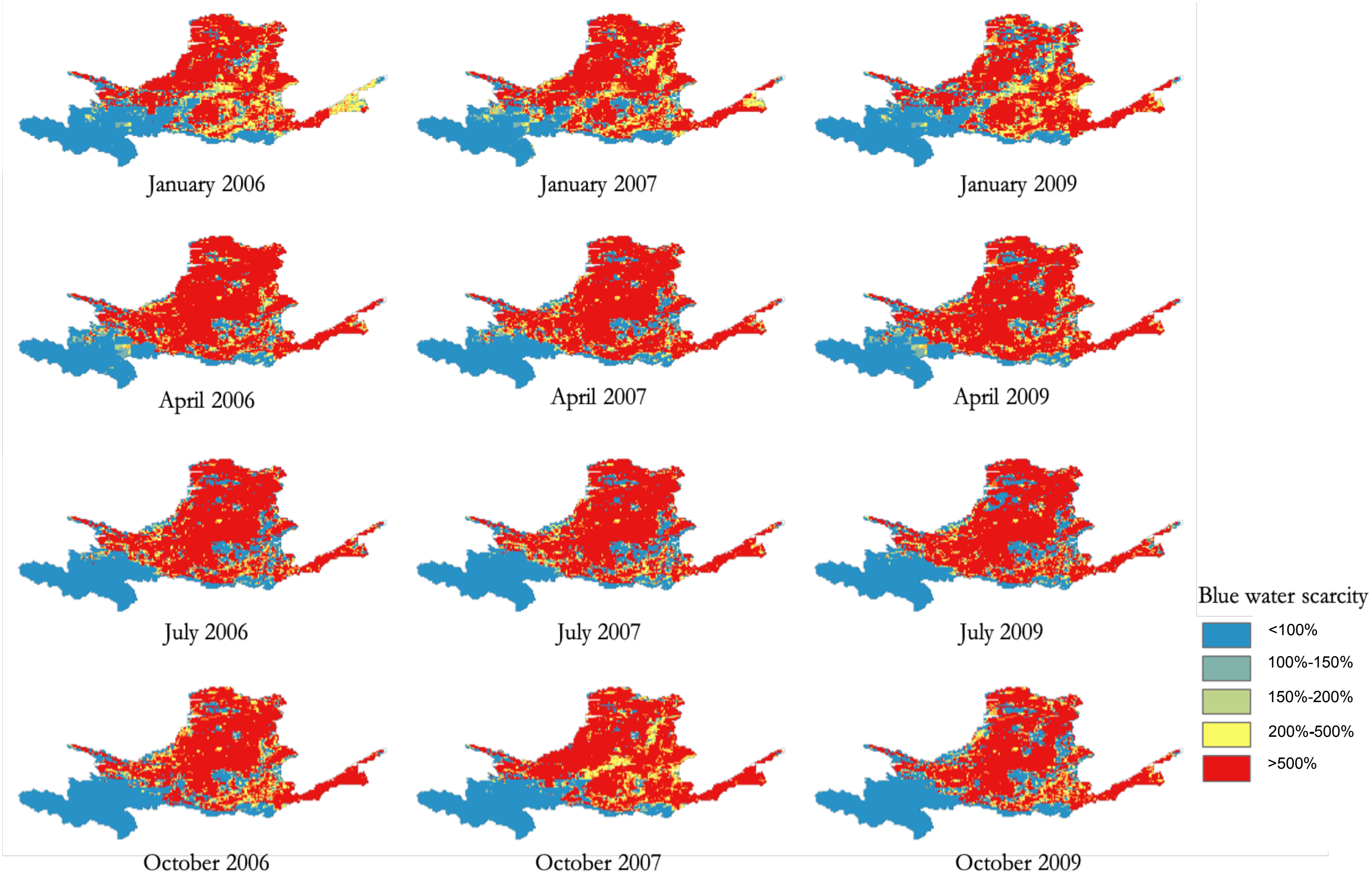


Figure 7: Spatial distribution of crops which have the highest share of the crop blue WF in March, April, May and June in 2009 (average year).

Table 6: The contribution of main crops to the total blue WF from March to June in 2009.

	March	**April**	**May**	**June**
Winter wheat	58%	51%	41%	12%
Maize	0%	10%	22%	43%
Rice	0%	0%	5%	8%
SpringWheat	1%	4%	5%	6%
Cotton	0%	3%	3%	4%
Rapeseed	2%	4%	4%	4%
Apple	2%	3%	3%	3%
Tomato	5%	5%	2%	0%



January 2006 January 2007 January 2009

April 2006 April 2007 April 2009

July 2006 July 2007 July 2009

October 2006 October 2007 October 2009

Figure 8: Monthly blue water scarcity of reference case in the month of January, April, July and October in 2006 (dry year), 2007 (wet year) and 2009 (average year).

3.2 The blue WF change of the two strategies and the four scenarios

3.2.1 Determine the lowest blue WF of strategy 1

The yield variation of 17 crops by applying the reference and 6 tests of irrigation strategies are plotted in Figure 9. The yield variation is essential to evaluate the different irrigation strategies. The blue WF can be relatively low with the cost of yield lost. For example, although the blue WF of cotton in 2007 decreased by 57% by applying test 3, the yield of cotton decreased by 14% simultaneously. The lowest blue WF comes with the cost of high yield loss by this irrigation strategy. The yield loss should be avoided while deciding from the tests. We notice from Figure 9 that one test may improve the yield at one year but lower the yield in the other yield. For example, by applying test 5 to rapeseed, we witness a slight yield increase in 2006 and 2007, but we also see great yield loss in 2009 by the same test. This is the combined effect of different crops' sensitivity to drought and the uneven distribution of available water resources in grid cells. This also indicates that it is not practical to apply one irrigation strategy to one crop throughout the whole basin and in all years. A smaller resolution of applying irrigation strategy is beneficial in terms of reducing the yield loss. For some crops, we also observed yield gain by applying irrigation strategies. This may be due to the effect of the organic mulching, which weakens the yield loss to some extent.

With the information on yield loss of each crop, the lowest blue WF is selected at grid cell level with less than 10% yield loss. If the lowest blue WF comes with more than 10% yield loss, the irrigation strategy is then switched to the one with the next lowest blue WF with yield loss within 10%. Results of the tests chosen as the irrigation strategy at each grid cell in 2006 are plotted in Figure 10. The same figure for 2007 and 2009 is in Figure 11 and Figure 12. We notice that for most of the crops like winter wheat, potato, sweet potato and tomato, a dominant test can be found at the regional level. However, for maize, sorghum and barley, the decision of the tests is relatively scattered. The tests that were chosen for dry, wet and average year for one crop species varies. The wet year tends to have more regions with the tests that less irrigation water is applied than the dry year and the average year, for example, the middle part of the middle basin of groundnut, the eastern part of the middle basin of cotton. Nevertheless, the lower basin of some crops (winter wheat, rice, cotton etc.) tends to decide on the tests with more irrigation at wet years, but on the tests with less irrigation at the dry and the average years. There is no clear pattern of how irrigation strategy changes with the precipitation. More data from a temporal serial should be analyzed to suggest a pattern.

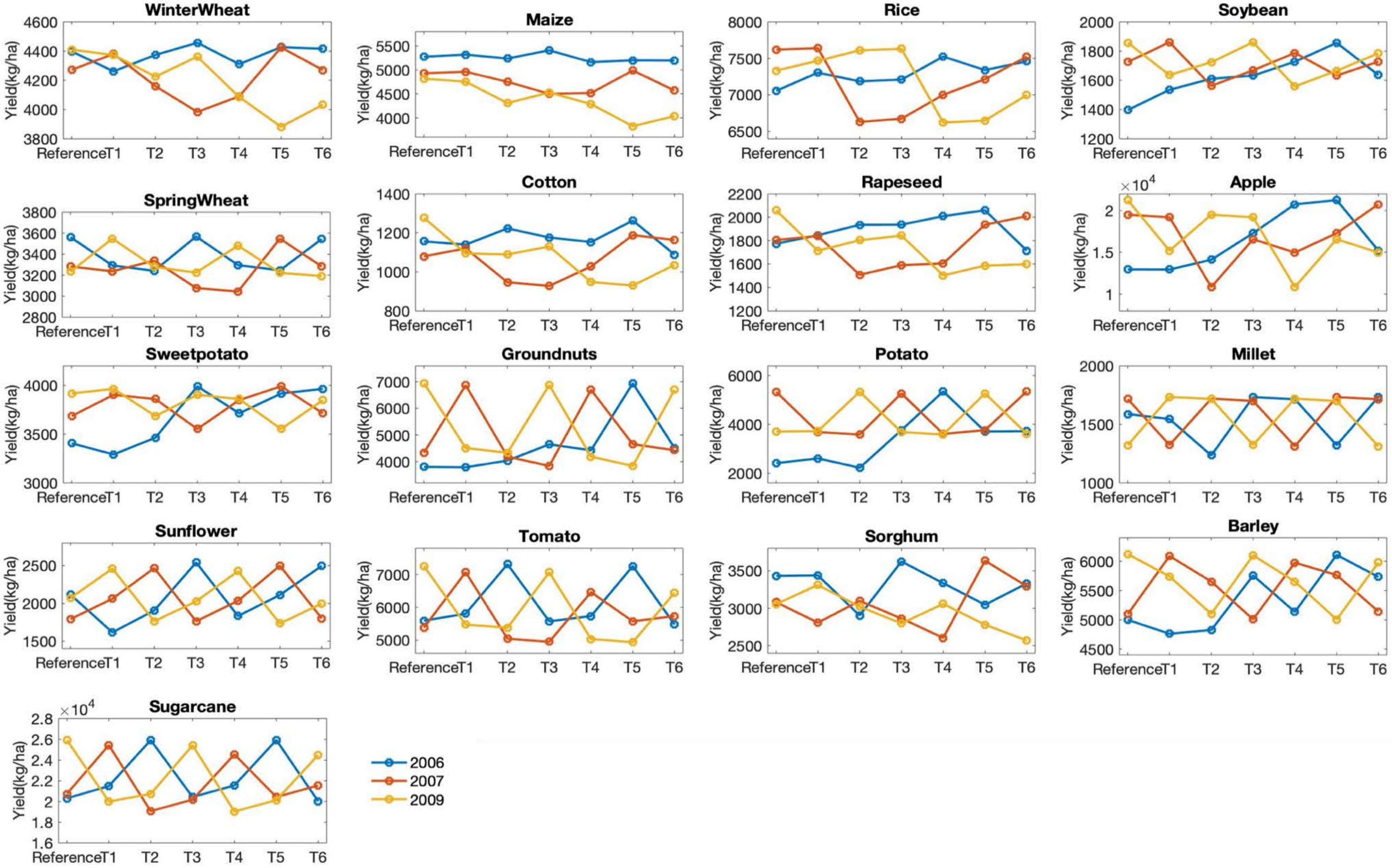


Figure 9: Yield variation by applying reference and 6 tests of irrigation strategies in 2006 (dry year), 2007 (wet year) and 2009 (average year).

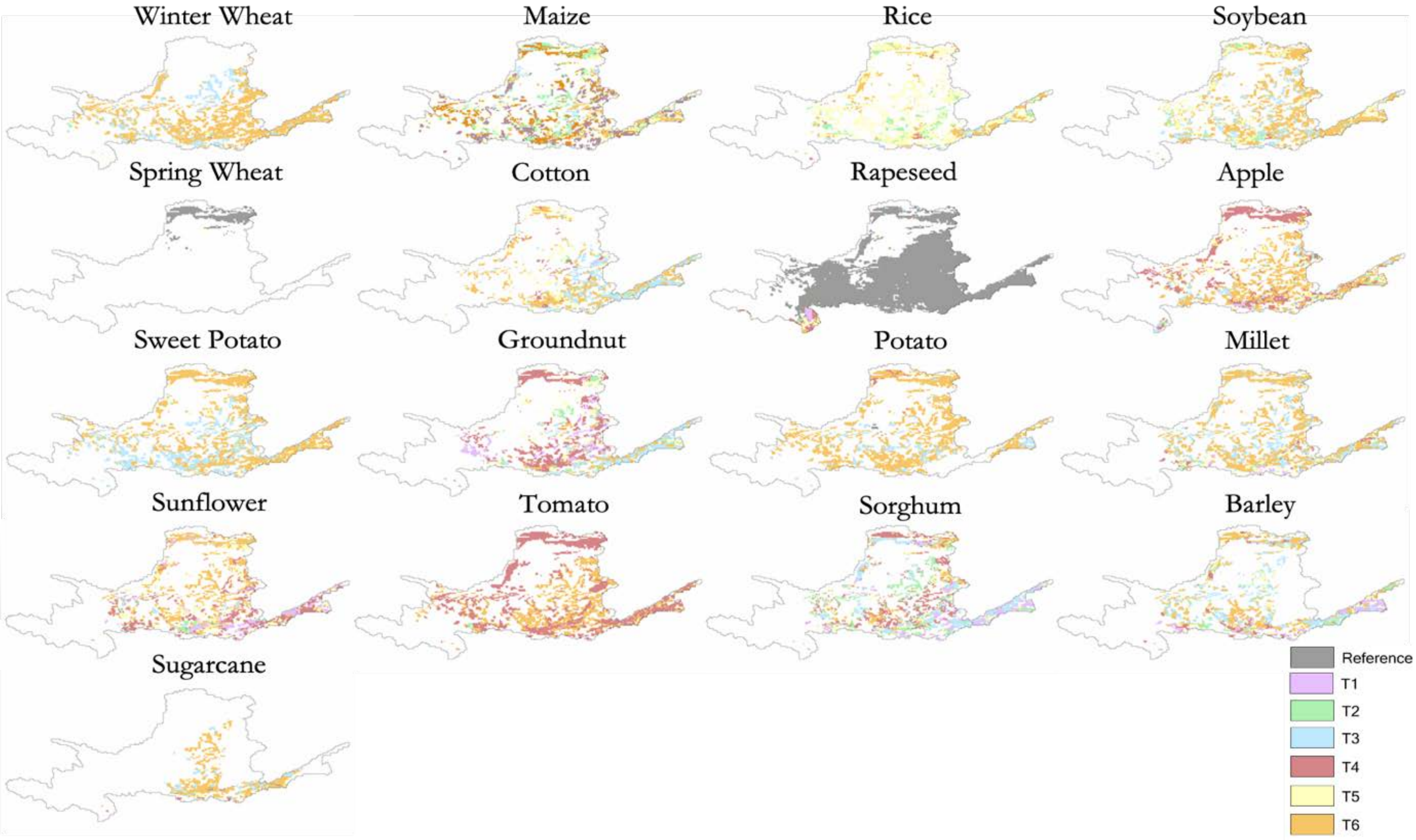


Figure 10: The tests chosen as irrigation strategy at grid cell level of 17 crops in 2006 (dry year).

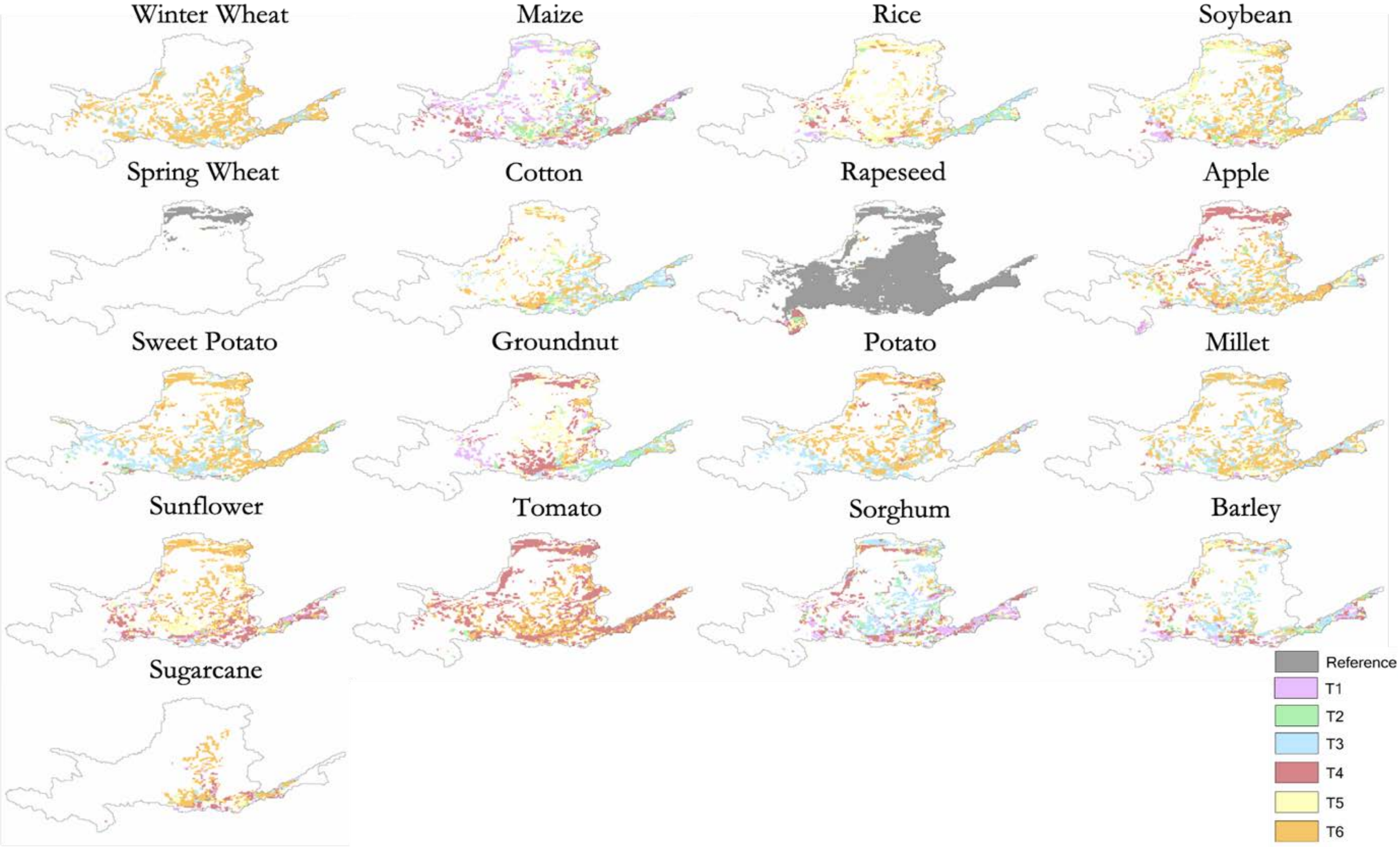


Figure 11: The tests chosen as irrigation strategy at grid cell level of 17 crops in 2007 (wet year).

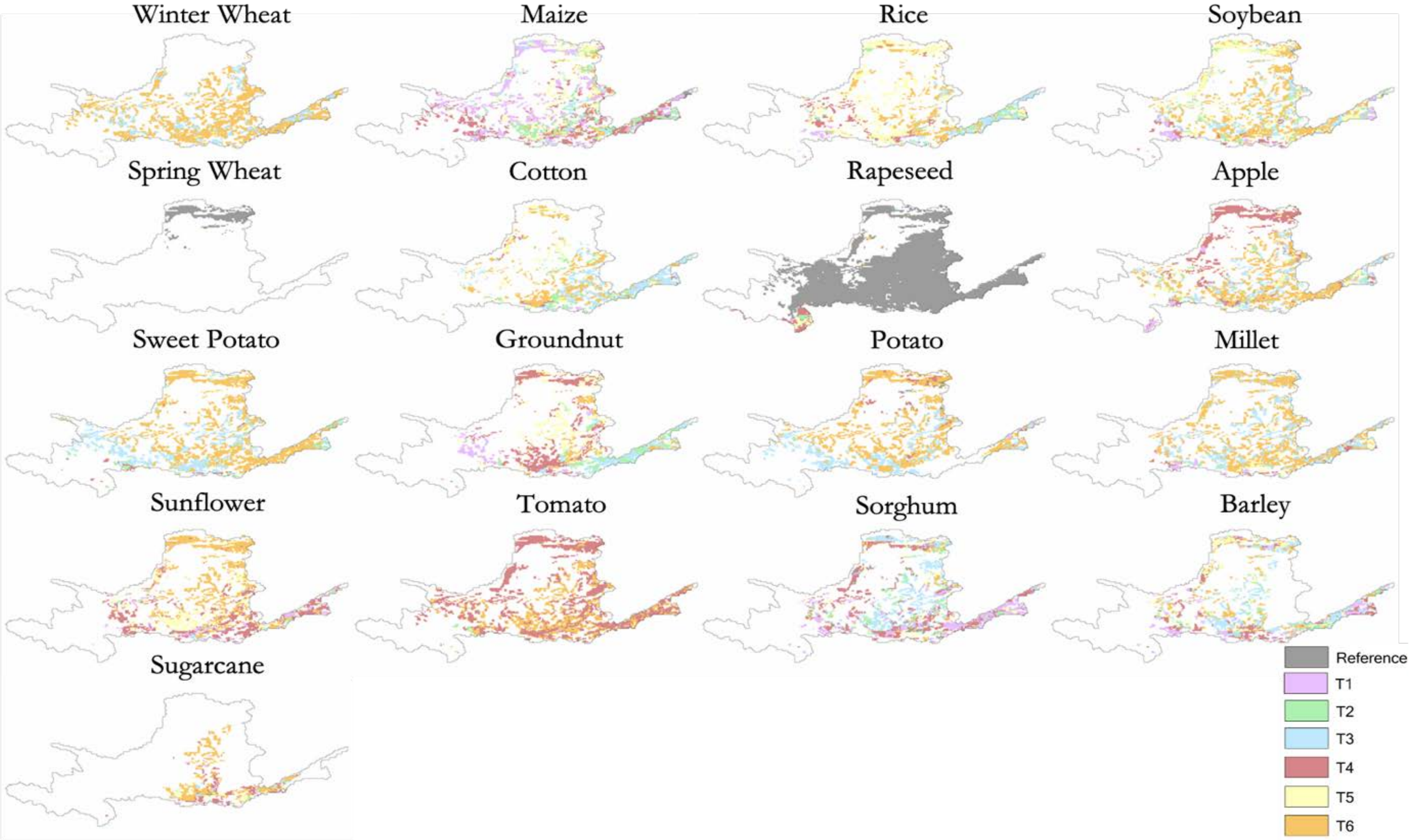


Figure 12: The tests chosen as irrigation strategy at grid cell level of 17 crops in 2009 (average year).

3.2.2 The blue WF (m^3/t) change of the two strategies

Table 7 selected the blue WFs (m^3/t) of reference, the blue WFs(m^3/t) of strategy 1 and strategy 2 and its change rate compared to the reference in 2009, with two additional columns indicating the production change rate of strategy 1 and strategy 2 compared to the reference. The last column indicates the yield gap that the strategy 2 closed. The output data of blue ET (mm), yield (t/ha), and blue WF (m^3/t) of each crop for the reference, strategy 1 and strategy 2 in all three years is shown as additional data in Appendix IV.

Table 7: The blue WFs of 17 crops at the reference case, the blue WFs of strategy 1 and strategy 2 and its change rate to reference, the production change rate of strategy 1 and strategy 2 to the reference and the yield gap closed by the strategy 2 in 2009.

	Reference	**Strategy 1**		**Strategy 2**		
	Blue WF (m^3/t)	**Blue WF (m^3/t)**	**Production change (%)**	**Blue WF (m^3/t)**	**Production change (%)**	**Yield gap (t/ha)**
Winter wheat	400.11	232.32 (42%)	7.99	142.30 (64%)	-181.18	7.93
Maize	364.96	215.93 (41%)	7.71	175.96 (52%)	-107.41	5.63
Rice	540.71	349.76 (35%)	-6.19	414.80 (23%)	-30.35	2.18
Soybean	712.43	316.23 (56%)	-11.97	173.01 (76%)	-311.79	5.02
SpringWheat	1239.50	1239.50 (0%)	0.00	544.11 (56%)	-127.81	4.14
Cotton	1980.40	1006.90 (49%)	2.83	150.38 (92%)	-1216.97	14.88
Rapeseed	780.92	774.46 (1%)	-0.56	291.13 (63%)	-168.24	3.26
Apple	63.55	17.25 (73%)	-40.31	184.54 (-190%)	65.56	-9.25
Sweetpotato	112.48	58.91 (48%)	-11.39	12.62 (89%)	-791.12	27.40
Groundnuts	274.81	86.76 (68%)	-67.34	236.71 (14%)	-16.10	0.65
Potato	67.35	29.75 (56%)	-64.15	19.60 (71%)	-243.73	5.42
Millet	296.01	175.21 (41%)	-6.66	37.38 (87%)	-692.00	8.55
Sunflower	232.30	150.57 (35%)	-6.33	319.74 (-38%)	27.35	-0.52
Tomato	229.10	137.66 (40%)	0.96	48.18 (79%)	-375.48	27.46
Sorghum	304.96	124.75 (59%)	-0.74	95.45 (69%)	-219.52	6.38
Barley	59.88	33.43 (44%)	-24.81	82.68 (-38%)	27.58	-1.33
Sugarcane	73.78	60.14 (18%)	5.42	5.47 (93%)	-1247.79	323.55

From the table, we can see that strategy 1 brought down the blue WFs of most of the crop to a great extent (more than 30%), with the production loss within 10%. However, there is no reduction found by applying strategy 1 to the spring wheat. The reference case is chosen for most grid cells as it can reach the lowest blue WF (Figure 12). The reason why deficit irrigation plus organic mulching fail might be at the climate zone where spring wheat grows in the YRB. The spring wheat is mainly located in Hetao irrigation area, north of Inner Mongolia, which is the arid area in YRB with annual precipitation (130-180mm) one-fourth to the annual evapotranspiration (1100-1600mm). The precipitation in July, August, and September accounts for 70%-80% of the total annual precipitation (YRCC, 2019). In this case, reducing the irrigation water led to yield failure and instead increased the blue WF. Similarly, strategy 1 did not significantly reduce the blue WF of rapeseed throughout the whole basin except in Sichuan province. This may be due to the high sensitivity of rapeseed to water stress.

The blue WF reduction after implementing strategy 2 shows a different pattern from strategy 1. Strategy 2 is more effective compared to strategy 1 in terms of bringing down the blue WF. 12 out of 17 crop species have a blue WF reduction of over 50%. For cotton and sugarcane, the blue WF reduction is up to 90%. The yield gap of cotton, sweet potato, and tomato is closed by more than 10 t/ha. Less irrigation with organic mulching cannot bring down the blue WF of spring wheat and rapeseed, but closing yield gap provides a promising result for these two crop species. Many studies show that AquaCrop outputs are sensitive to the regional parameters such as the time to CCx and sowing date (Sun et al., 2017). The reason that we have a negative yield gap for some of the crops (sunflower, barley, and apple) is possibly related to the lack of validation of sensitive parameters at regional scales.

3.2.3 The blue WF (m^3) change of the four scenarios

Table 8 shows the blue WF (m^3) reduction compared to the reference by applying scenarios. Columns 2-4 show the crop blue WF reduction of all crops in all the grid cells in three years, and the last three columns show the total blue WF reduction including the industrial and domestic sector in three years.

Table 8: The crop blue WF reduction and the total blue WF reduction to reference by applying 4 scenarios in 2006 (dry year), 2007 (wet year) and 2009 (average year).

	Crop blue WF (m^3) reduction %			**Total blue WF (m^3) reduction %**		
Scenarios	2006	2007	2009	2006	2007	2009
S1	41.46	43.93	41.60	32.31	34.16	31.91
S1AA	39.67	42.19	40.08	30.91	32.05	32.45
S2	0.00	0.00	0.00	0.00	0.00	0.00
S2A-	58.02	58.54	56.22	45.21	43.95	45.53

The average of blue WF reduction varies with year. Wet year shows in general a higher potential to reduce the blue WF, but the potential in blue WF reduction is not as obvious among scenarios compared to the reduction rate when switching from the reference to scenarios. In terms of the crop blue WF and total blue WF, S2A- reduces the blue WF the most, followed by S1 and S1AA. The total blue WF reduction achieved by S2A- is around 1.5 times higher than the reduction achieved by S1 and S1AA. S2 shows no reduction in crop blue WF and total blue WF, since this scenario focus on closing the yield gap. However, S2 has a great gain in total production (Table 9). In terms of land control, S2A- saves the land the most with the same production level as in reference and S1AA. Besides the absolute water saving perspective, all the scenarios can have considerable improvement on the crop blue WF (m^3/t). The crop water use efficiency is improved by at least 40% in all three years by the four scenarios, yet the difference among scenarios can reach 25% (Table 9).

S1AA is the least effective in bringing down the blue WF both in m^3/kg and m^3 (Table 8 and Table 9). Main crops like winter wheat and maize consume more water when switching from S1 to S1AA since the production loss is quite large of S1 (8%, Table 7). To compensate for the production loss, more blue water is required to irrigate. But for tubers and oil-crop, less water is consumed when switching from S1 to S1AA, since S1 brings production gain to these crops, and S1AA cut them off which results in less blue water demand. The interaction of all the crops results in the scenario with most crop blue WF but the least production.

Table 9: The reduction in production (tonne), crop blue WF (m^3/t), and cropping area (ha) by applying scenarios in 2006 (dry year), 2007 (wet year) and 2009 (average year).

	Production (tonne) reduction %			**Crop blue WF (m^3/t) reduction %**		
Scenarios	2006	2007	2009	2006	2007	2009
S1	-4.88	-8.12	-7.71	44.19	48.14	45.79
S1AA	0.00	0.00	0.00	39.67	42.20	40.09
S2	-166.33	-182.88	-162.49	62.45	64.65	61.91
S2A-	0.00	0.00	0.00	58.02	58.54	56.23

Scenarios	**Cropping area (ha) reduction %** 2006	2007	2009
S1	0.00	0.00	0.00
S1AA	2.63	3.25	2.95
S2	0.00	0.00	0.00
S2A-	61.54	63.32	61.22

The crop contribution to crop blue WF reduction (m^3) of S1AA and S2A- in 2009 is shown in Figure 13. Winter wheat, maize and rice together reduced 86% of the crop blue WF by S1AA and 89% of the crop blue WF by S2A-. These are the main crops on blue WF reduction in the YRB. Potato and sweet potato as the crop with third and fourth largest cropping area and as fourth and sixth largest production together contribute 4% of crop blue WF reduction by S1AA and 2% by S2A-. The potential of blue WF reduction is different for different crop species. For crops which have relatively large production and cropping area but little contribution to crop blue WF reduction, different measures should be considered to bring down the crop blue WF.

The crop blue WF reduction also shows a temporal variation within one year. Figure 14 shows the reduction of monthly crop blue WF in 2009 by applying scenarios. For S1 and S1AA, the highest reduction (in December) can be twice as much as the lowest reduction (in July). As we observed in 3.1.2, July 2009 has the moderate blue water scarcity. However, many crops in YRB are having drought sensitive period during July, especially for the major crop maize. Therefore, crop water use cannot be effectively reduced in July due to the crop water requirement to maintain the stable yield. The crop blue WF reduction in winter is larger than in other seasons by applying S1 and S1AA. This is possible due to the less crop blue WF in YRB in winter from less crop. Any reduction is effective to crop blue WF reduction during the winter. Closing yield gap (S2A-) results in a more stable reduction over the year, the difference between the highest reduction and the lowest reduction is within 10%.

Figure 15 demonstrates the spatial reduction rate of crop blue WF by applying S1, S1AA and S2A- in 2009. The reduction rate of grid cells by applying S1 and S1AA gradually decreases from southeast to northwest. This has to do with the spatial distribution of precipitation in YRB which also gradually decreases from southeast to northwest. The crop blue WF reduction range between 0-80% by S1 and S1AA. The potential of reducing the crop blue WF by applying S2A- is relatively even over the YRB, and the reduction rate is larger than 40% all over the basin. Most of the middle basin experienced a crop blue WF reduction rate between 60% - 80%.

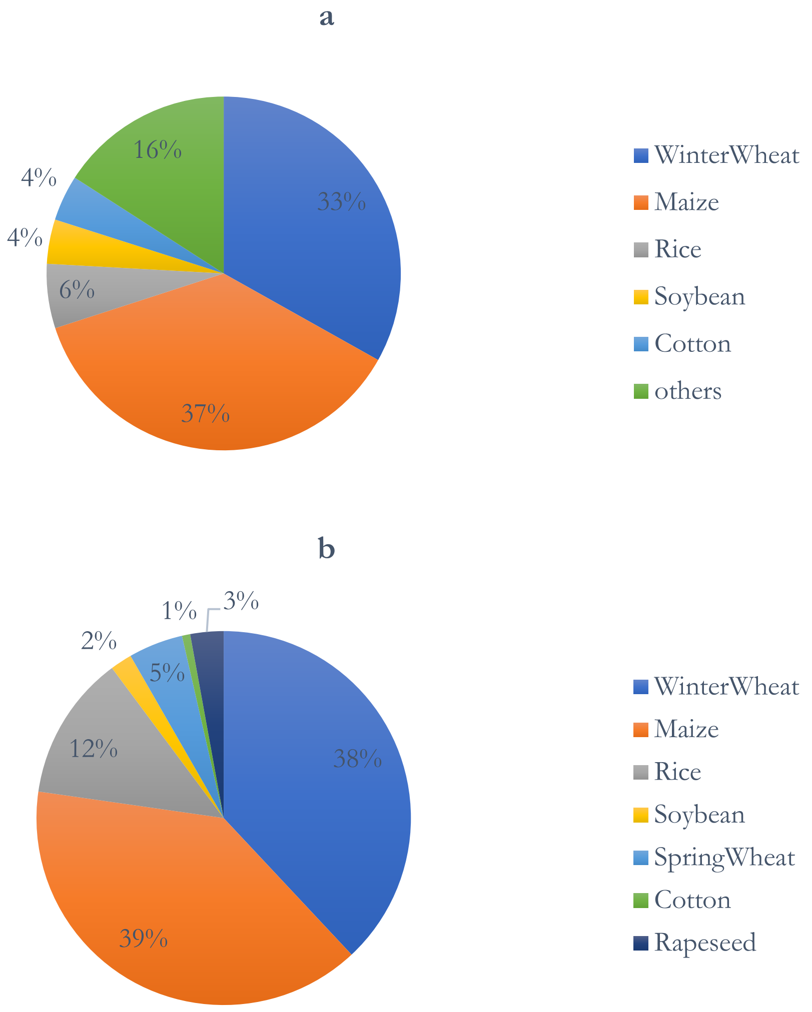


Figure 13: The crop contribution to crop blue WF reduction (m^3) of (a) S1AA and (b) S2A- in 2009.

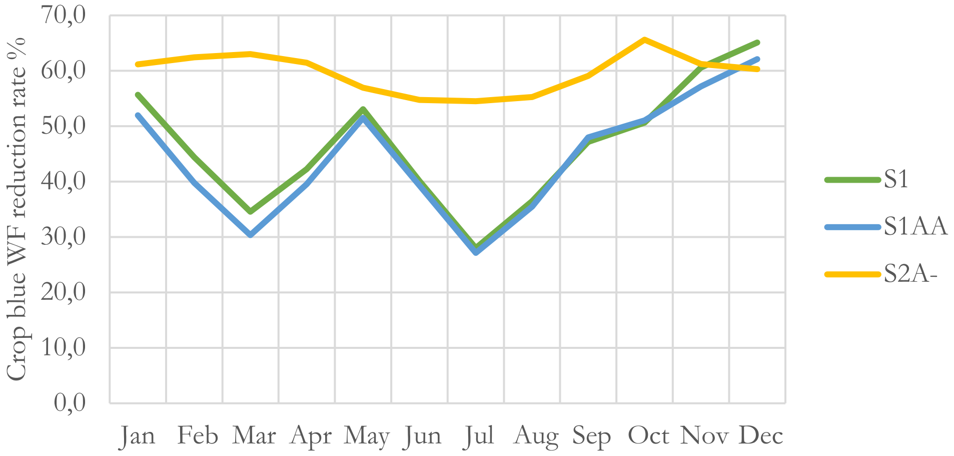


Figure 14: The reduction of crop blue WF (m^3) in 2009 (average year) by applying S1, S1AA and S2A-.

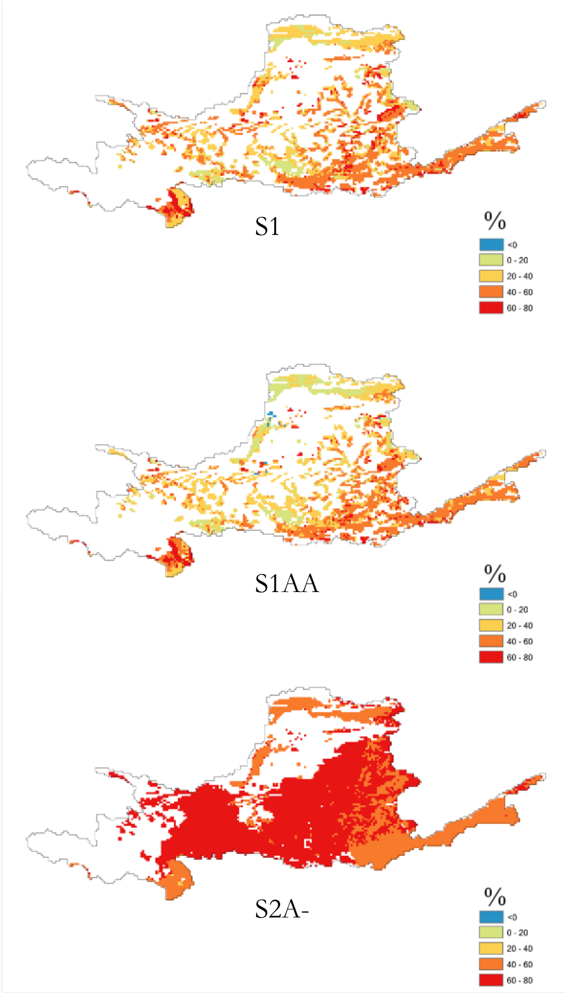


Figure 15: The spatial crop blue WF (m^3) reduction of S1, S1AA, and S2A- in 2009 (average year).

3.3 Blue water scarcity of the scenarios

We are now concerned about the reduction in the blue water scarcity after implementing the scenarios and whether the scenarios can relieve the water scarcity or whether scenarios are effective to bring down the blue water scarcity in extreme months and extreme locations. Following the structure of section 3.1, we also study the blue water scarcity after applying the scenarios from three perspectives: yearly blue water scarcity, monthly blue water scarcity, and spatial blue water scarcity.

3.3.1 Yearly blue water scarcity

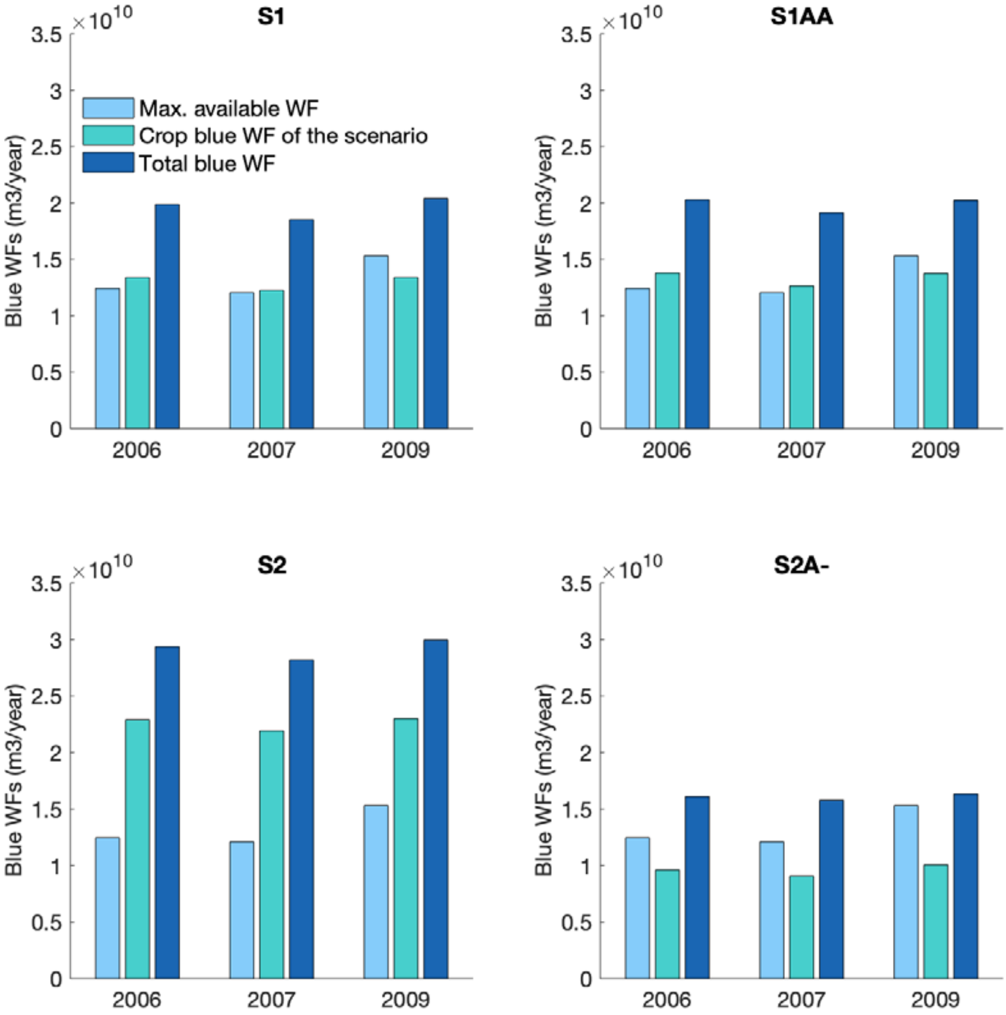


Figure 16: The total blue WF, crop blue WF, maximum available blue WF, and precipitation in 2006 (dry year), 2007 (wet year) and 2009 (average year) of 4 scenarios

Figure 16 shows the relation of the total blue WF, crop blue WF and maximum available blue WF in each year of the four scenarios. None of the scenarios can bring down the total blue WF to the maximum available blue WF level. This means the YRB will still face some degree of blue water scarcity during these three years with any of the scenarios. However, the blue water scarcity in YRB is relieved from severe water scarcity to moderate water scarcity or significant water scarcity after implementing scenarios. The blue water scarcity by applying scenarios in three years is listed in Table 10. By applying S1and S1AA, the blue water scarcity of all three years is relieved one level down. By S2A-, the blue water scarcity reaches the moderate level for all three years.

Table 10: The blue water scarcity indicator of 2006 (dry year), 2007 (wet year) and 2009 (average year) by applying scenarios.

Scenarios	2006	2007	2009
S1	159.65% (Significant)	153.45% (Significant)	133.25% (Moderate)
S1AA	162.95% (Significant)	158.35% (Significant)	132.15% (Moderate)
S2	235.8% (Severe)	233.1% (Severe)	195.7% (Significant)
S2A-	129.2% (Moderate)	130.65% (Moderate)	106.6% (Moderate)

3.3.2 *Monthly blue water scarcity*

Figure 17 presents the curve of monthly natural runoff, maximum available blue WF, and the total blue WF of four scenarios (S2 has the same curve as reference) in 2006, 2007, and 2009. With S1, S1AA and S2A-, the sharp water use peak in May and June is effectively flattened. Even though S2A- can bring down the total crop WF by an average of 60%, we can still see the enormous gap between the total blue WF and the maximum available blue WF from March to July especially in 2006 and 2009. From the figure we also notice that. in the wet year (2007), the maximum available blue WF is relatively close to reach the total blue WF. With more precipitation during a wet year, the monthly water scarcity might be relieved by the scenarios. However, the phase lag between maximum available water and the total blue WF cannot be overcome by less irrigation plus organic mulching or closing yield gaps in the dry or average year. Measures that can compensate for the phase lag, such as changing the sowing date of major crops or regulating the runoff of reservoirs, should be considered.

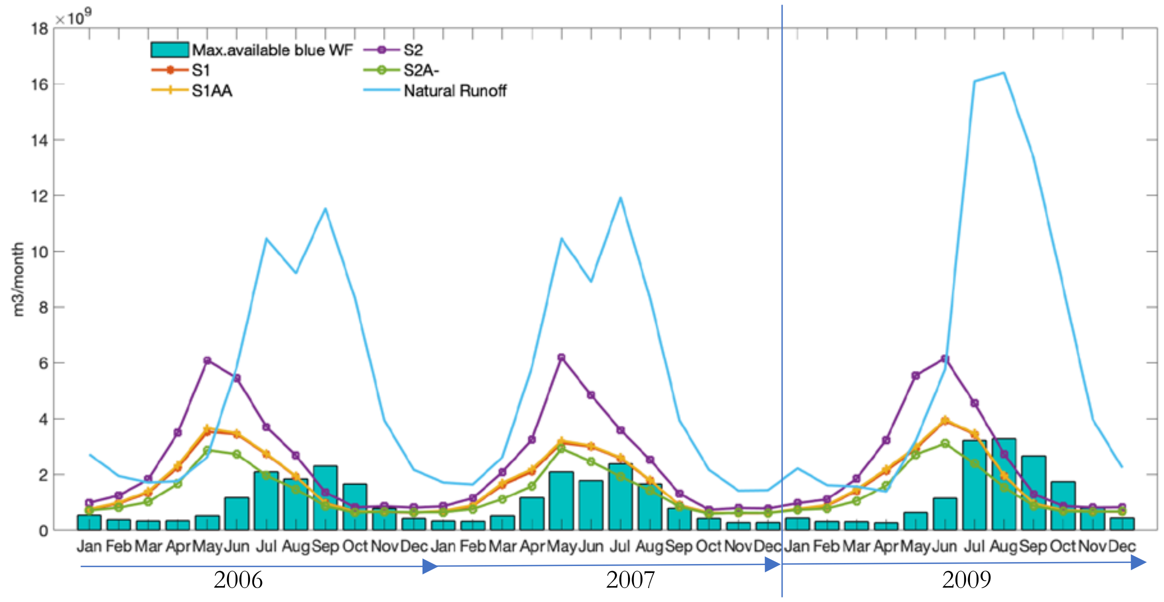


Figure 17: Monthly blue WF of reference and scenarios, natural runoff and maximum available blue WF within YRB in 2006 (dry year), 2007(wet year) and 2009 (average year).

Table 11 shows the number of months in 2006, 2007, and 2009 that experience low, moderate, significant, severe water scarcity and complete depletion by applying scenarios (S2 equals to the reference case). In general, the monthly blue water scarcity shows one scarcity level down by scenarios, especially by S2A-. Among all the months in three years which experience complete depletion, S1 and S1AA relieve the number by half (7 to 3). S2A- brings down this number by three (7 to 2). Only five months out of all the months of three years have low water scarcity at reference case, but S2A- doubles this number. S1 and S1AA relieve seven and five months correspondingly to moderate blue water scarcity. However, the effect of scenarios on monthly blue water scarcity is limited. It is not expected to completely solve the monthly water scarcity problem. Months like February and March each year still experience severe water scarcity by any scenario.

Table 11: The number of months in 2006 (dry year), 2007 (wet year) and 2009 (average year) that experience low, moderate, significant, severe water scarcity and complete depletion (blue WF larger than 500% of maximum available blue WF) after applying scenarios.

	S1			**S1AA**		
	2006	2007	2009	2006	2007	2009
Low water scarcity (blue WF<100% max.available blue WF)	3 (Sep, Oct, Nov)	0	4 (Aug, Sep, Oct, Nov)	3 (Sep, Oct, Nov)	0	4 (Aug, Sep, Oct, Nov)
Moderate water scarcity (blue WF is between 100%-150% max.available blue WF)	4 (Jan, Jul, Aug, Dec)	5 (May, Jul, Sep, Oct)	2 (Jul, Dec)	4 (Jan, Jul, Aug, Dec)	4 (Jul, Aug, Sep, Oct)	1 (Jul)
Significant water scarcity (blue WF is between 150%-200% max. available blue WF)	0	2 (Apr, Jun)	1 (Jan)	0	3 (Apr, May, Jun)	2 (Jan, Dec)
Severe water scarcity (blue WF>200% max. available blue WF)	5 (Feb, Mar, Apr, Jun)	5 (Jan, Feb, Nov, Dec)	5 (Feb, Mar, Apr, May, Jun)	5 (Feb, Mar, Apr, May, Jun)	5 (Jan, Feb, Mar, Nov, Dec)	5 (Feb, Mar, Apr, May, Jun)
Complete depletion (blue WF>500% max. available blue WF)	2 (Apr, May)	0	1 (Apr)	2 (Apr, May)	0	1 (Apr)

	S2			**S2A-**		
	2006	2007	2009	2006	2007	2009
Low water scarcity (blue WF<100% max. available blue WF)	2 (Sep, Oct)	0	3 (Aug, Sep, Oct)	5 (Jul, Aug, Sep, Oct, Nov)	2 (Jul, Aug)	5 (Jul, Aug, Sep, Oct, Nov)
Moderate water scarcity (blue WF is between 100%-150% max. available blue WF)	2 (Aug, Nov)	0	2 (Jul, Nov)	2 (Jan, Dec)	5 (Apr, May, Jun, Sep, Oct)	0
Significant water scarcity (blue WF is between 150%-200% max. available blue WF)	3 (Jan, Jul, Dec)	4 (Jul, Aug, Sep, Oct))	1 (Dec)	0	1 (Jan)	2 (Jan, Dec)
Severe water scarcity (blue WF>200% max. available blue WF)	5 (Feb, March, Apr, May, Jun)	8 (Jan, Feb, Mar, Apr, May, Jun, Nov, Dec)	6 (Jan, Feb, Mar, Apr, May, Jun)	5 (Feb, Mar, Apr, May, Jun)	4 (Feb, Mar, Nov, Dec)	5 (Feb, Mar, Apr, May, Jun)
Complete depletion (blue WF>500% max. available blue WF)	3 (March, Apr, May)	0	4 (Mar, Apr, May, Jun)	1 (May)	0	1 (Apr)

3.3.3 Spatial blue water scarcity

Similar to section 3.1.3, the spatial distribution of blue water scarcity in January, April, July, and October in 2009 by applying S1, S1AA, and S2A- are plotted in Figure 18. Row figures present the months and column figures present the scenarios. For all months presented in the figure, the water scarcity in the north and middle Inner Mongolia, middle Shaanxi province, and west of Qinghai province are relieved by scenarios compared to the reference case. Among scenarios, changes in blue water scarcity are less obvious to observe, since the scenarios bring down the blue water scarcity to almost the same level in these months. In October, half of the basin is still going through the highest level of blue water scarcity even though the total blue water scarcity as a whole is low (see Table 11). To understand the reason behind this, we examined, by applying S2A-, the blue water scarcity value distribution of October 2009. 41%, 2%, 2% and 54% of the grid cells have low water scarcity, moderate water scarcity, significant water scarcity and severe blue water scarcity correspondingly. However, the indicator of 'severe water scarcity' can only represent the blue WF larger than 200% of maximum blue WF. There is 48% of the grid cells that the blue WF is larger than 500% of the maximum available blue WF in October 2009 by S2A-. This can explain the effect that the overall blue scarcity of the month is relieved with S2A- but no noticeable reduction at the spatial scale. The blue water scarcity of a lower level is relieved with scenarios, but the blue water scarcity of a higher level shows less response to the scenarios. In the grid cells where any scenario does not affect, the main contradiction might be the uneven spatial distribution of blue water resources in the grid cells. Any usage of blue water in those grid cells will result in extreme blue water scarcity. The results indicate that measures to reduce the geographical unevenness of blue water distribution can be more effective to bring down the blue water scarcity.

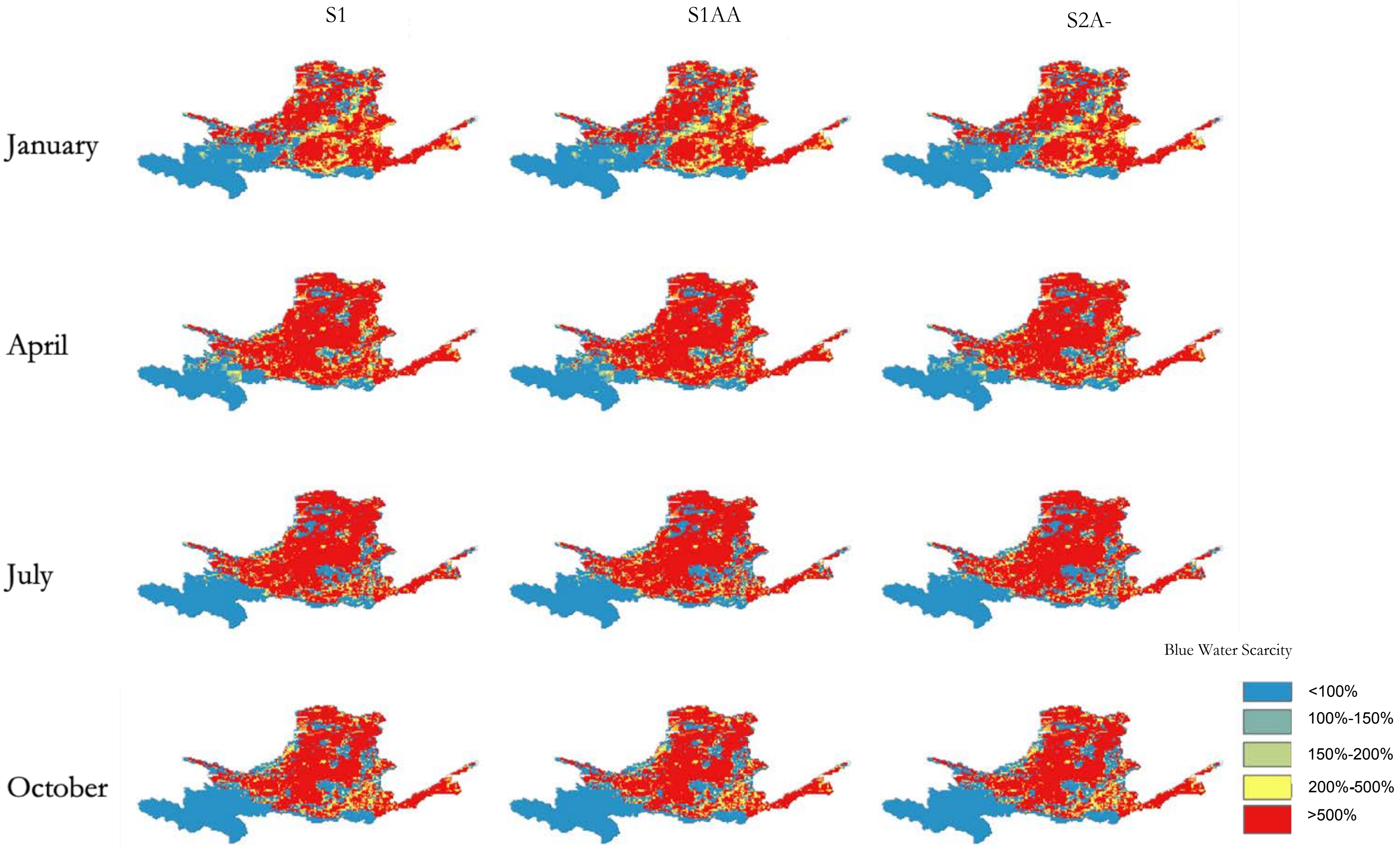


Figure 19: Blue water scarcity map of S1, S1AA and S2A- in the month of January, April, July and October in 2009 (average year).

4. Discussion

4.1 Limitations and evaluation of the results

The current study has some limitations which can influence the results of the blue water scarcity. This section serves to explain the limitation, and the implications of these limitations to the final results will be evaluated.

Environment flow requirements (EFRs)

The determination of EFRs considers the natural river flow variability to maintain the ecosystems. The presumptive EFRs developed by Richter et al. (2012) pointed out that daily flow alterations should not be greater than 20% for a moderate level of ecosystem protection. They also mentioned that limiting the flow variation to 20% might be conservative and precautionary. Then, Pastor et al. (2014) tested five hydrological methods with local case studies. They argued that only 37% percent of annual discharge is required to sustain the ecosystem on average. While during the low flow periods, 46%-71% of river discharge is required, and during the high flow period, 17%-45% of river discharge is required. Therefore, we may wonder if the EFRs we chose are too strict and responsible for higher water scarcity over the YRB. Hence, we calculated the blue water scarcity with 37% EFRs standard, and the monthly results are visualized in Figure 19. The crest value differences between maximum available blue WF and the blue WF is of S1, S1AA, and S2A- are narrowed down significantly, but the phase lag between maximum available water and the blue WF of scenarios still exist. Switching to 37% of EFRs relieved the water scarcity in 2006, 2007, and 2009 greatly, especially during the growing season. It freed all the months in the wet year out from severe blue water scarcity. The spatial distribution of blue water scarcity when switching to 37% EFRs change very little. This reconfirms that the scarcity level varies significantly temporally and spatially in YRB. The key to solving the blue water scarcity is to distribute the blue water use in a way that matches the blue water availability.

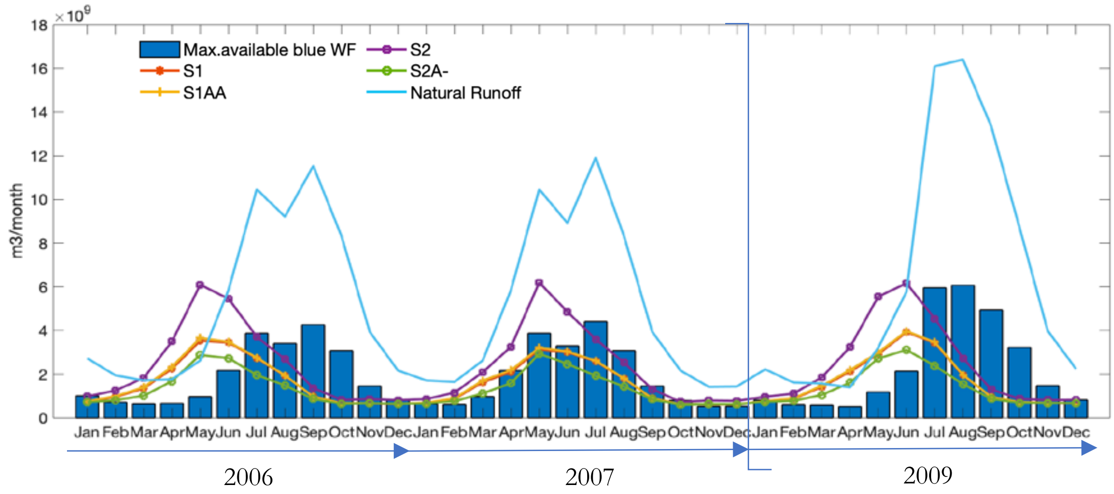


Figure 20: Monthly blue WF of scenarios, natural runoff and maximum available blue WF within YRB with EFRs as 37% of natural runoff.

Moreover, Sun et al. (2007) calculated the EFRs of the Yellow River Estuary and indicated that the minimum and medium levels of annual EFRs could be 23.7% , 28.7% and 48.5% of the natural river discharge at different flow level. This can be considered as the upper limit for water withdraw in YRB. Any violation to the limit can result in irreversible ecological damage. The EFR rule we chose for this study, the 80% EFRs, is widely adopted by earlier studies on YRB (Zhuo et al., 2016, b; Zhuo et al., 2018; Zeng et al., 2012). The change in EFRs rule will not change the essence implication of the results.

The effect of the reservoirs on blue water scarcity.

The maximum blue WF in this study is calculated under natural background conditions. The effect of the reservoirs over time and space was not included. The ideal effect of the reservoir is to redistribute the blue water and make up for the blue water scarcity. From this perspective, we may under-estimate the maximum blue water availability and over-estimate the blue water scarcity of YRB in some areas and some months. Zhuo et al. (2018) found that reservoirs can shift the phase of maximum available blue WF to match the blue WF. Then the blue water scarcity in dry years is significantly reduced. However, the blue water scarcity in the wet months especially in wet years is increased due to the inability of flood discharge to meet the high flow of environmental flow requirements of the basin. Reservoirs undeniably influence the blue water scarcity results, but reservoirs can also be operated in a way as a solution to the blue water scarcity.

The effect of the South-North Water Diversion Project (SNWDP)

This study is focusing on 2006, 2007, and 2009, no less than three years before the South-to-North Water Diversion Project was fully accessible. From one perspective, adding water to the basin may ideally decrease the blue water scarcity in the basin, but researchers also argue that adding water may increase both crop blue WF and blue WF loss along with the transportation (Wei et al., 2016). A higher crop blue WF may still result in higher blue water scarcity in some areas of the basin. This has to do with the marginal effect of blue water utilization for agriculture. From another perspective, the South-to-North Water Transfer Project artificially manages the total amount of water resources. The blue WFs and blue water scarcity under natural background conditions as in our study can guide the direction of future water resources distribution in a more precise and optimal way.

The blue water consumption in industrial and domestic sectors

The industrial and domestic blue water WF is assumed to be evenly distributed to 12 months of each year in this study since the ratio of the industrial and domestic sectors together is no more than 24% of the total blue WF in the reference case. Spatially, the blue WF of the industrial and domestic sector is also assumed to be distributed evenly based on the population density. But when the proportion of industrial and domestic blue water in the total blue water increases (applying scenarios), the methodology of equal distribution deviates from the actual situation. By applying S2A-, the ratio of the industrial and domestic sectors to total blue WF can increase up to 40%. Naturally, this is an average of the total value, but when assigning to the grid cell and monthly scale, the proportion will also change with the situation in the region. In that way, we may overestimate or underestimate the blue water scarcity in certain areas in certain months. For further research on the change of blue water scarcity of high resolution, data of industrial and domestic sectors of YRB in detail should be obtained.

Other limitations

There are other limitations of this study which may also influence the results from many aspects. For example, the effect of organic mulching may have more uncertainties: it is not suitable for all the crops like rice to apply organic mulching throughout its lifetime; the decomposition of organic mulching that adding the soil fertility cannot be quantified, etc. Another limitation could be no accounting of the field application efficiency. But these will not contradict the object of accessing the blue water scarcity change by applying crop-water management in a higher resolution. And we believe the results of this study can provide a valuable scientific base for the strict water management in YRB.

4.2 Comparison to other studies

The blue WF reduction rate by crop-water management we did in this study is to reduce the water footprint as much as possible without changing the planting time and gene types of crops. In other words, it is to find the lowest water footprint of the crop while ensuring the yield. This is consistent with the idea of establishing a water footprint benchmark. Thus, the blue water reduction rate of the current study is compared to the reduction rate from the average WF to the benchmarked WF studied by the other researchers. The benchmark level of Mekonnen and Hoekstra (2014), Wang et al. (2019), and Zhuo et al. (2016, a) are all decided by the 20% rule, which is the rank of WF within the best 20% of the producer. However, the WF of current study only focus on blue portion. There is no close match from the previous study on blue WF reduction. We may compare the separated blue and green water footprints of the Yellow River Basin in addition to comparing water footprint reduction ratios. The only literature that separates blue and green WF in YRB of major crops is Zhuo et al. (2016, b). However, the values are given as an average of continuous years during 1996-2005. Although the comparison is not a direct connection, it can still provide evidence and reference for the current research.

The current blue WF reduction rate is compared to the average blue WF reduction rate to the benchmarked blue WF of literature, and the results are listed in Table 12. For main crops such as wheat, maize, rice, cotton, and millet, the WF reduction rate to the benchmark level by Mekonnen and Hoekstra (2014) is similar to the reduction rate of S1. Nevertheless, this is not the case for other crops that account for less total production in YRB. The comparison confirms, to some extent, the feasibility of reducing irrigation water to bring down the water footprint to the lowest level. The significant difference in the WF reduction rate of other crops can be due to the data range where the WF benchmark is computed. The benchmark level from Mekonnen and Hoekstra (2014) compute the WF at a global scale. This cannot stand for the regional benchmark of a higher resolution. Wang et al. (2019) and Zhuo et al. (2016, a) studied the WF benchmark of wheat in China. Both of the studies have a smaller water WF reduction rate than the current study, which may be due to the non-separation of the green-blue WF benchmark.

The comparison of reference blue WF in YRB to the average blue WF of 1996-2005 from Zhuo et al. (2016, b) is also listed in Table 13. The estimation of Zhuo et al. (2016, b) is in general smaller than the estimation of current study. This may be due to the difference in the year of blue WF calculation. Also, Zhuo et al. (2016, b) combined the winter wheat and the spring wheat as a whole when calculating the blue WF.

Table 12: Literature comparison: the reduction rate of blue WF of crop production to the reduction rate of average blue WF to benchmark blue WF (lowest level of blue WF).

	Mekonnen and Hoekstra (2014)	**Wang et al. (2019)**	**Zhuo et al. (2016, a)**	**S1**	**S2**
Wheat	38.76%	19.65%	22.9% - 24.1%	41.94%	64.43%
Maize	47.00%	-	-	40.83%	51.79%
Rice	42.10%	-	-	35.31%	23.29%
Soybean	23.82%	-	-	55.61%	75.72%
Cotton	49.30%	-	-	49.16%	92.41%
Potato	38.38%	-	-	55.83%	70.91%
Millet	37.17%	-	-	40.81%	87.37%
Sorghum	63.40%	-	-	95.45%	59.09%

Barley	60.00%	-	-	82.68%	44.17%
Sugarcane	37.56%	-	-	5.47%	18.49%

Table 13: Comparison between reference blue WF of the average year and the average blue WF of 1996-2005 from Zhuo et al. (2016, b).

	Reference blue WF (m^3/kg)	**Zhuo et al. (2016, b) (m^3/kg)**
WinterWheat	400.11	510
Maize	364.96	195
Rice	540.71	225
Soybean	712.43	482
SpringWheat	1239.5	-
Cotton	1980.4	494
Rapeseed	780.92	-
Apple	63.549	72
Sweetpotato	112.48	57
Groundnuts	274.81	494
Potato	67.354	15
Millet	296.01	89
Sunflower	232.3	145
Tomato	229.1	19
Sorghum	304.96	45
Barley	59.878	61
Sugarcane	73.782	-

4.3 Scientific and practical potential of the study

The study analyzes the blue water scarcity of a river basin at a finer resolution from temporal and spatial resolution and explores possible changes in blue water scarcity through crop-water management which can reduce the water use of major crops in the basin. The study results have some scientific and practical significance in reducing the blue water scarcity in the river basin.

Scientific

The blue water scarcity assessments conducted at a finer time resolution (month) show that the annual assessment fails to capture the water scarcity that prevails during the dry season. The spatial water scarcity assessment reveals the uneven distribution of the blue WF. There can be regional water scarcity even during a wet month of the year. The blue water scarcity assessment on this scale can locate in detail when and where the scarcity happens. This method overcomes the generalization of the blue water scarcity in the YRB on an annual scale and the whole basin scale from previous studies. The study also covers a broader ground in bringing down the blue water scarcity and reveals the lowest water scarcity level reached with crop management and closing the yield gap.

Practical

This research has certain practical significance. Different irrigation volume is designed for the drought-sensitive and drought-tolerant stages of different crops. The formed irrigation strategy for each crop can be used in practice to increase crop productivity. However, this irrigation strategy needs to be adjusted artificially according to each year's precipitation time and depth. For example, if precipitation occurs during a drought-sensitive period, the irrigation time can be slightly delayed. Moreover, the organic mulching of all the crops throughout the life cycle might be dependent on manpower, since the mulch can fade away in months and new mulch is then required. The feasibility of organic mulching is still doubtful. As for closing the yield gap, it is theoretically feasible to reduce the yield gap to 100%. In practical applications, large-scale application of fertilizers and pesticides will bring a high grey water footprint. The margin returns for additional input makes the closing yield gap by fertilizers and pesticides less feasible.

4.4 Generalization of the methods and results

We can also apply this research method to other large river basins where water is scarce but engaged in food production. When data (climate, precipitation, soil characteristics, agricultural information, field management, etc.) are available and complete, the method can be extended to other river basins. This method can also evaluate water scarcity in other crop-intensive river basins with higher solutions and a temporal and spatial perspective. Therefore, analyzing whether reducing the water footprint through crop-water management can solve blue water scarcity in the basin. It can also help to understand the potential of water scarcity alleviation from complete perspectives and make policies correspondingly.

5. Conclusions and recommendations

5.1 Conclusions

Nowadays, the conflict between water scarcity in the river basin and the increase in food demand is deepening. Among all the water use sectors, agriculture consumes the primary part of blue water resources globally. Yellow River basin is a crop-intensive basin that has to feed 60 million people. However, the current water scarcity in the basin is not optimistic. Studies have accessed the blue WF of YRB and evaluated the water scarcity, but mostly in a lower resolution or cover either temporal or spatial aspect. Meanwhile, we want to know if crop-water management can solve the water scarcity problem in YRB, or to what extent.

We assessed the blue water scarcity of YRB in a dry year (2006), a wet year (2007), and an average year (2009) temporally (yearly and monthly) and spatially (grid cells) as reference case. The water scarcity is estimated as the total blue WF ratio to the maximum available blue WF; the values are classified into four levels: low, moderate, significant, and severe water scarcity. The blue WF of 17 crops in YRB is calculated at a 5*5 arcmin resolution with daily time step in three years. After simulating ET and yield by AquaCrop, partitioning blue ET from total ET, the blue WF is computed. After the general knowledge on how to calculate blue WF and blue water scarcity, we designed crop-water management strategies to bring down the crop blue WF. We collected the sensitivity of the crop growth stage to drought. In order to stabilize the yield, water stress that can affect leaf expansion or trigger early senescence is avoided during drought-sensitive periods, water stress that can affect induce stomatal closure during drought-tolerant periods is avoided. Six irrigation strategy tests are designed for each of the crops. Thus, strategy 1 is the combination of irrigation strategy (which can result in the lowest blue WF from the six tests) and organic mulching. Strategy 2 assumes that the yield gap can be closed by fertilizers and pesticides; thus, the potential yield is reached. We then designed an additional scenario for each strategy by changing the cropping area to compensate for the change in total production in order to compare the blue WF (m^3) reduction at the same production level. The four scenarios are: S1 (strategy1), S1AA (Strategy 1 with area adjusted), S2 (Strategy 2), and S2A- (Strategy 2 with area reduction). The blue water scarcity by applying scenarios is also analyzed temporally and spatially.

We found that the YRB experience severe, severe, and significant blue water scarcity in 2006, 2007, and 2009 as in reference case. The YRB faces severe water scarcity for 5-8 months a year. Three months in 2006 and four months in 2009 has the blue WF larger than 500% maximum available, which we define as complete depletion for this study. The total blue WF is six-folds of the maximum available blue WF in May. Spatially, half of the YRB is suffering from severe water scarcity throughout the whole year in all three years. Winter wheat and maize together contribute half of the total blue WF from March to August. The monthly blue WF can be relieved if the blue WF of major crops is brought down. The blue WF (m^3/t) can be significantly reduced by the two strategies and the four scenarios. The strategies are effective in bringing down the blue WF, especially for strategy 2. Twelve crops have a blue WF reduction above 50% by strategy 2. S2A- is the most effective scenario to bring down the blue WF (m^3) with a reduction rate of over 60% of all three years. 90% of the reduction brought by S2A- is contributed from wheat, maize, and rice. The variation blue WF reduction by S2A- is less than S1 and S1AA both temporally and spatially. Crop-water management cannot solve the blue water scarcity in YRB completely, but it can bring down the water scarcity to some extent. By applying the scenarios, the annual blue water scarcity in YRB is relieved, especially by S2A-. From March to June, the peak water demand in all three years is significantly mitigated by all the scenarios, particularly by S2A-. Monthly blue water scarcity is brought one level down for most months in three years. The spatial water scarcity is relieved in the north and middle Inner Mongolia, central Shaanxi province, and west of Qinghai province by all scenarios. However, by S2A-, almost half of the basin still having complete depletion in October (the least water-scarce month) while the other half of the basin has no water scarcity. This indicates that the water resource of some areas is too little that any utilization may result in severe water scarcity.

5.2 Recommendations

From the temporal scale, there is always a time lag of about three months between the crest value of maximum available blue water and the total blue water WF, no matter in the current case (reference case) or under the scenarios. The current research does not consider the impact of reservoirs. The current consideration is the blue water scarcity in the natural context, and the impact of artificial management and policies on blue water scarcity can be the follow-up management basis. Therefore, in order to improve the blue water scarcity in spring and summer caused by the time difference, we suggest using manual control to adjust the storage and discharge time of the reservoir to match the peak water consumption during plant growth. As long as the volume of discharge to the net flow is well controlled, the blue water scarcity can be well controlled in a lower range. Assessing the blue water scarcity with the concern of reservoirs may provide a different water scarcity pattern in YRB.

The study helps identify where and when water scarcity happens in the YRB and whether it can be improved by bringing down blue WF by crop-water management. It can be fundamental to set a scientific basis for policymakers to cope with the water scarcity in YRB.

This study is only performed on current crop species to bring down the blue WF, but not considering other techniques like conservation tillage, change to water-tolerant species with stable yield, changing crop patterns. Combinations with all other measurements to bring down the crop blue WF may suggest a new insight to solve the water scarcity problem in YRB.

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Appendix

I Crop growing stages, planting date, HI_0 and maximum rooting depth

Table 14: The planting date, relative crop growing stages, HI_0 and maximum rooting depth of 17 crops in the YRB. L_{ini} represents the initial stage of crop growing, L_{dev} represents the developing stage, L_{mid} represents the middle stage and L_{late} represents the late stage. Source: Zhuo et al. (2016, b).

Crop	**Planting date**	**Relative crop growing stages**					**Max. rooting depth (m)**	
		L_{ini}	L_{dev}	L_{mid}	L_{late}	HI_0	Irrigated	Rain-fed
Winter wheat	15/Oct	0.48	0.22	0.22	0.07	40%	1.5	1.8
Spring wheat	15/Mar	0.15	0.19	0.44	0.22	39%	1	1.5
Rice	01/May	0.20	0.20	0.40	0.20	43%	0.5	1
Maize	01/May	0.20	0.27	0.33	0.20	44%	1	1.7
Sorghum	01/May	0.15	0.27	0.35	0.23	39%	1	2
Millet	15/Apr	0.14	0.21	0.39	0.25	38%	1	2
Barley	15/May	0.13	0.21	0.42	0.25	39%	1	1.5
Soybean	01/Jun	0.13	0.17	0.50	0.20	44%	0.6	1.3
Potato	01/May	0.19	0.23	0.35	0.23	59%	0.4	0.6
Sweet potato	01/May	0.13	0.20	0.40	0.27	69%	1	1.5
Cotton	01/Apr	0.17	0.28	0.31	0.25	38%	1	1.7
Sugarcane	15/Apr	0.28	0.22	0.28	0.22	71%	0.7	1.2
Groundnut	15/Apr	0.25	0.32	0.25	0.18	43%	0.5	1
Sunflower	15/Apr	0.19	0.27	0.35	0.19	31%	0.8	1.5
Rapeseed	13/Mar	0.20	0.40	0.20	0.20	25%	1	1.5
Tomato	15/Jan	0.22	0.30	0.30	0.19	40%	0.7	1.5
Apple	01/Mar	0.13	0.21	0.54	0.13	20%	0.7	1.5

II Conversion factors from biomass to yield

Table 15: The conversion factors used to convert the biomass generated from AquaCrop to the fresh yield. Source: Fischer et al. (2012).

Crop	Conversion factor
Winter wheat	0.875
Spring wheat	0.875
Rice	0.875
Maize	0.87
Sorghum	0.88
Millet	0.9
Barley	0.9
Soybean	0.9
Potato	0.25
Sweet potato	0.3
Cotton	0.35
Sugarcane	0.1
Groundnut	0.67
Sunflower	0.9
Rapeseed	0.9
Tomato	0.15
Apple	0.15

III Blue ET, Y and blue WF of Reference, Strategy 1 and strategy 2

The blue ET (mm), Y(t/ha) and blue WF (m3/t) of each crop of the reference, strategy 1 and strategy 2 in all three years are calculated. The results of strategy 1 are calculated based on the best-practice maps. Yearly results are shown in Table 16, Table 17, and Table 18.

Table 16: The blue ET, Y and blue WF of the reference, strategy 1 and strategy 2 in 2006 (dry year).

	Blue ET (mm)			**Y (t/ha)**			**Blue WF (m3/t)**		
	Reference	Strategy 1	Strategy 2	Reference	Strategy 1	Strategy 2	Reference	Strategy 1	Strategy 2
Winter wheat	203.22	116.45	203.22	4.40	4.11	11.91	462.06	283.22	170.64
Maize	191.21	103.39	191.21	5.28	5.13	11.73	362.33	201.43	162.96
Rice	370.77	245.32	370.77	7.06	7.38	9.25	525.53	332.38	400.97
Soybean	106.14	53.26	106.14	1.40	1.59	6.01	759.94	334.16	176.56
Spring wheat	367.76	367.76	367.76	3.56	3.56	7.30	1032.80	1032.80	503.90
Cotton	195.22	85.38	195.22	1.16	1.06	16.43	1688.70	805.47	118.84
Rapeseed	155.19	154.61	155.19	1.77	1.80	5.11	875.03	858.94	303.49
Apple	112.19	46.41	112.19	12.96	16.30	4.62	86.54	28.47	242.83
Sweetpotato	41.25	22.71	41.25	3.41	3.89	28.80	121.09	58.31	14.32
Groundnuts	104.94	50.00	104.94	3.81	4.37	6.42	275.69	114.55	163.46
Potato	17.41	11.94	17.41	2.41	3.61	5.36	72.17	33.07	32.49
Millet	34.66	20.31	34.66	1.59	1.72	9.96	218.27	117.91	34.81
Sunflower	52.84	34.39	52.84	2.12	2.46	2.08	249.62	139.89	254.18
Tomato	193.26	121.28	193.26	5.59	5.56	35.18	345.46	217.94	54.93
Sorghum	85.35	34.92	85.35	3.43	3.51	10.03	248.81	99.41	85.07
Barley	24.77	15.22	24.77	5.00	5.69	4.46	49.53	26.77	55.49
Sugarcane	221.35	168.92	221.35	20.31	18.97	346.25	109.00	89.05	6.39

Table 17: The blue ET, Y and blue WF of the reference, strategy 1 and strategy 2 in 2007 (wet year).

	Blue ET (mm)			**Y (t/ha)**			**Blue WF (m3/t)**		
	Reference	Strategy 1	Strategy 2	Reference	Strategy 1	Strategy 2	Reference	Strategy 1	Strategy 2
Winter wheat	190.23	103.85	190.23	4.26	3.86	12.02	446.38	268.88	158.24
Maize	181.13	93.61	181.13	5.32	4.85	12.17	340.37	192.93	148.81
Rice	370.34	230.71	370.34	7.30	7.40	9.27	507.01	311.77	399.40
Soybean	95.83	46.98	95.83	1.53	1.69	6.53	624.33	277.31	146.68
Spring wheat	365.04	365.05	365.04	3.29	3.29	7.33	1108.70	1108.70	498.15
Cotton	193.90	76.65	193.90	1.14	1.03	16.84	1701.70	745.82	115.15
Rapeseed	140.28	139.94	140.28	1.85	1.86	5.17	759.92	754.11	271.08
Apple	92.31	29.76	92.31	12.94	19.06	5.04	71.32	15.62	183.02
Sweetpotato	37.10	18.84	37.10	3.29	3.61	30.25	112.68	52.25	12.26
Groundnuts	103.56	48.65	103.56	3.79	4.14	6.82	273.23	117.50	151.93
Potato	14.17	10.53	14.17	2.61	5.29	8.86	54.32	19.91	15.99
Millet	32.96	18.78	32.96	1.55	1.70	9.34	213.33	110.34	35.28
Sunflower	53.98	32.99	53.98	1.62	1.75	2.06	333.93	188.95	261.59
Tomato	182.58	108.20	182.58	5.81	5.73	34.95	314.38	188.95	52.24
Sorghum	83.41	31.50	83.41	3.44	3.28	10.04	242.59	96.10	83.07
Barley	23.66	15.05	23.66	4.76	5.07	4.51	49.66	29.67	52.45
Sugarcane	211.65	160.33	211.65	21.50	20.39	347.06	98.45	78.61	6.10

Table 18: The blue ET, Y and blue WF of the reference, strategy 1 and strategy 2 in 2009 (average year).

	Blue ET (mm)			**Y (t/ha)**			**Blue WF (m3/t)**		
	Reference	Strategy 1	Strategy 2	Reference	Strategy 1	Strategy 2	Reference	Strategy 1	Strategy 2
Winter wheat	175.03	93.51	175.03	4.37	4.02	12.30	400.11	232.32	142.30
Maize	191.22	104.41	191.22	5.24	4.84	10.87	364.96	215.93	175.96
Rice	388.53	266.87	388.53	7.19	7.63	9.37	540.71	349.76	414.80
Soybean	114.73	57.02	114.73	1.61	1.80	6.63	712.43	316.23	173.01
Spring wheat	401.78	401.78	401.78	3.24	3.24	7.38	1239.50	1239.50	544.11
Cotton	242.09	119.60	242.09	1.22	1.19	16.10	1980.40	1006.90	150.38
Rapeseed	151.10	150.69	151.10	1.93	1.95	5.19	780.92	774.46	291.13
Apple	89.69	34.16	89.69	14.11	19.80	4.86	63.55	17.25	184.54
Sweetpotato	38.96	22.73	38.96	3.46	3.86	30.87	112.48	58.91	12.62
Groundnuts	111.05	58.67	111.05	4.04	6.76	4.69	274.81	86.76	236.71
Potato	14.98	10.86	14.98	2.22	3.65	7.65	67.35	29.75	19.60
Millet	36.57	23.09	36.57	1.24	1.32	9.78	296.01	175.21	37.38
Sunflower	44.30	30.53	44.30	1.91	2.03	1.39	232.30	150.57	319.74
Tomato	167.56	99.71	167.56	7.31	7.24	34.78	229.10	137.66	48.18
Sorghum	88.58	36.50	88.58	2.90	2.93	9.28	304.96	124.75	95.45
Barley	28.91	20.15	28.91	4.83	6.03	3.50	59.88	33.43	82.68
Sugarcane	191.31	147.50	191.31	25.93	24.53	349.47	73.78	60.14	5.47