Defining and distinguishing water footprint benchmarks in crop production

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Abstract

Fresh water consumption increases with a growing world population and a switch to more water resource demanding diets. Agriculture accounts for 92% of humanity's water footprint (WF) (Hoekstra & Mekonnen, 2012). Therefore, a high potential in increasing water availability lies in decreasing the consumptive WF of crop production. The reference level to which the WF can be brought back is the water footprint benchmark (WFB). The WFB is the WF in m^3/ ton of yield that is grown under non-stressed conditions using the most water conserving cultivation practices. The development of WFBs has only started in 2013 and is therefore in an early stage. The objective of this research is to investigate if climate, soil or type of hydrological year give rise to the need to distinguish WFBs and how this is related to the physical environment and its interaction with the crop. To explore the differences in WFB caused by these environmental factors, WFBs were defined by performing a modeling study in AquaCrop, a crop growth model based on the water balance, developed by the FAO. A 30-year time series (1960-1990) of WFs were simulated for four crops (maize, wheat, potato and cotton) under "best practice", i.e. optimal growth conditions and most water efficient irrigation method in terms of resulting water productivity of the crop combined with organic mulching. Per crop, 16 scenarios with different climate-soil combinations were formulated (combining four climates from the Köppen-Geiger classification, Cfb, Af, Aw, Bsh, and four different soils, from low to high saturated hydraulic conductivity, namely clay, clay loam, silt, sand). The results suggest that it is relevant to distinguish WFBs based on climate, but not on soil type. No ground to distinguish WFBs for type of hydrological year was found as no strong relationship was observed between the WF and total precipitation over the growing season. WFBs need to be specified per type of climate because the weather pattern and total evaporative demand of the atmosphere over the growing season significantly affect both ET and Y and thus WFB. As no specific correlation between WF and hydrological year could be recognized, it is suggested to set the WFB at the highest best-practice WF that was found over of the 30-year study period. These WFBs are all lower than global WFBs resulting from a previous study. Therefore, this study suggests that if a crop is cultivated under best practice, it is reasonable to set WFBs lower than as yet established. Generally, a higher total atmospheric demand for water vapor over the growing season requires higher WFBs. Temperature seasonality can decrease the WFB and low temperatures can lead to cold stress and a higher WFB. The current research has focused on full irrigation. Under rain-fed conditions or supplemental or deficit irrigation, water stress could become important and the type of soil and hydrological year more relevant when specifying WFBs.

1 INTRODUCTION

Earth's freshwater resources are finite, and therefore their growing consumption leads to increased water scarcity (Hoekstra & Mekonnen, 2012; Vörösmarty et al., 2010). The demand for fresh water grows with the world population and a switch to more resource intensive diets. 92% of humanity's WF can be attributed to the agricultural sector (Hoekstra & Mekonnen, 2012). The Food and Agriculture Organization of the United Nations (FAO) estimates that by 2050, an increment of 60% over current agricultural production will be required in order to ensure worldwide food provision (Sadras et al., 2015). This implies that an effort to sustain fresh water availability is needed. This effort can be of two kinds; 1) constraining the growth of the total demand, and 2) increasing the efficiency of water use (Hoekstra, 2013 a)). This study feeds into the latter approach, with a focus on decreasing the consumptive water footprint (WF) of crop production. The consumptive WF is the amount of water that is lost from a river basin to consumption through crop evapotranspiration and "non-beneficial" evaporation per unit of yield (Hoekstra, 2013 b); Sadras et al., 2015). Decreasing the WF can be achieved by either increasing the yield per used unit of water ("more crop per drop") or by decreasing the amount of water used to produce one unit of crop ("less drop per crop") (Blum, 2009). The "more crop per drop" approach encompasses breeding towards varieties with higher yields per unit of transpired water, as discussed by Sadras & Richards (2014). The "less crop per drop" approach involves preventing transpiration, either by breeding towards varieties that transpire less water to produce the same amount of yield, or by under-irrigating the crop while minimizing yield compromise. Furthermore, preventing soil evaporation can decrease the amount of water used per unit of crop (Blum, 2009). The latter approach of decreasing the WF is the focus of this study.

The lowest level to which the WF can be reduced is understood as the Water Footprint Benchmark (WFB). The WFB is defined here as the WF in m^3/metric ton of a crop that is grown under the absence of water and nutrient stress, diseases and pests and using "best practice", i.e. most water conserving technology and cultivation practices (Hoekstra, 2013 b)). This makes the WFB the maximum WF that is required to produce optimal yield. WFBs can be used as a reference level to measure water efficiency performance and to develop WF reduction targets (Zwart et al., 2010; Mekonnen & Hoekstra, 2014). Moreover, they serve to identify priority areas, i.e. where most can be gained by WF reduction in terms of water scarcity mitigation (Zwart et al., 2010).

Former studies have mapped water productivity (WP) and WFs of crop production (Zwart et al., 2010; Mekonnen & Hoekstra, 2014; Zhuo et al. 2016). The maps showed high spatial variance, which can be related to the fact that environmental factors such as climate and soil influence the crop WF (Siebert & Döll, 2010; Hoekstra et al., 2011; Tuninetti et al, 2015). This suggests the requirement of context-specific WFBs. Namely, a WFB that is set too general may be met in one location A, but not in location B because more water may be required here due to different soil and climate conditions. Results by Zwart et al., (2010), Mekonnen & Hoekstra (2014) and Zhuo et al. (2016) all pointed out that the WF is primarily determined by the climate. However, low and high benchmarks were found within the same climate zones. This implies that other factors such as soil and agricultural practices may affect the WF significantly. Hence, a distinction may have to be made based not only on climate zone, but on a smaller resolution, e.g. for different soil types. The separate effects of climate parameters such as aridity, precipitation and temperature and soil have been systematically examined by Zhuo et al. (2016) in the case of winter wheat in China. However, the effects of combinations of factors have not yet been systematically examined. The studies cited above suggested to set WFBs as the WF at a certain production percentile, e.g. as the WF that is not exceeded by the lowest 25% found in the study area, i.e. the 25th production percentile. A problem inherent to this method is that it is not exactly known under which circumstances a WFB applies that is set at e.g. the 25th production percentile. The alternative is to determine "best practice WFBs", for known circumstances. Chukalla et al. (2015) followed this approach and focused on how different irrigation and field management practice can reduce the WF under specified sets of circumstances. A next step that can complement current knowledge is a systematic study of how environmental factors such as climate and soil determine the WFB that is sat as the WF obtained while using best practice. It is the purpose of this research to provide such a study.

1.1 PREVIOUS LITERATURE

The development of WFBs is currently in an early stage. Research fields that have played a role in the development of WFBs are yield gap analysis and water productivity benchmarking. Yield gap analysis encompasses the comparison of modeled yields under irrigated conditions to actual yields in order to detect potential to increase crop production. In yield gap analysis, potential yields are used as a benchmark (Van Ittersum et al., 2013). Research concerning WP benchmarks has been conducted for wheat in dry environments by Sadras & Angus (2006) and for sunflowers in semi-arid regions by Grassini et al. (2009). Following these regional studies, a pioneering publication on global WP benchmarks was made by Zwart et al., (2010). First global maps of water footprint benchmarks were published by Mekonnen & Hoekstra (2014). Research addressing WFBs for winter wheat in China was conducted by Zhuo et al. (2016). Each of the mentioned authors emphasize that more knowledge is required in order to ultimately make WFBs a good norm for setting WF reduction targets.

WFBs for crop production that have been suggested so far are total WFBs, i.e. they comprise the consumed water originating from both, precipitation (green water) and ground or surface water abstraction (blue water). The WFB (and also the WF) has a blue share if a crop is irrigation with ground or surface water. Based on results of former studies, the blue share in the water footprint benchmark, or "blue WFB", is expected to be dependent on green water availability and is thus expected to vary with precipitation (Zhuo et al., 2016). Complementing available green water with an amount of blue water that is just enough to enable optimal crop growth results in the highest WP (lowest WF). From this follows the presumption that the blue share of the WFB will increase with a decreasing green water availability. Within one climate, green water availability, and thus precipitation, naturally varies inter-annually. The consequences of this climate variability for the blue WFB has not directly been investigated so far (Zhuo et al., 2016). Neither has it been investigated how strong the relationship between total WF and precipitation is. If there is a strong relationship between total and blue WF and precipitation, a distinction of total and/ or blue WFBs for relatively dry and wet years may be in order.

1.2 OBJECTIVES AND RESEARCH QUESTION

The objective of this research is to explore if there is a need to distinguish WFBs for different climate zones, or if a distinction on a smaller resolution is necessary based on soil type. For this purpose, the differences in WF that climate and soil can cause will be compared. The extent to which the inter-annual variation in total precipitation over the growing season is responsible for inter-annual variation in WF is investigated to test if WFBs need to be distinguished for wet and dry years. Furthermore, this study aims to explain how interactions between crop and physical environment cause differences in WF. This understanding will be relevant in supporting the argumentation that WFBs need or need not to be distinguished based on one of the examined factors.

The research question (RQ) and sub-questions that follow from these objectives are:

RQ: *Do climate, soil and inter-annual climate variation cause differences in the WF that suggest a distinction of WFBs based on these factors?*

Sub-questions:

1) What is the best-practice WF for each climate-soil combination?
2) Are the differences in WF between climate zone, soil and years with different precipitation large enough to suggest a distinction of WFBs?
3) What interactions between the crop and its physical environment explain these differences?

2 METHOD AND DATA

2.1 GENERAL APPROACH

With a modeling study in AquaCrop, WFs were simulated for several scenarios in which extremes were sought for in order to cover a wide range of circumstances. Four crops (maize, wheat, potato and cotton, see section 2.3.3) and four different climate zones (Köppen-Geiger classes from humid to semi-arid: Cfb, Af, Aw, Bsh, see section 2.3.1 for definition) were selected with each four different soils (from low to high saturated hydraulic conductivity (Ksat): clay, clay loam, silt, sand, see section 2.3.2 for further detail). This results in 16 different climate-soil scenarios per crop, as illustrated in **Figure 1**. For cotton, modeling was omitted for the temperate Cfb climate (see section 2.3.3,**Table 3**) because it is not feasible to grow cotton in this climate. Therefore, the total number of modeled scenarios is 60. A WFB is defined as the WF under non-stress conditions and thus, the growth conditions were assumed optimal and uniform throughout a hypothetical field located within the 0.5x0.5-degree grid cell for which meteorological data were retrieved. Crop water stress was eliminated to a negligible extent by applying full irrigation (see section 2.3.4 for definition). Nutrient supply was assumed optimal. Temperature stress can still occur, depending on climatic conditions. Although Zhuo et al. (2016) omitted temperature stress from their study, it is considered important to include in the research as temperature stress is a factor that can influence the WFB (see calculation procedures, **Figure 2**). Besides, it cannot be controlled in a field situation, in contrast to water and nutrient stress or diseases and pest infestation. Salt stress was excluded from this study in order to keep the simulated WFs comparable. For each crop-climate-soil scenario, WFs were modeled for four irrigation methods (IMs) (Furrow, sprinkler, drip and sub surface drip (SSD) irrigation, see section 2.3.4 for definition), once combined with organic mulching (OM) and once without.

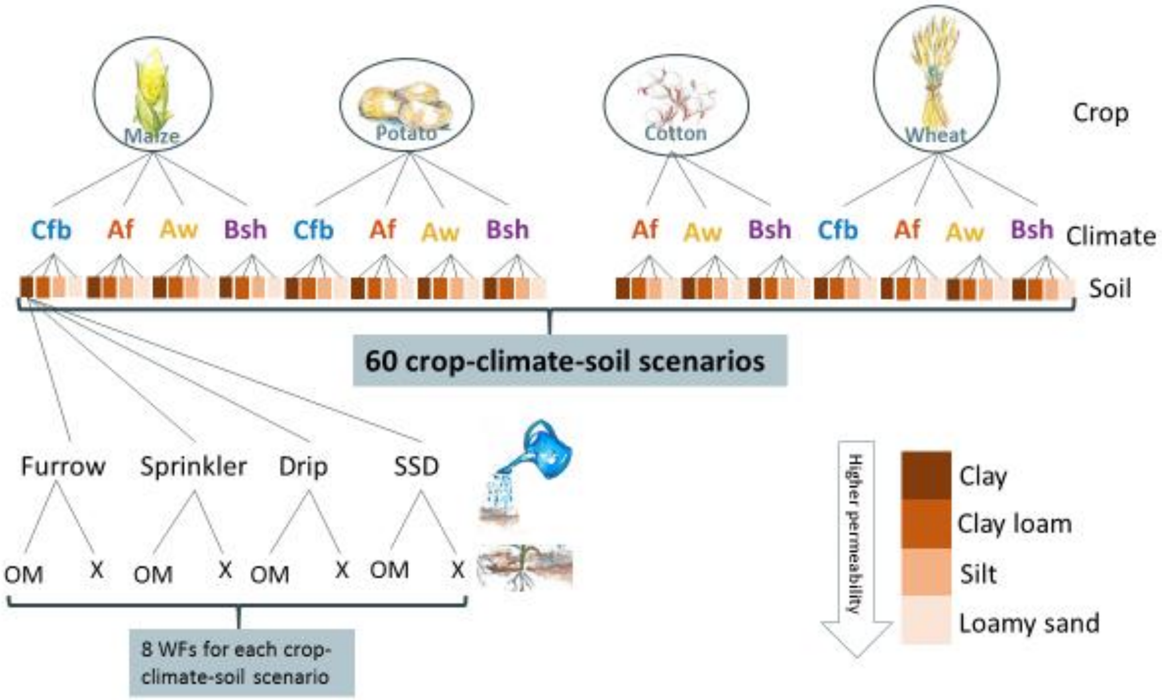


Figure 1 Scheme visualizing how scenarios are set up Af = equatorial, fully humid; Cfb=warm temperate, fully humid, warm summer; Aw=equatorial, winter dry; Bsh=arid, steppe, hot arid. SSD=sub surface drip irrigation. OM=with organic mulching, X=without organic mulching

This was done for a growing season with average climate conditions. The WF could be computed using the AquaCrop outputs for evapotranspiration (ET) and yield (Y) by

$$WF[m^3/ton] = \frac{CWU}{Y} = \frac{\sum ET}{Y}$$ (Hoekstra et al. 2011) [1]

Where CWU is consumptive crop water use. The differences between WFs obtained with different practices were examined to 1) be able to tell how large the effect on the WF of changing irrigation method (IM) are compared to the effect of applying mulch and 2) how large the differences between best and “worst” practice are.

For each crop-climate-soil scenario, the IM, either with or without mulching, under which the lowest WF was simulated will be defined as best practice. The WF that is obtained with this practice will be referred to as the best practice WF.

The best practice WF for each crop-climate-soil scenario was modeled for a time series of 30 years between 1960 and 1990. For each crop, the 30-year time series for each climate-soil scenario could be compared to each other by visualizing them as boxplots (Potter, 2006). Doing so, the differences caused by climate and soil and inter-annual variability could be deduced.

Inter-annual variability originates from climate variability, as soil is fixed and diseases, salt and nutrient stress are omitted from this research. Especially the blue WF is assumed to vary corresponding to the total availability of green water (precipitation (P)) over the growing season. Therefore, it is investigated how pronounced the dependence of the blue WFB on P is, and if there are other factors that cause inter-annual variability in WFs. For this purpose, the total WF was split into green and blue shares (see section 2.2.1) and plotted in dependence of the total amount of precipitation during the growing season for every crop in every climate on a clay loam soil. Clay loam was used for this exercise because it has the most average soil water holding properties. Dependent on the strength of the relationship, this will lead to an estimate if it is reasonable to make separate WFBs for years of which the growing season has a relatively high or low total P over the growing season.

2.2 SIMULATING ET, Y AND WF WITH AQUACROP

2.2.1 The AquaCrop model

AquaCrop simulates attainable crop yield in response to water (Steduto et al., 2009). As AquaCrop models ET and yield, WFs can be computed with the output. Origins of differences in WFs between different scenarios can be traced back by examining the output variables of crop growth and the water balance. AquaCrop responds to differences in cultivation practices, which allows to examine their effect on the WF and what best agricultural practice is for each scenario. A further advantage of AquaCrop compared to other crop simulation models is that “its parameters are explicit and mostly intuitive and the model was built to achieve a balance between accuracy, simplicity, and robustness” (Steduto et al., 2009).

The way in which AquaCrop models yield response to water is based on the empirical production function

$$\left(1 - \frac{Y}{Y_x}\right) = K_y \left(1 - \frac{ET}{ET_x}\right) \qquad [2]$$

Where Y_x and Y are the maximum and actual yield and ET_x and ET the maximum and actual evaporation (Raes et al., 2011). The terms $\left(1-\frac{Y}{Y_x}\right)$ and $\left(1-\frac{ET}{ET_x}\right)$ represent relative yield decline and relative water stress, respectively. K_y is the proportionality factor between these terms.

AquaCrop adds to this approach through the separation of ET into Tr and E by $ET = E + Tr$. This enables to distinguish between soil evaporation, which is seen as non-productive consumptive use, and productive consumptive use in Tr. It also enables to model the influence of irrigation and field management, which is important for this study as different irrigation methods and mulching will be considered.

AquaCrop also separates Y into B and HI by $Y = HI\ (B)$. This has the advantage that the effect of stresses on these variables can be modeled separately and thus make process more realistic (Raes et al., 2011).

Fout! Verwijzingsbron niet gevonden. schematically presents how yield is calculated in AquaCrop and which factors are involved and how they are influenced. In the following, the most important processes for this study will be addressed in more detail.

Growing degree days (GDD). GDD is a heat unit which is calculated as

$$GDD = T_{avg} + T_{base} \tag{3}$$

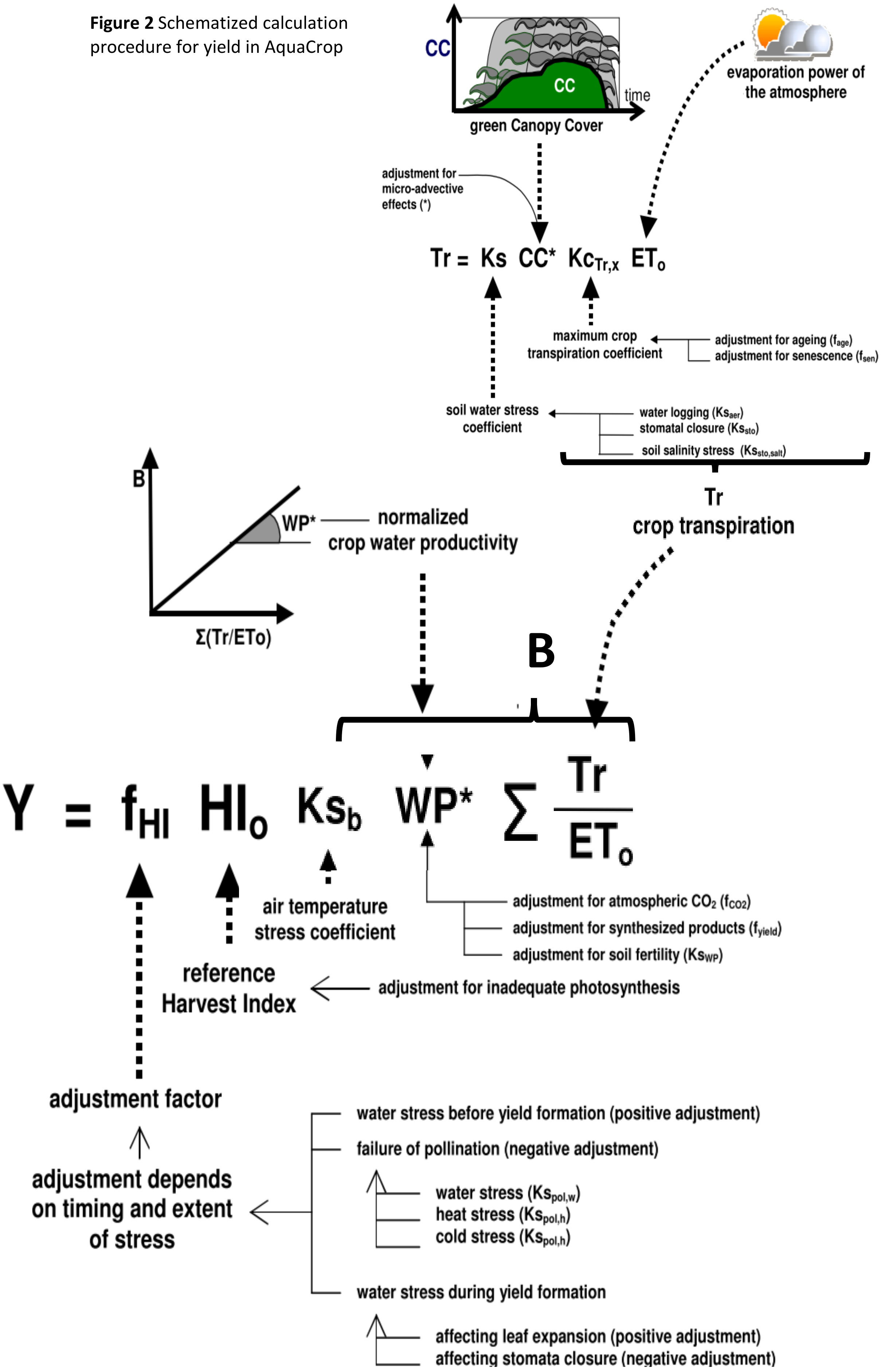
Where T_{avg} is the average air temperature and T_{base}, is the temperature below which crop development does not progress (Raes et al., 2012).The duration of crop development phases in this study are expressed in GDD.

Canopy development. Canopy development is simulated by the exponential growth function

$$CC = CC_0\, e^{t\, CGC} \tag{4}$$

Where CC is canopy cover, CC_0 is initial canopy cover at the time of 90% crop emergence (Raes et al., 2012b), t is time in days or as in this study GDD and CGC is the canopy growth coefficient, which is the increase of fraction ground cover per day or growing degree day (Raes et al., 2012). According to equation 4, canopy development increases faster under higher GDDs and thus under higher temperatures.

Figure 2 Schematized calculation procedure for yield in AquaCrop



How and why WP is normalized for climate. The crop water productivity (WP) is the amount of biomass (B) that a crop produces per unit of transpiration (Tr). B and T have been widely accepted to be strictly linearly related (Tanner and Sinclair, 1983; Howell, 1990). On the leaf scale the water productivity through photosynthesis WP_P is given by

$$WP_P = \frac{A_1}{T_1} = \frac{r_b + r_s}{r'_b + r'_s} = \frac{r}{r'}\frac{\Delta c}{\Delta w} = 0.625\frac{\Delta c}{\Delta w} \quad [5]$$

Where A=carbon assimilation, T is transpiration, r, r_b and r_s are the total boundary layer and stomatal resistances for CO_2 transport, respectively; r, r_b and r_s are the total boundary layer and stomatal resistances for water vapor transport; Δc and Δw are the concentration differences of CO_2 and water vapor, respectively, between the atmosphere and the inside of the leaf (Steduto et al., 2007). A substantial body of experimental evidence show that for a wide range of species the CO2 concentration in the leaf remains constant under varying conditions (Wong et al. 1979; Pearcy 1983; review by Morrison 1987; Hsiao and Jackson 1999). This was tested for variation in temperature, radiation, water supply, leaf nitrogen content and salinity stress (Steduto et al., 2007). The physical reason is that plants have evolved mechanisms to adjust assimilation to the inflow of CO_2. In C4 crops, the CO_2 concentration in leafs is generally lower than in C3 crops due to differences in photosynthetic pathways (Steduto et al., 2007). This causes an elevated Δc in C4 crops, which in turn is responsible for their higher WPs compared to C3 crops.

To be able to state WP_P as a constant crop parameter, it has to be normalized for climate (Steduto et al., 2007; Perry et al., 2009). To explain this, suppose two identical crops are grown at the same time of the year in different climate zones. The atmospheric concentration of CO_2 is equal and the CO_2 concentrations in the leaves are also constant. Therefore, there is no difference in Δc between the crops. However, the atmospheric demand for water vapor, represented by reference evapotranspiration (ET_0) in this study, can differ for the two climate zones, as well as for different sections of the growing season. If ET_0 increases, Δw increases and thus WP_P decreases. On a leaf scale, the normalization is executed by multiplying with Δw on both sides of equation 5. This gives the normalized WP_P in carbon assimilation per unit of Tr/Δw.

On the scale of biomass production, the normalization for climate suggested by Steduto et al. (2007) and Perry et al. (2009) is to give WP in biomass produced per unit of the ratio total Tr over total ET_0 in one time step. In equation form this becomes

$$WP* = \frac{B}{\sum \frac{Tr}{ETo}} \quad [6]$$

Where WP* is normalized water productivity and B is biomass. Values for WP* that are used in AquaCrop are taken from Raes et al. (2012a). All crop parameters, including WP*, are obtained by calibrating and validating the model with experimental data. The corresponding field experiments were conducted in diverse locations and under conditions that vary in favorability (Raes et al. 2012a). As WP* is given in units of $\sum \frac{Tr}{ETo}$, biomass produced over a certain time interval is calculated by

$$B = WP^* * \sum \frac{Tr}{ETo} \quad [7]$$

From this it follows that the slope of the linear relationship between B and Tr is steeper for a lower ET_0 than for a higher ET_0, i.e. crops are less productive in circumstances of high ET_0 as compared to in circumstances with a low ET_0. This is visualized in **Figure 3**, where A’’’ is WP for low ET_0 and A’’ is WP for high ET_0. Equation 7 applies for unstressed conditions. AquaCrop accounts for plant stress by multiplying by stress coefficients in various steps in the process of calculating yield (Y) (see **Figure 2**).

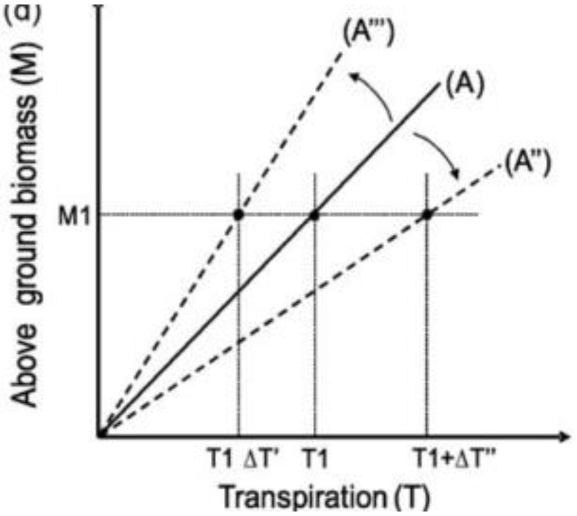


Figure 3 WP for different ET_0 (from Perry et al., 2009). A''': WP for low ETo. A'': WP for high ETo.

2.2.2 Post-processing of AquaCrop output to obtain green and blue WF

The output data of AquaCrop were post-processed to separate ET into a blue and a green fraction. For every day, the relative color composition of the soil water content was derived (see equations in Appendix I). The same color composition was assumed for E and T, which allows to compute the green and blue fraction of E and T for every day, and thus for the whole growing season.

2.2.3 Cropping calendar, initial soil moisture and irrigation schedule

In AquaCrop, the user decides on which crop files to use, initial soil water conditions and depleted percentage of readily available soil water before irrigation takes place. How these decisions were made for this study and how they can influence the resulting WFs is discussed in Appendix III.

2.3 INPUT DATA

2.3.1 Climate

Four typical and diverse climate classes from the Köppen-Geiger classification (updated version by Kottek et al., 2006) were selected in which agriculture takes place on a large scale. Fout! Verwijzingsbron niet gevonden. shows an estimate of worldwide crop land distribution for the year 2000, overlain by the climate classes selected for this study (Ramankutty et al., 2008). Most of the areas that have a high concentration of cropland (green color in Fout! Verwijzingsbron niet gevonden.) are located within one of the selected climate classes or in a class that is well comparable to one of them. The Köppen-Geiger classification is the most widely used classification for climate related studies (Kottek et al., 2006). It is applicable because the classification is based on climatic parameters (and not e.g. vegetation), which are also used as input for AquaCrop.

The selected climate classes are:

- **Af** (equatorial (A), fully humid (f)), because it is extreme in a sense that it is the warmest and at the same time the most humid climate in which agriculture takes place.
- **Cfb** (warm temperate (C), fully humid (f), warm summer (b)), because it represents the areas with concentrated agriculture of the mid latitudes in eastern US, Europe, eastern China, Argentina, eastern Australia. Fout! Verwijzingsbron niet gevonden. reveals that agriculture

production in the mid latitudes is also located in the Dfb climate. The difference is that snow is common in winters of D climates. As cultivation of the crops examined in this study mainly takes place during summer, it is assumed that the Cfb climate is still a good representative of agricultural areas in the mid latitudes.

- **Aw** (equatorial (A), winter dry (w)) is representative for areas with concentrated agriculture in semi-arid climates. Aw covers extensive areas in South America (mainly Brazil), Central Africa and India
- **Bsh** (arid (B), steppe (s), hot arid (h)) because it is the most extreme climate under which agriculture takes place on a large scale. Assuming it to be comparable to Bsk (arid, steppe, cold arid) in terms of water availability, Bsh is considered representative for areas with concentrated agriculture in large part of Australia, Sub Saharan Africa and India.

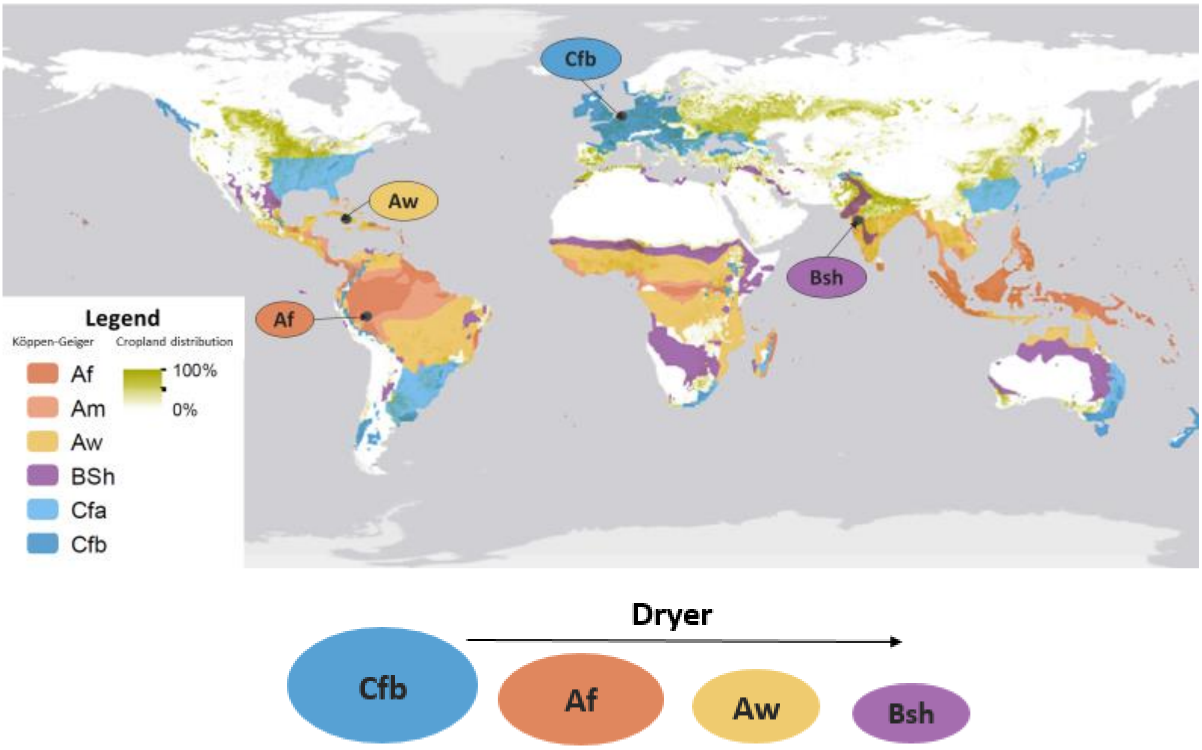


Figure 4 Köppen-Geiger classes used in this study and estimate of cropland distribution for the year 2000 by Ramankutty et al. (2008). Selected representative locations are indicated with arrows and abbreviation of the climate class.

The meteorological data that represents the selected climate zones were acquired from the Climate Research Unit (CRU) dataset, version 3.23 (Harris, 2015). This dataset contains world maps (only for land cells) with a 0.5x0.5 degree resolution of daily values from 1961 to 1990 for amongst others precipitation, maximum and minimum temperature and ET_0, which are required as input for AquaCrop.

The four locations from which climate data is used are the grid cells with the most representative climate for each zone. For each zone, this cell was selected from the five most average cells, i.e. those with the smallest absolute normalized difference from the average over the years 1961-990 within the zone. The five most average cells from each zone were compared based on the sum of the absolute normalized differences of average yearly ET_0, yearly precipitation, annual temperature, temperature range and aridity index. The process that was used to obtain the cells is attached in Appendix II.

The locations of the five cells were selected as the five most average land based crop land cells for each zone. The crop land distribution map by Ramankutty et al. (2008) was used as a reference to identify the cells as crop land (see **Figure 4**). The selected locations are displayed in **Table 1**. In the course of this thesis, the locations will be referred to with the abbreviations of the climate zone they represent.

Table 1 Locations and years for which climate data are retrieved

Climate		**Location**		
Abbr.	Meaning	Coordinates (longitude; latitude)	Country	Province
Af	equatorial, fully humid	-71.75; -7.75	Brazil	Acre
Aw	equatorial, winter dry	-77.75; 21.25	Cuba	Camagüey
Bsh	arid, steppe, hot arid	74.25; 20.75	India	Maharashtra
Cfb	warm temperate, fully humid, warm summer	4.25; 51.75	Netherlands	Zeeland

2.3.2 Soil

This study aims to simulate WFs that are generated under known conditions. Hence, not the default soils of AquaCrop were used because the textures of these soils other than the required hydrological parameters are unknown. The newly selected soils are systematically spread throughout the soil texture triangle as proposed by the United States Department of Agriculture (USDA, 1951) (see **Figure 5**). To fulfill the purpose of obtaining a complete range of WFBs, soil textures were selected close to each corner of the triangle and one from the center. This results in the following soil textures:

- Loamy sand (80% sand, 10% silt, 10% clay)
- Silt (80% silt, 10% clay, 10% sand)
- Clay (52% clay, 25% silt, 23% sand)
- Clay loam (30% clay, 30% silt, 30% sand)

The composition of the clay soil was altered from an initial 80:10:10 to the composition listed above, because the saturated hydraulic conductivity (K_{sat}) was as low as that in many scenarios it caused too much water stress in the early growing stages of crops for them to survive. The composition was changed in a way that it doubled the former K_{sat}. This resulted in the composition 52:25:10.

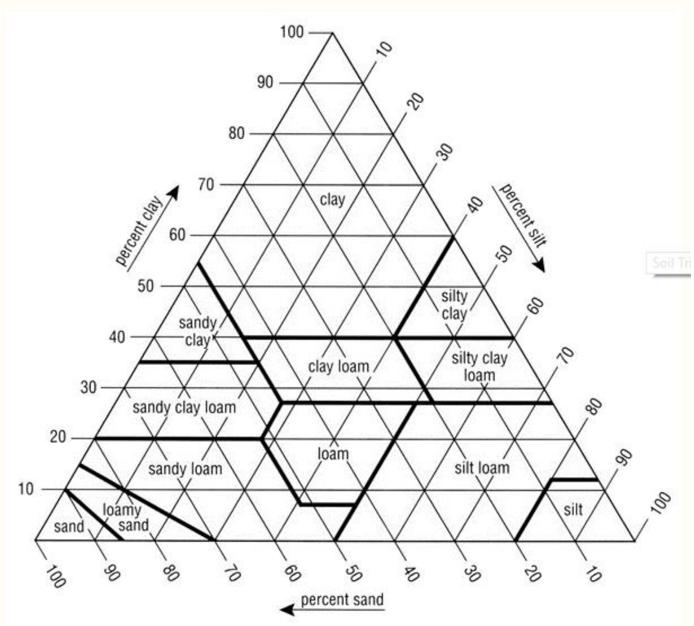


Figure 5 USDA Soil texture triangle (USDA, 1951)

To estimate the hydrological properties of these soils, the soil texture-based estimation routine of the USDA's Soil-Plant-Air-Water (SPAW) model was used (Saxton & Willey, 2006). In **Table 2**, the soil water holding characteristics for every of the four soil types are listed.

Table 2 Soil water holding characteristics of selected soils

	Clay	Clay loam	Silt	Loamy sand
Saturation [%]	50.0	42.8	84.4	44.6
Field capacity (FC) [%]	42.8	33.8	31.7	14.6
Permanent wilting point (PWP) [%]	30.9	19.1	8.4	8.0
Ksat [mm/d]	24.4	158.5	402.3	1499.6

2.3.3 Crops

The crops that were selected for this study are maize, wheat, potato and cotton. This selection was made respecting the following criteria.

1) The crop should account for a major part of global agricultural production as these have the largest influence on water resources globally.
2) The four crops should be diverse in sort
3) It should be feasible to irrigate the crop with drip or SSD irrigation to make sure that the analysis of the influence of these practices are relevant.
4) The crop should be possible to grow in all selected locations from which climate data are retrieved.
5) Preferably the crop has been examined in previous WF studies to be able to compare results.

Table 3 shows a ranking of the 10 most produced commodities in quantity according to the FAO database FAOSTAT (2016). Table 3 explains which of these crops were selected and how they meet the criteria.

Table 3 Motivations for crop selections

Rank	Crop	Criteria fulfilled	Explanation
1	Sugar cane	1, 2, 3	
2	Maize	1, 2, 3, 4, 5	2) Maize is a C4 crop. 4) Maize was chosen over sugar cane (also C4) because it can be grown in all the selected climates and 5) because it is included in studies by D. Chukalla et al. (2015) and Mekonnen & Hoekstra (2014)
3	Rice, paddy	1	Was not selected because only meets criterion 1.
4	Wheat	1, 2, 3, 4, 5	2)Wheat is a cereal, just as Maize, but it is a C3 crop 3) Drip irrigation in wheat is economically feasible for some species in arid climates (El-rahman 2009) 5) Is included in studies by and Zhuo et al. (2016) Zwart et al. (2010) and Mekonnen & Hoekstra (2014)
5	Milk, whole fresh cow	Not a crop	
6	Potatoes	1, 2, 3, 4, 5	2) Tuber crop 3) Drip and SSD can be beneficial under many circumstances (Shock et al. 2013) 5) Included in Chukalla et al. (2015) and King & Stark (1997).
7	Vegetables, fresh		
8	Sugar beet		
9	Cassava		
10	Soybeans		
	Cotton	1, 2, 3, 5	Cotton was selected as the fourth crop because 1) Although it is not in the 20 top commodities in quantity, it is famous for its large effects on water resources as it is grown and irrigated mainly in warm and dry climatic regions. (Hoekstra 2008) 2) It is different from the other 3 as it is a fiber crop 3) Drip and SSD are emerging and suggested in cotton production (Cetin & Bilgel, 2002) 4) Analysis for the Cfb climate will be omitted as it is not feasible to grow cotton in this climate. 5) Cetin & Bilgel, 2002)

2.3.4 Agricultural practice

Irrigation method (IM). All the IMs that are possible to apply in AquaCrop are included. These are furrow, sprinkler, drip and subsurface drip irrigation. AquaCrop distinguishes irrigation method by the wetted percentage of the soil surface. **Table 4** shows the wetted percentage of the soil surface for all four IMs.

Table 4 Percentage of wetted surface for irrigation methods

IM	Furrow	Sprinkler	Drip	SSD
% wetted surface	80	100	30	0

Irrigation strategy. Full irrigation will be used in all the agricultural practice component types. Full irrigation means that the crop is supplied with enough water at all times. This strategy aims to maximize production per hectare. The alternative, deficit irrigation (DI), aims to maximize production per volume of water by under irrigating in development phases in which yield is compromised the least. Full irrigation is used in this study for all scenarios. This is considered a reasonable decision because on average, DI decreases the WF only by one to a few percent (Chukalla et al., 2015; Hoekstra, 2013). Besides, full irrigation is currently most commonly used as in most cases a switch to DI is laborious and expensive. Such a switch might be realistic for high value crops, but not for the low value crops that are considered in this research. Full irrigation is translated to AquaCrop by defining the irrigation depth that is applied per irrigation event as the amount of water that is to be added to bring soil moisture back to field capacity. An irrigation event occurs as soon as the readily available water is depleted by a defined percentage. This percentage defines the timing of irrigation events and therefore the irrigation schedule and was set at 20% for this study (see Appendix III for motivation).

Mulching. Only organic mulch (OM) is included in this study. OM consists of crop residue or other plant material that is applied onto the soil surface between crops. Synthetic mulching was excluded from this study because it is not realistic for example to cover extensive cereal fields with plastic foil. Organic mulching can decrease the WF substantially under drip and SSD irrigation, especially under humid climates (Chukalla et al., 2015). In this study, a WF will be modeled for every irrigation method once with OM ("OM" in Figure 1) and once without ("X" in Figure 1). Doing this, it is possible to see for example if mulching on its own can have comparable effects as switching irrigation method. In AquaCrop, OM is assumed to reduce soil evaporation by 50%.

3 RESULTS

3.1 SELECTION OF WHAT IS BEST-PRACTICE (PER CROP-CLIMATE-SOIL SCENARIO)

Fout! Verwijzingsbron niet gevonden. shows the WFs for all climate-soil scenarios for maize under different combinations of irrigation technique and mulching practice. The same figures for wheat, potato and cotton can be found in Appendix IV. The lowest attainable WF for each climate-soil combination is marked in blue. These WFs are always obtained under the application of mulch. The irrigation method (IM) under which the lowest WF is obtained is considered best practice in combination with mulching. It occurs that two IMs have an equal impact on WFs. Consequently, they are equivalent for best practice. In cases where no irrigation takes place due to the high availability of green water, e.g. in the Af climate, all WFs with the same field management are equal. Best practice IM differs between climate-soil combination, but is always either drip or SSD.

The differences in WFs caused by IM and mulching practice were examined to enable an objective and situation specific view on what is best practice. **Table 5** shows the average WF reductions from worst to best practice IM, both when mulch is already applied (column 1) and when it is not (column 2) and the average WF reductions when mulch is applied (column 3).

The reductions achieved by mulching (column 3) are from 1.5 to 3.5 times higher than the reductions achieved by switching from worst to best IM (column 2). When mulching is already applied, the WF reductions by changing IM are even smaller

The reasons why reductions in WF by changing IM are so small within one climate-soil scenario is related to the absence of water stress. As this excludes limitations to Tr, any differences in WF within a climate-soil-scenario are caused by differences in E. The amount of irrigation water that is lost by evaporation due to differences in a more or less efficient IM is very small compared to irrigation depth.

The reduction in WF caused by applying organic mulch are larger because AquaCrop assumes that 50% of E is prevented in all cases. However, the difference of mulching versus no mulching is not the same for every IM. This has to do with the difference in wetted surface between IMs. As sprinkler irrigation causes the largest wetted surface (100%), of all IM's, it causes the largest soil evaporation. Therefore, reducing it by 50% has a relatively large effect on the WF for this IM.

Table 5 WF reduction by switching IM versus applying mulch

	Worst to best IM with mulch	Worst to best IM without mulch	By applying mulch
Maize	3%	5%	13%
Wheat	2%	5%	16%
Potato	4%	11%	18%
Cotton	2%	4%	14%

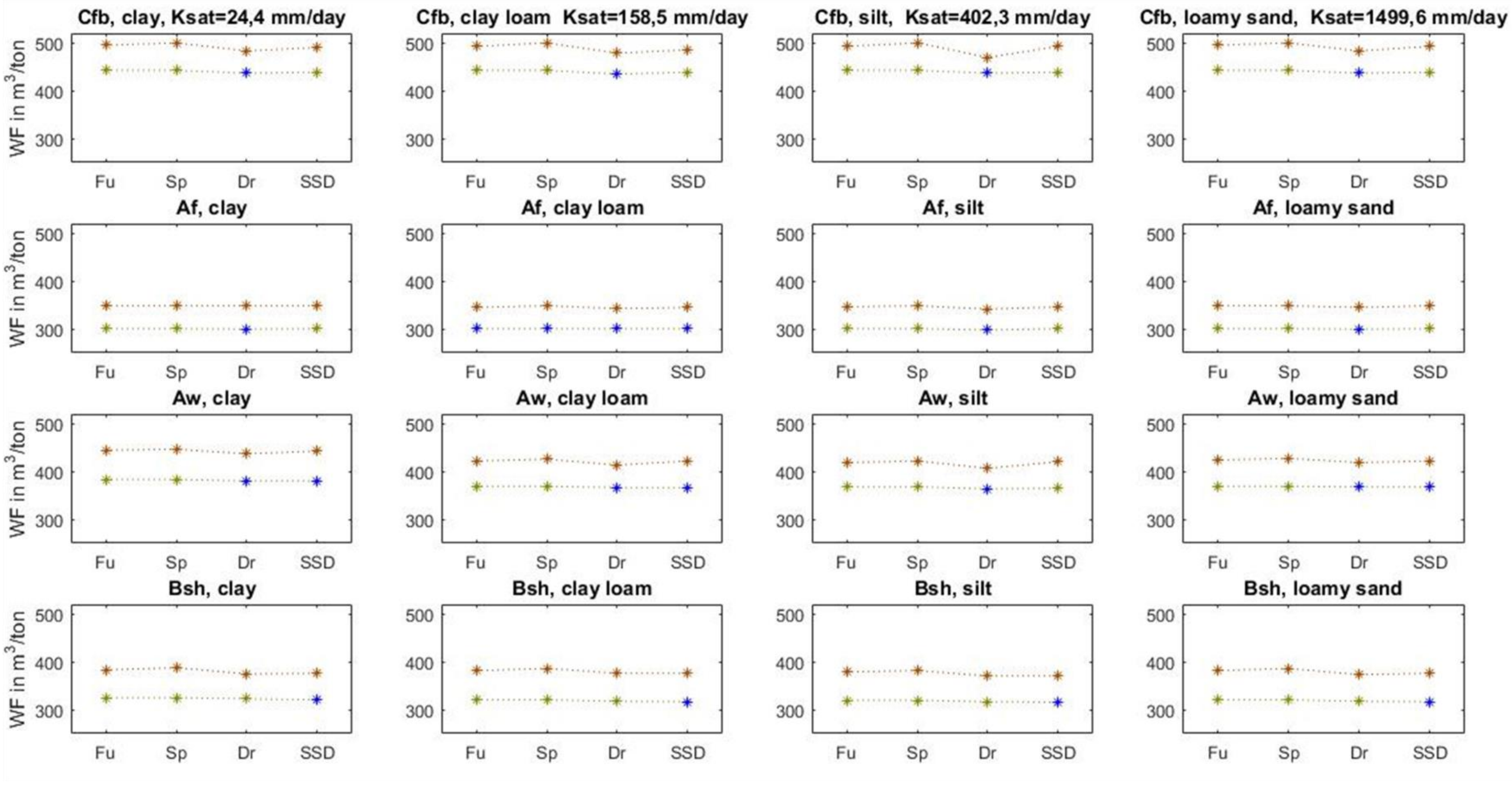


Figure 6 WFs for maize in all climate-soil-management scenarios. Brown: WFs simulated without mulch. Green: WFs simulated with mulch. Blue: lowest WF for the climate-soil-scenario. Fu = Furrow, Sp= Sprinkler, Dr = Drip, SSD = Sub surface drip

3.2 DIFFERENCES IN WFB CAUSED BY SOIL, CLIMATE AND TOTAL P OVER THE GROWING SEASON

Figure 7 displays all WFs simulated under best practice for all crop-climate-soil scenario. Each boxplot contains the WFs simulated for the growing season of the corresponding crop in each year between 1960 – 1990 for one soil type. The soil type is indicated on the x-axis. The color of the boxplot represents the climate.

Comparing the boxplots for one climate for one crop in the horizontal direction reveals that the differences in WF caused by soil are relatively small as they lay in the order of magnitude of several to tens of m^3. Expressed in percentages this is a difference of 2% for maize to 4% for cotton. Comparing the boxplots in the vertical direction brings out that the differences in WF caused by climate are larger than those caused by soil, laying in the order of magnitude of hundreds of m^3. It differs per crop which climates have relatively high and low WFs.

The differences caused by inter-annual variability of the climate is reflected in the ranges around each boxplot that are covered by the whiskers. These ranges are often larger than the differences between climates. This can cause the ranges around scenarios differing in climate to overlap. The smaller this overlap is, the less likely it is that similar WFs occur in the scenarios that are being compared. There are scenarios between which climate causes as much difference as that there is no overlap between the uncertainty ranges, e.g. for cotton. It differs per crop how much overlap there is and between which climates.

To know if total P can give reason for distinction for the total WF and possibly the blue WF between wet and dry years, the relationship between the total and blue WF and P was investigated. **Figure 8** displays for each crop in each climate the total WF split into green and blue shares, plotted in dependence of the total amount of precipitation during the growing season of the year in which the corresponding WF was simulated. The scales are adjusted to the largest occurring values per climate, so direct comparison is possible between climates. The plots include linear regression lines between total and blue WF and P (dotted lines). The coefficient of determination (R^2) is displayed next to each regression line. The R^2 values range between 0 – 0.226. This implies that the correlation between P and the total and blue WF is weak and that the inter-annual variance in WFs is hardly explainable by the total amount of P over the growing season.

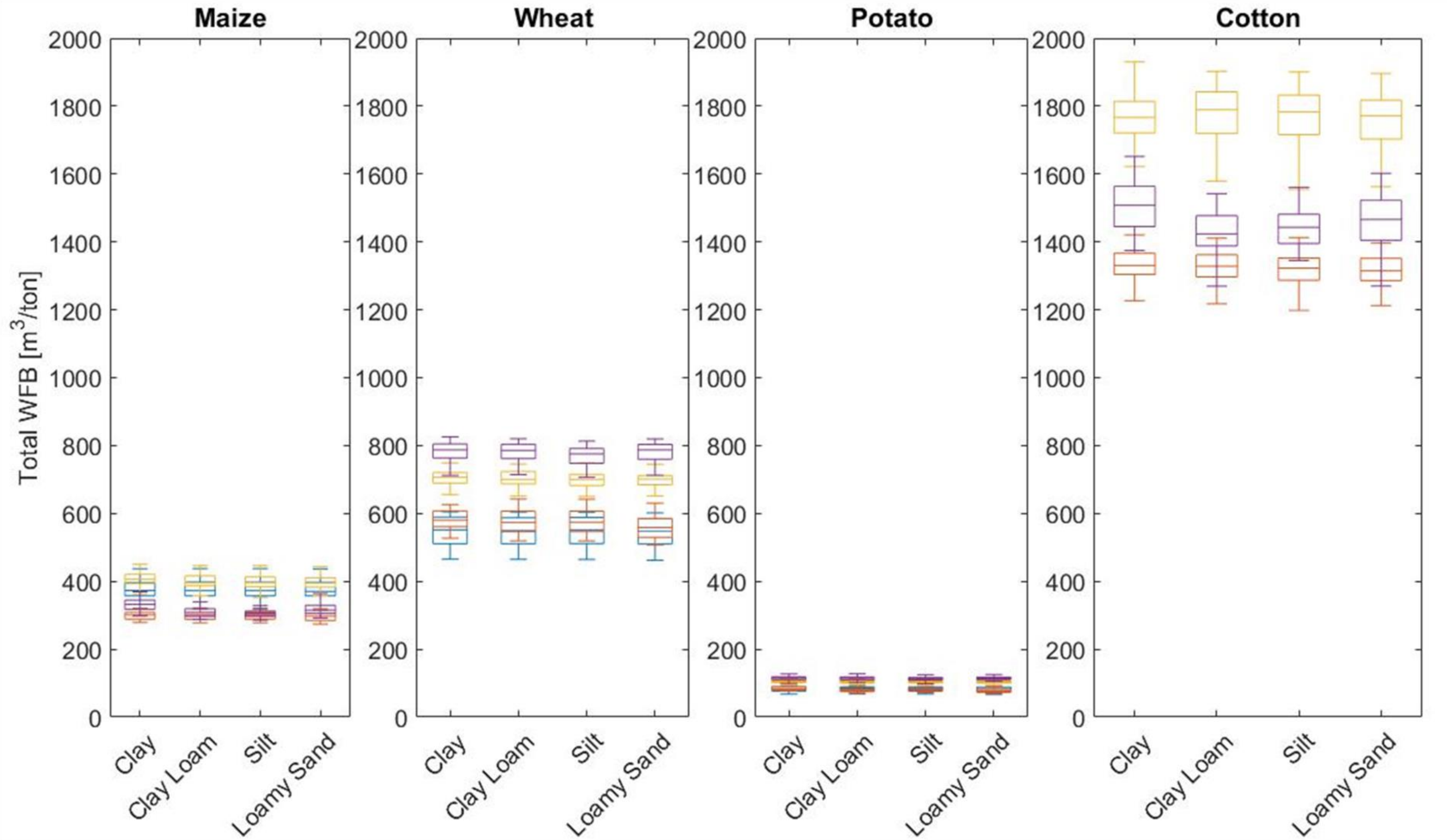


Figure 7 WFs for all crop-climate-soil scenarios for the 30-year time series from 1960-1990

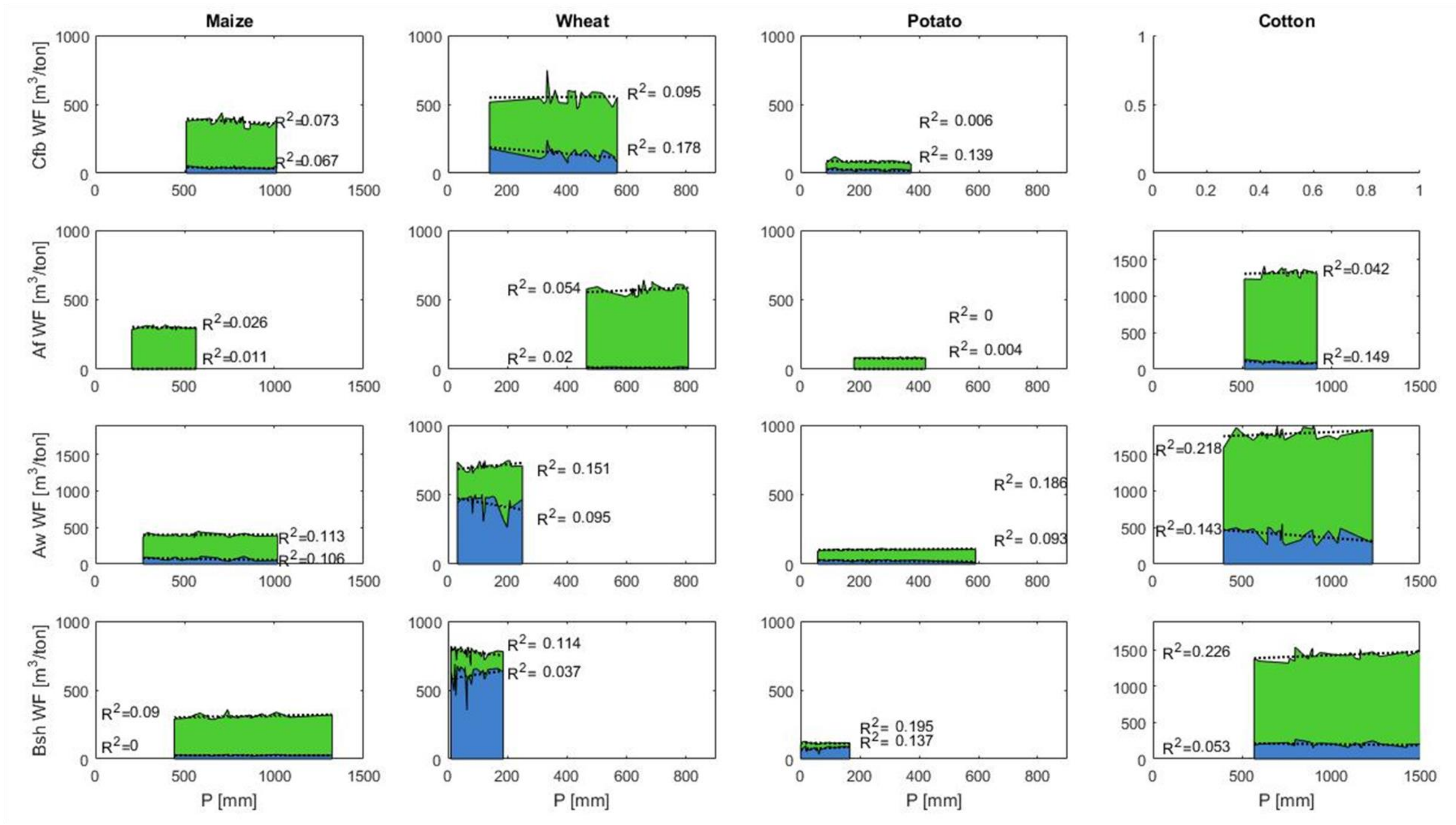


Figure 8 Dependence of the total and blue WF on total P over the growing season. For each crop in each climate the total WF is displayed split into green and blue shares. These are plotted in dependence of the total amount of precipitation during the growing season of the year in which the corresponding WF was simulated. Dotted lines: linear regression. R^2: coefficient of determination.

3.3 CLIMATE FEATURES THAT INFLUENCE THE WF

The WF can be influenced by ET_0, temperature and precipitation and their distribution over growing seasons of crops. The latter depends on the time of the year that growing season includes. **Figure 9** visualizes the timing of the growing seasons for each crop in the context of each climate, together with the average temperature, precipitation, ET_0 and aridity index (AI, right part of the figure). An indication to what extent the WF of a crop is determined by total ET_0 over the growing season can be deduced from comparing the relative magnitudes of total ET_0 and WF of the different climates (see section 4.1.1). **Figure 10** displays the best practice WFs for all scenarios and the average total ET_0 for all crops over the growing seasons corresponding to each climate. **Figure 10** also shows the average yield for each crop in each climate. This information is required to support the explanation of how other climate properties influence the WF.

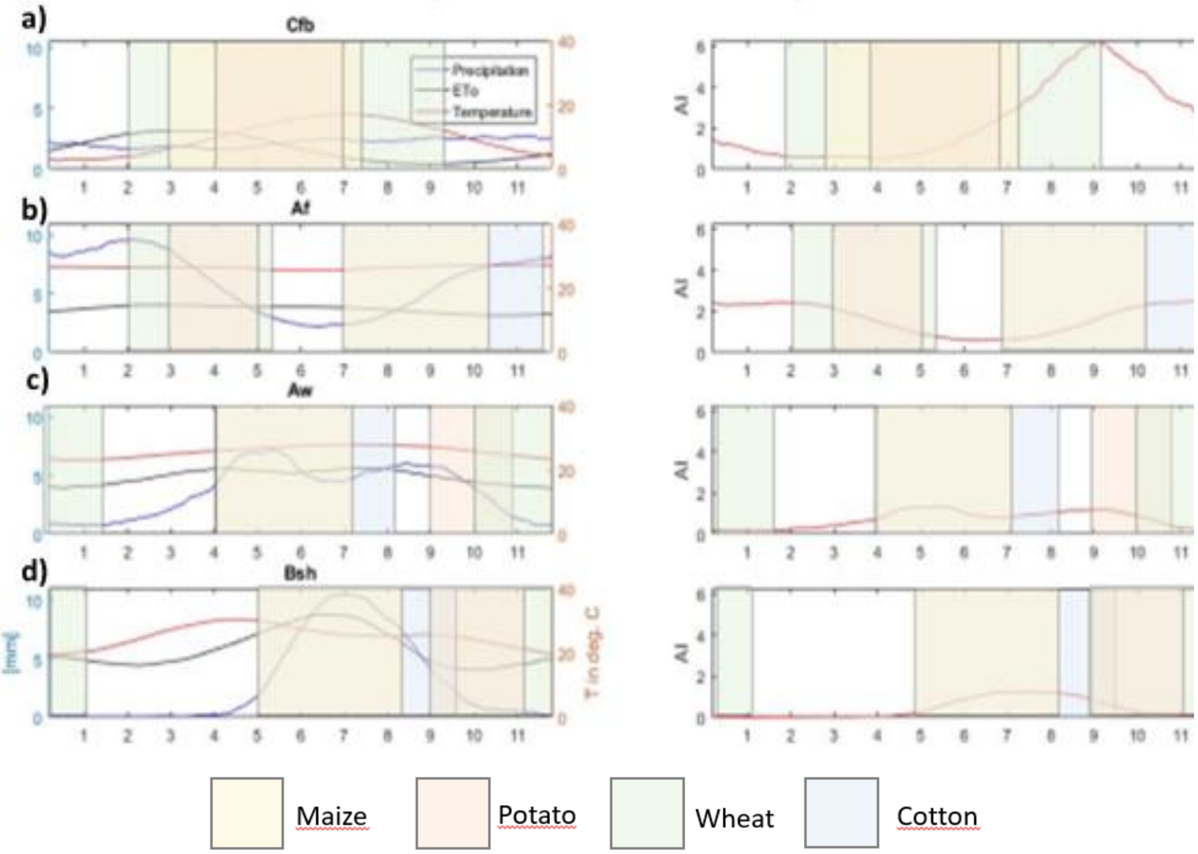


Figure 9 Average yearly climate in the period 1960-1990 and growing seasons of the studied crops

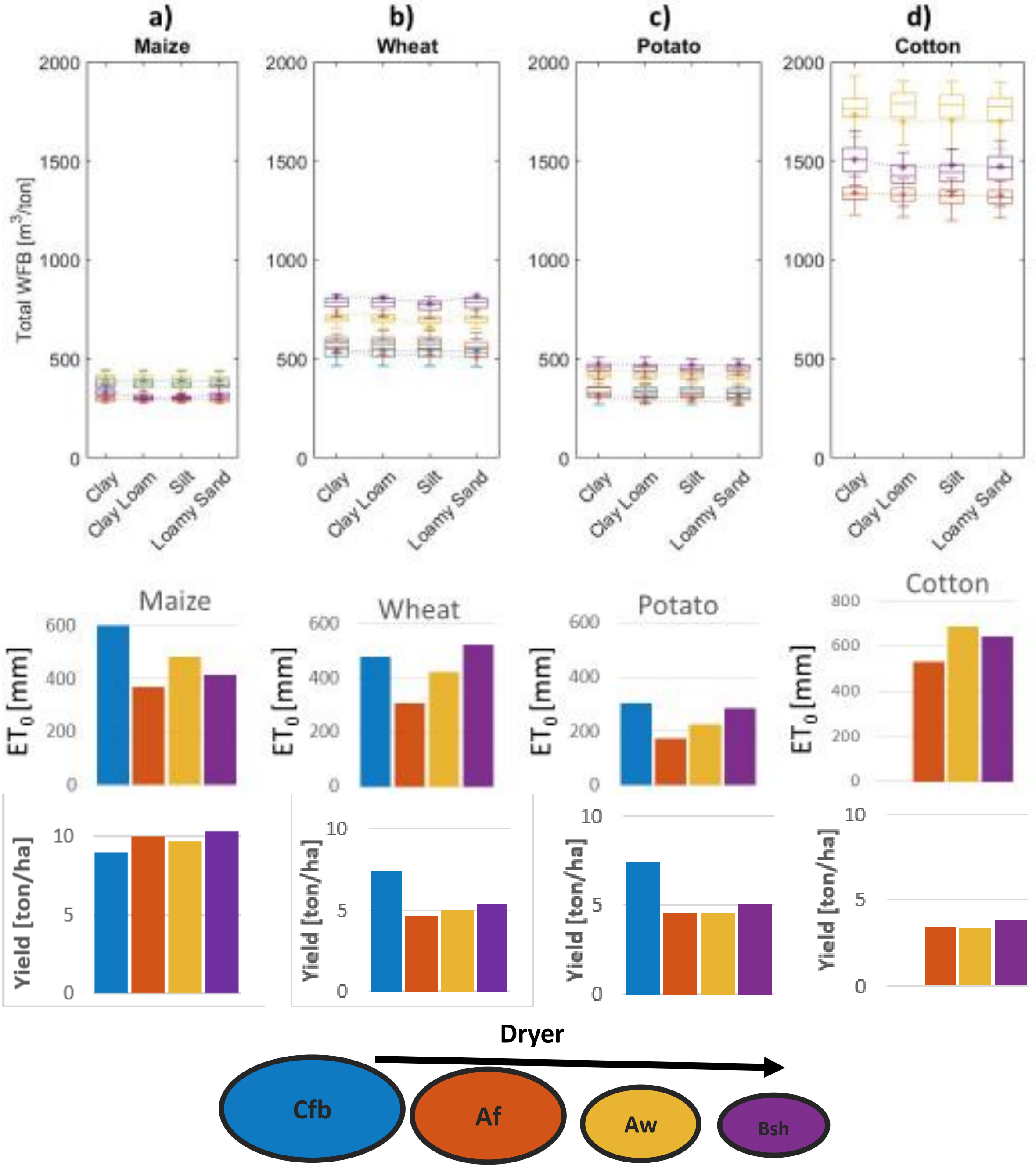


Figure 10 Best practice WFs for all scenarios and average total ET_0 and yield over the growing season per crop and climate (bars in corresponding colors).

4 DISCUSSION

4.1 EVALUATION AND EXPLANATION OF DIFFERENCES IN WF

This section serves to compare and explain the differences in best-practice WF between different climate zones and soil types and to evaluate if they are large enough to give rise to the need of distinguishing WFBs. Subsequently the correlation between the WF on total precipitation over the growing season will be evaluated.

4.1.1 Differences in WFB due to climate

According to the results presented in Figure 7, the differences due to climate can be considered large, as it occurs for all crops that there are at least two climate zones of which the uncertainty ranges due to inter-annual variability do not overlap. Explanations for how climate causes differences in WFB were found to be a combination of total ET_0 over the growing season, temperature seasonality and the height of the temperature during the growing season. This was derived from the calculation procedures of AquaCrop and the meteorological input data.

Total ET_0 over the growing season

Total ET_0 over the growing season can be more determining for the magnitude of the WF than the average aridity of the climate class. The total ET_0 over the growing season, representing the evaporative demand of the atmosphere, influences the amount of ET according to the calculation procedures in AquaCrop. From equation 7 for biomass production (see section 2.2.1), follows that a crop produces less biomass(B) per unit of transpiration with increasing ET_0 over the corresponding period. Because Y=HI*B, this results in less yield produced per unit of Tr and in turn leads to higher WFs where total ET_0 over the growing season is higher. Similar findings are presented in earlier studies (Zwart et al., 2010; Zhuo, Mekonnen, & Hoekstra, 2014; Zhuo et al., 2016). In the case of wheat and potato, **Figure 10** b) and c) show that when comparing for the three most arid climates (Af, Aw, Bsh), the ascending order of average aridity of the climate class is the same as the ascending order of total ET_0 of the growing season and WFs. In the cases of maize and cotton (**Figure 10** a) and d)) it becomes evident that the total ET_0 over the growing season is more determining for the magnitude of the WF than the average aridity of the climate class. This is for example illustrated by the fact that the total ET_0 over the growing season is higher for Aw than for Bsh while Bsh is classified as the more arid climate. The ascending order of WFs in these two climates corresponds to the ascending order of total ET_0 over the growing season (see **Figure 10**).

Temperature seasonality

Temperature is the input variable with the highest influence on ET_0 (Howard & Lloyd 1979). This makes the distribution of ET_0 over the growing season dependent on the corresponding temperature and thus on temperature seasonality (the difference between summer and winter temperature). The distribution of ET_0, and thus temperature seasonality over the growing season can be determining for the magnitude of the WF. **Figure 10** for wheat (b) and potato (c) reveals that the total ET_0 over the growing season in Cfb is higher than in the more arid climates, while the WFs are the lowest (for wheat) or hardly to distinguish from those in Af (for potato). The origin of this phenomenon can be attributed to the distribution of ET_0 over the growing season and the procedure of calculating yield in AquaCrop. **Figure 9** displays the climates of the growing seasons in question in an annual context. Comparing **Figure 9** a) (Cfb) to **Figure 9** b) c) and d) reveals that the growing seasons in Cfb are relatively long, which explains that total ET_0 in Cfb is higher. To "zoom in", **Figure 12** shows the distribution of Tr and ET_0 over the growing season averaged over the period 1960-1990 for wheat in all four climates. In the 3 hot climates Af, Aw and Bsh, ET_0 is spread roughly equally over the growing season and large differences between ET_0 and Tr occur in the growing and declining phase of crop development. In Cfb in contrast, the distribution of ET_0 is similar to the distribution of Tr (see **Figure 11**). This is due to the temperature seasonality in this temperate climate. Temperature and thus ET_0 increases while the crop is in its primary development phase (see **Figure 11**). This results in ET_0 and Tr increasing simultaneously. Besides, temperatures are relatively low throughout the growing season, which is why it takes more time for the crop to mature. This in turn has the effect that temperature is already decreasing at the end of the crop cycle which makes Tr and ET_0 decline simultaneously. Consequently, the differences between ET_0 and Tr at the beginning and the end of the growing season are smaller than in the hot climates. This leads to a relatively high ratio of $\Sigma Tr/ET_0$ in Cfb. As this ratio is a factor in biomass production, more biomass and thus more yield is produced in Cfb than in the other climates (see **Figure 2**) for calculation procedure). This is illustrated in **Figure 10** b) and c). The relatively high yields cause the WF for Cfb to be relatively low, despite the fact that more Tr occurs in Cfb because of the longer growing season. This indicates that a relatively high temperature seasonality can have a decreasing effect on the WF, if the crop calendar is timed in a way that Tr and ET_0 increase and decrease simultaneously.

Low temperatures

Cold temperature tress can lead to reduced yields and therefore, higher WFs. In AquaCrop, this is simulated by multiplying biomass with a coefficient Ks_b for temperature stress (see Figure 2). This coefficient becomes smaller than 1 if GDD is smaller than T_{base}. An example for which this effect is observed is maize in the Cfb climate. As illustrated in **Figure 10** a), the total ET_0 over the growing season for maize in Cfb is the highest of the four climates, but also the ratio $\Sigma Tr/ET_0$ is about twice as high as for Af, Aw and Bsh. This could have the same decreasing effect on the WF as for wheat, but yields for maize are the lowest for Cfb (see **Figure 10** a)). A likely explanation is temperature stress, which was observed for maize in Cf, when GDD were smaller than T_{base} (8°C) (see Appendix V). Consequently, yields are reduced. This is how temperature stress can increase WFs for cold-sensitive crops and why maize in Cfb has the second highest WF of all four climates in the current study.

Another cause of the low yields of maize in Cfb may be that the model simulation in AquaCrop was executed with the calendar days version of the crop file instead of the GDD version (see Appendix III). In addition to the crop experiencing cold stress, the crop cannot reach its full maturity as it can in the warmer climates while using the GDD-version of the crop file.

High temperatures

It is suggested that relatively high temperatures at the beginning of the growing season can decrease the WF. This may be the explanation for the observation that for maize and cotton, the differences between WFs between Aw and Bsh are larger than between Af and Bsh, while the differences in total ET_0 between Af, Aw and Bsh are about equal. **Figure 12** displays a comparison of the climates Aw and Bsh for daily values for each year between 1960-1990 of the ratio Tr/ET_0, GDDs and cumulative transpiration and biomass. It was found that at the beginning of the growing season, higher values of Tr/ET_0 occur for Bsh in most years. This is likely to be related to higher temperatures – and thus GDDs – in Bsh during this period. **Figure 12** c) shows that this tends to create an “advance” in cumulative biomass in Bsh with respect to Aw. This relatively high biomass, and thus yield production, in adition to and a relatively low ET_0 as compared to Aw, leads to lower WFs in Bsh than expected when only looking at total ET_0 over the growing season.

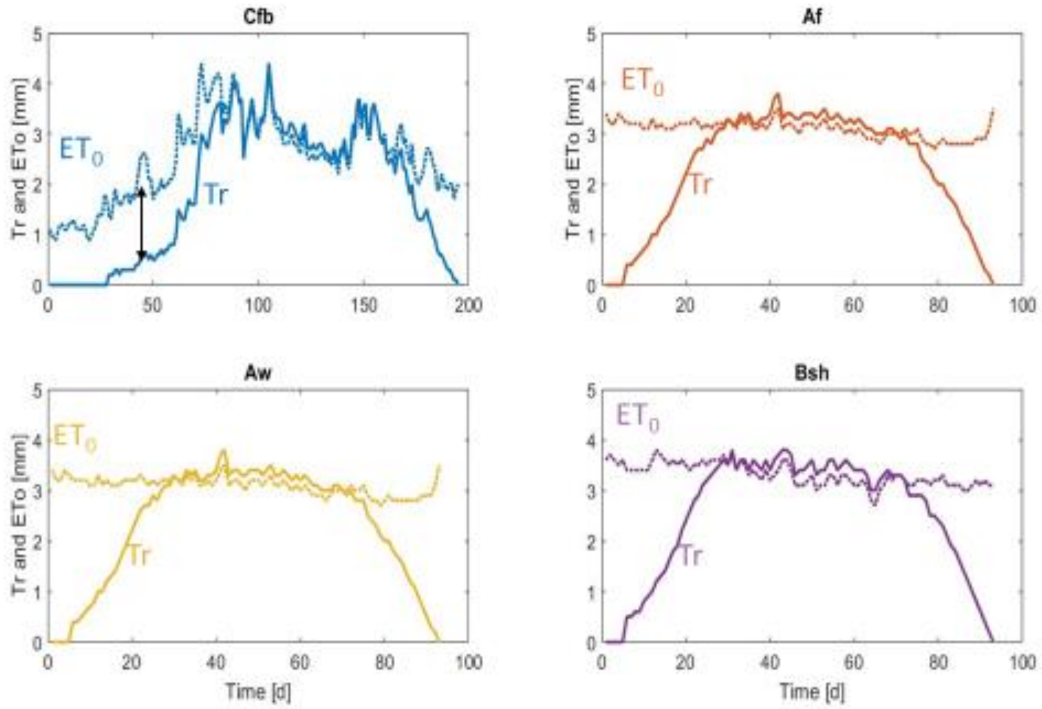


Figure 11 Tr and ETo during the growing season for wheat in each climate.

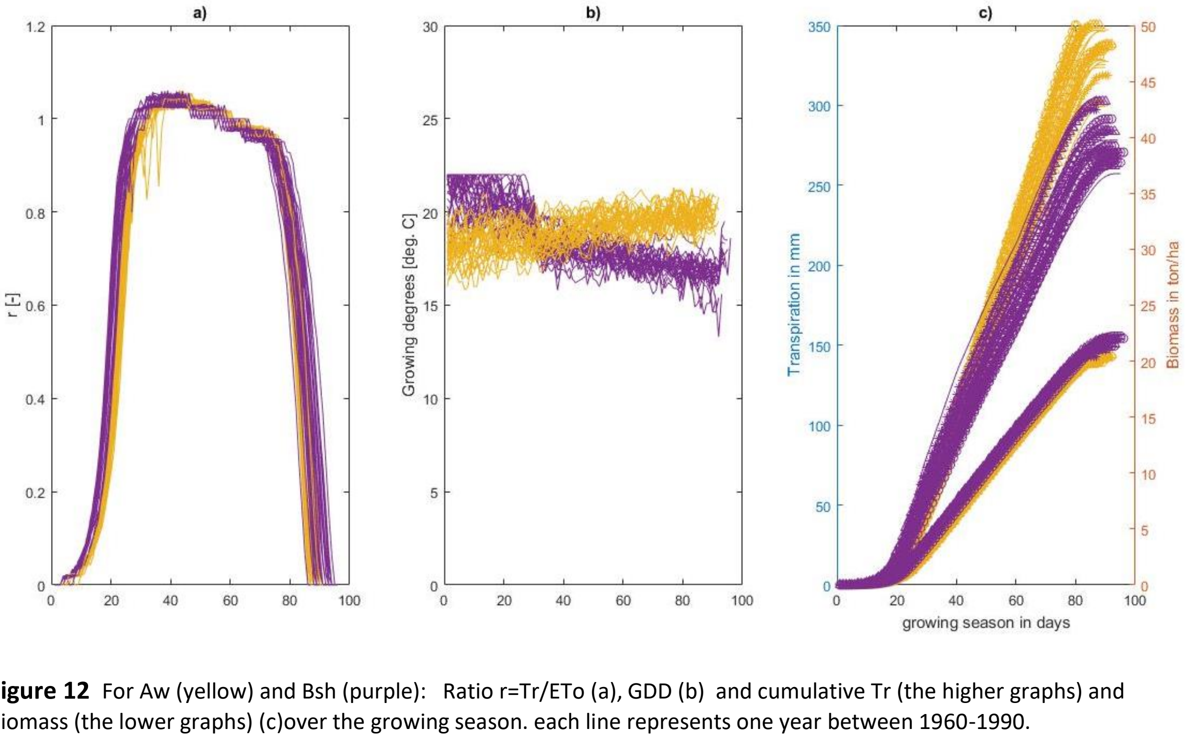


Figure 12 For Aw (yellow) and Bsh (purple): Ratio r=Tr/ETo (a), GDD (b) and cumulative Tr (the higher graphs) and biomass (the lower graphs) (c)over the growing season. each line represents one year between 1960-1990.

4.1.2 Differences due to soil

Differences in WFs due to soil type were observed to be relatively small. This can be explained as follows. The WF is defined as the ratio WF = ET/ Y (see equation 1). In general, soil characteristics can influence this ratio by affecting E and Y. Y is indirectly affected when Tr is hampered due to water stress, which in turn induces stomatal closure (see Figure 2). This occurs when the permanent wilting point (PWP) is reached or when water logging occurs causing oxygen stress. These situations occur at different water contents in different soils, which is why the (indirect) effect on yields differs with soil characteristics.

Water logging leads to decreased transpiration in clay when high intensity rainfalls are common in the growing season. This in part leads to the slightly higher WFBs for clay for the climates Aw and Bsh in Cotton, for Af and Aw in Potato and for Af in wheat (Figure 7 WFs for all crop-climate-soil scenarios for the 30-year time series from 1960-1990).

Larger differences in the total WFBs due to soil originate from differences in E. In humid climates, E often only makes up a negligible part of ET. Therefore, total WFB differences due to soil are absent in the climates Cfb and Af. The drier the growing season is, the larger is E, and the larger are the total WFB differences due to soil. This is visible for cotton and maize (, which are grown in the dry season in the climates Aw and Bsh (see **Figure 9**). Here, WFBs are highest in clay, the soils with the lowest permeability, and WFBs are the lowest in the more permeable soils. This can be explained by the fact that in clay, water is more prone to evaporation before it percolates, while water in the more permeable soils turns into deep percolation sooner (Asseng et al. 2015). DP is not lost from the catchment and is therefore not accounted for in the WF.

4.1.3 Correlation between total P and WF

The low coefficients of determination (see Fout! Verwijzingsbron niet gevonden.) do not allow to attribute low WFs to years of high precipitation during the growing season or vice versa.

The explanation that years with different total P during the growing seasons can have similar blue WFs may lay in the distribution of P over the growing season. If the intensity of rain showers is high, a larger amount of water turns into runoff and deep percolation than when the intensity of a rain shower is low. Thus, if a growing season has a relatively low total P but a relatively high number of low intensity rain showers, the total irrigation depth, and thus the blue WF, may be still be equal to the blue WF in a growing season that has a higher total P, but a relatively low number of high intensity rain showers of which a considerable part turns into runoff and deep percolation. This green water stays unused by the crop. This effect of unusable green water also occurs when the distribution of P over the growing season is concentrated in a small section of the season. For example, in the growing seasons for potato and wheat in Bsh, all precipitation falls in the first 30 days in high intensity rain showers (see **Figure 9**). In this period only a fraction of this green water can be used for transpiration. This is about the same amount every year if ideal conditions are assumed. Excess precipitation turns into runoff or deep percolation and becomes unavailable for crop use. The remainder of the growing season, irrigation is applied as no precipitation occurs anymore. This results in a similar green-blue composition of the WF every year.

As the inter-annual variation in total and blue WF could not be explained with inter-annual variations in total P over the growing season, it is suggested to preliminarily set the WFB for a crop in a certain climate as the maximum non-outlier WF that was found for this climate within a 30-year study period. This makes the WFB reliable in a sense that it can be expected achievable at all times – in contrast to a WFB set at e.g. the average WF over the study period.

4.2 PRACTICAL APPLICABILITY OF RESULTS

4.2.1 Use of full irrigation

In this study, full irrigation was used as irrigation strategy. This may result in smaller differences in WFs than if crops were grown rainfed or with supplemental or deficit irrigation.

Differences due to soil may be affected as follows. Full irrigation provides the crop with enough water at any time, preventing stress due to a lack of water. Therefore, yield is not affected by soil water holding characteristics, and neither is the WF. In contrast, stress that results from reaching PWP does have an effect in rain fed agriculture or under deficit irrigation. Under these circumstances it depends on soil characteristics how long water is held in the soil and when PWP is reached. For example, Zhuo et al. (2016) found that the WFBs differ about 10-12% when modeling WFs for irrigated and rain-fed winter wheat in China. Consequently, if we would set WFBs for rainfed crop production or for supplemental or deficit irrigation, possibly WFBs may have to be distinguished based on type of soil.

The low correlation between total P and the total WF is a consequence of the fact that under full irrigation, all water demands are met, independent of the amount of available green water. Hence, yield is not compromised if total P is smaller and the WF does not increase with lower P and vice versa. As minor compromises in yield are accepted in supplemental and deficit irrigation, the WF may be larger in dry years and smaller in wet years. This could result in a stronger correlation between total P over the growing season and the total WF if supplemental or deficit irrigation were used.

Differences in WF due to IMs are small as simulated in this study with full irrigation (see **Figure 6**). If for example deficit irrigation is used, water stress may occur between the irrigation events, which reduces yield. Results of Chukalla et al. (2015) showed that when no mulch is applied, the differences in WF between different IMs are larger when deficit irrigation is used than when full irrigation is used.

4.2.2 Modeling irrigation and mulching practice

The way in which the use of different irrigation methods and mulching are translated to the AquaCrop model comes along with uncertainties that may affect the applicability of the modeled WFBs to reality.

In the modeling method, the differences in evaporation of irrigation water are only determined by the wetted soil surface. In practice, irrigation water may evaporate before it arrives at the soil surface in furrow and sprinkler irrigation. However, AquaCrop only incorporates evaporation that takes place at the soil surface. The water loss that takes place during water application through evaporation before it arrives at the soil surface partly determines the irrigation efficiency, being part of the field application efficiency (FAO, 2016 b)). This is not accounted for in the WF.

The result that mulching can cause comparatively large reductions in E suggests that applying mulch while using any IM already brings the WF as close to the WFB that a reduction by a better IM is almost insignificant. However, the effect of mulching on evaporation may contain a high uncertainty. In AquaCrop, it is assumed that mulching prevents 50% of evaporation. However, it depends for example on the amount of time after an irrigation or precipitation event how much E is prevented compared to a bare soil situation (McMillen, 2013). Also variations in thickness of the mulch layer may cause deviation from this value. McMillen (2013) found in physical experiments that using a layer with the thickness of 5cm or a 10cm can cause differences in prevented evaporation of 10%, whereas this study found values between 13%-18%.

Apart from model uncertainties, it may be understood as a flaw of this study that the lowest resulting WFs for every scenario were used as a benchmark, but in reality the corresponding IM or mulching may be unreasonable to demand. Here, reasonable is understood as technically and economically feasible for an agricultural enterprise under the current (economic) situation. This means for example that the investment in a new irrigation system must be proportional to the value of the crop. For example, installing drip irrigation on a 60 ha wheat field is a major investment that will not increase revenues enough to be economically viable in most circumstances (El-Rahman, 2009). In this case a benchmark may have to be set at the WF obtained for sprinkler or furrow irrigation. Another potential flaw of this study is that best practice for each crop-climate-soil-scenario was identified from modeling WFs for different IMs and mulching for a growing season with average climate conditions. It was not investigated if growing seasons with a different aridity result in a different best practice. However, as computed by AquaCrop, differences between IMs are small. Hence the decision to use the lowest WF for each scenario under average aridity, disregarding if the corresponding IM is reasonable or not is assumed not to impact the outcome of the study significantly.

4.3 COMPARISON TO EXISTING WFBS

Figure 13 shows the WFs for all studied crops simulated in the current study in comparison to the WFs found by Mekonnen & Hoekstra (2014) (M&H, 2014). The boxplots represent the range of WFs found in the current study. The dots in the color codes of the climates are linked to the percentile in which the WFs of the representative locations were found by M&H, 2014. For maize, wheat and cotton, the WFs for the locations used for the three most arid climates were found to be higher than the lowest 50% globally. For the same crops and locations, all WFs found in the current study – under optimal conditions, best practice in IM and mulch, and full irrigation - are lower than lowest 25%found by M&H, 2014. For maize, all WFs found in the current study even lay in the lowest 10% globally. This implies that at the studied locations for Af, Aw and Bsh, WFs could be decreased significantly by improving agricultural management practices. However, this implication is to be treated with reservation as it has not known how much of the difference in WF between the two studies can be attributed to applying better irrigation and field management and how much of the differences is caused by e.g. temperature stress or a lack in management concerning risks as pest infestation, diseases or salt stress.

Zhuo et al. (2016) simulated WFs for winter wheat in China and investigated the differences in WF between climate zones with a difference in aridity index of about 0.8 (1.0-02). In this study the range of aridity index between the driest and wettest climate is comparable, being 1.1 (1.6-0.5). They found that for the lowest 10%, the WFBs in the humid zone were 26% lower than in the arid zone. The range of WFs that were found for wheat in this study covered a comparable range as the WFs of the lowest 10% in Zhuo et al. (2016). In this study, it was found that the difference in average WFs for wheat due to climate in the growing season is about 25%. This means that the findings of the two studies are in accordance with each other with respect to how much difference in WFB climate can cause. The current study adds to this finding by explaining why different climates can cause these differences and that this is not necessarily related to the average aridity of the climate zone.

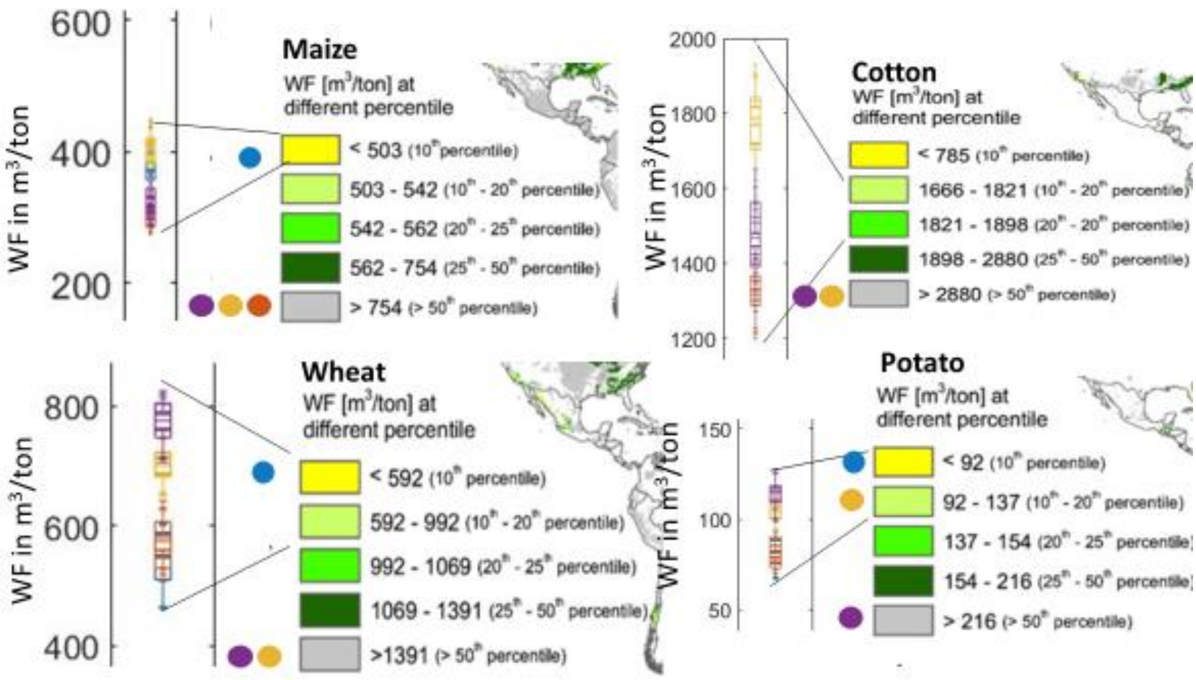


Figure 13 Comparison of WFs simulated in the current study to WFs obtained by Mekonnen & Hoekstra, 2014.

5 CONCLUSION

In this this study, WFBs were estimated for 4 crops grown under 4 different climates on 4 different types of soil. Varying type of soil while keeping other factors equal does not cause sufficient differences in WFB to warrant setting different WFBs per type of soil. Differences caused by soil are relatively small, ranging between 2% for maize and 4% for cotton. For climate, a distinction in WFBs is suggested to be adequate, as the overlap of uncertainty ranges due to inter-annual variability is often absent or marginal. These conclusions for the relevance of distinguishing WFBs based on soil or climate confirm the findings by Zhuo et al. (2016).

As the low coefficients of determination do not allow to attribute low WFs to years of high precipitation during the growing season or vice versa, the results from this study offer no reasonable ground to distinguish WFBs for growing seasons with relatively high or low total P. The WF is suspected to be dependent on the distribution of P over the growing season rather than on total P. Therefore, a criterion to distinguish WFBs for different hydrological years is to be sought for in the weather pattern of the growing season. As long as no distinction criterion for the type of hydrological year is found, it is suggested to set the WFB at the highest non-outlier WF occurring in a period of 30 years, as this can be considered achievable at all times.

How large the differences in WFBs caused by climate are is determined by total ET_0 and the distribution of ET_0 over the growing season. The latter is dependent on the temperature seasonality of the climate. Besides, temperature was found to influence the WFB through cold stress and enhancing crop growth in the early growing phase.

By simulating WFs under best practice and assuming optimal conditions, all WFBs were found to be lower than the 25% best found by M&H, 2014. The results of this study suggest that WFs can often even be brought back from larger than 50th percentile to the 10th percentile. According to Mekonnen & Hoekstra (2014), 39% of fresh water can be saved globally if WFs are reduced to the lowest 25% lowest

WFs globally. The WFBs for all crops found in this study are lower than this level, which confirms that a global WFB set at the lowest 25% globally would be reasonable, as this level can be attained when agricultural water management is improved to best practice.

The findings of the current study suggest that a finer distinction of WFBs between climates is possible below the global lowest 25%, considering that the differences between WFBs in different climates are large enough to allow for a distinction. This is a favorable outcome in terms of fresh water conservation. Namely, if it is feasible to implement lower WFBs, more fresh water is saved if these benchmarks are met.

6 RECOMMENDATIONS

- **Conduct a similar study with different irrigation strategies**. The use of full irrigation in the simulations conducted for this study causes the differences in WF due to soil and irrigation method to be small and the correlation between total P over the growing season and the WF to be weak. Larger differences and a stronger correlation may be found if supplemental or deficit irrigation were used. This may have consequences for the scale for which WFBs apply, because it may become relevant to distinguish WFBs for soil or type of hydrological year in addition to climate class. Besides, WFBs may be lower than those for full irrigation. Therefore, it is recommended to conduct a similar study using different irrigation strategies to test their implications for the WFB.
- **Conduct more simulations per climate class.** In this study climate data acquired from one specific location were selected to represent a climate class. The WFBs that were defined using these climate data were thus specifically defined for these locations and may not apply for the whole climate class. For further development of WFBs it is important to take into consideration that the magnitude of the WFB generally increases with total ET_0 in the growing season, but that it also depends on the seasonality of the climate. Seasonality influences the height of the temperature in general and it largely determines how ET_0 is distributed over the growing season. This can vary between different regions within one climate class. To obtain WFBs that apply more generally, simulations for more locations per climate class will have to conducted.

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APPENDIX

I EQUATIONS ON WHICH SEPARATION OF ET INTO BLUE AND GREEN FRACTION IS BASED

Green fraction of soil water content: $\frac{dS_g}{dt} = R - (Dr + ET)\left(\frac{S_g}{S}\right) - RO\ \left(\frac{R}{I+R}\right)$

Blue fraction of soil water content: $\frac{dS_b}{dt} = I - (Dr + ET)\left(\frac{S_b}{S}\right) - RO\ \left(\frac{I}{I+R}\right)$

S_g= green fraction of soil water content (from rain water), S_b= green fraction of soil water content (from irrigation), R=rainfall, I=irrigation, Dr=drainage, ET=evapotranspiration, S = soil water content, RO = runoff.

II PROCESS OF EXTRACTING CLIMATE DATA FROM CRU DATASET

```
# Extracts data from the CRU TS 3.23 netCDF data set per Koeppen
zone
# over the reference period 1961-1990 and ranks them accordingly
#
# get koeppen classification as map
cp /home/beek0120/netData/GlobalDataSets/Koeppen-Geiger/Koeppen-
Geiger-ASCII-Reclassified.map koeppen_classes.map
# get mean monthly climatology as netCDF
#cdo ymonmean -seldate,1961-01-01,1990-12-31
/data/hydroworld/basedata/forcing/CRU_TS3.23/data/pre/cru_ts3.23.190
1.2014.pre.dat.nc cru_ts3.23.1961.1990clm_pre.nc
#cdo ymonmean -seldate,1961-01-01,1990-12-31
/data/hydroworld/basedata/forcing/CRU_TS3.23/data/tmp/cru_ts3.23.190
1.2014.tmp.dat.nc cru_ts3.23.1961.1990clm_tmp.nc
#cdo ymonmean -seldate,1961-01-01,1990-12-31
/data/hydroworld/basedata/forcing/CRU_TS3.23/data/pet/cru_ts3.23.190
1.2014.pet.dat.nc cru_ts3.23.1961.1990clm_pet.nc
#-get yearly values
cdo yearsum  cru_ts3.23.1961.1990clm_pre.nc
cru_ts3.23.1961.1990sum_pre.nc
cdo yearsum  cru_ts3.23.1961.1990clm_pet.nc
cru_ts3.23.1961.1990sum_pet.nc
cdo yearmean cru_ts3.23.1961.1990clm_tmp.nc
cru_ts3.23.1961.1990avg_tmp.nc
cdo yearmin  cru_ts3.23.1961.1990clm_tmp.nc
cru_ts3.23.1961.1990min_tmp.nc
cdo yearmax  cru_ts3.23.1961.1990clm_tmp.nc
cru_ts3.23.1961.1990max_tmp.nc
#-convert to PCRaster maps
gdal_translate -of PCRaster -ot FLOAT32
cru_ts3.23.1961.1990sum_pre.nc cru_ts3.23.1961.1990sum_pre.map
gdal_translate -of PCRaster -ot FLOAT32
cru_ts3.23.1961.1990sum_pet.nc cru_ts3.23.1961.1990sum_pet.map
gdal_translate -of PCRaster -ot FLOAT32
cru_ts3.23.1961.1990avg_tmp.nc cru_ts3.23.1961.1990avg_tmp.map
gdal_translate -of PCRaster -ot FLOAT32
cru_ts3.23.1961.1990min_tmp.nc cru_ts3.23.1961.1990min_tmp.map
```

```
gdal_translate -of PCRaster -ot FLOAT32
cru_ts3.23.1961.1990max_tmp.nc cru_ts3.23.1961.1990max_tmp.map
rm *.aux.xml
#-temperature range
pcrcalc cru_ts3.23.1961.1990dtr_tmp.map=
cru_ts3.23.1961.1990max_tmp.map-cru_ts3.23.1961.1990min_tmp.map
#-evaporation is in mm/day, so multiply by average number of days in
month
pcrcalc cru_ts3.23.1961.1990sum_pet.map=
"(cru_ts3.23.1961.1990sum_pet.map*365.24/12)"
#-aridity
pcrcalc cru_ts3.23.1961.1990_aridityindex.map=
"cru_ts3.23.1961.1990sum_pet.map/cru_ts3.23.1961.1990sum_pre.map"
#-get averages
pcrcalc cru_ts3.23.1961.1990sum_koeppen_pet.map=
"areaaverage(cru_ts3.23.1961.1990sum_pet.map,koeppen_classes.map)"
pcrcalc cru_ts3.23.1961.1990sum_koeppen_pre.map=
"areaaverage(cru_ts3.23.1961.1990sum_pre.map,koeppen_classes.map)"
pcrcalc cru_ts3.23.1961.1990avg_koeppen_tmp.map=
"areaaverage(cru_ts3.23.1961.1990avg_tmp.map,koeppen_classes.map)"
pcrcalc cru_ts3.23.1961.1990min_koeppen_tmp.map=
"areaaverage(cru_ts3.23.1961.1990min_tmp.map,koeppen_classes.map)"
pcrcalc cru_ts3.23.1961.1990max_koeppen_tmp.map=
"areaaverage(cru_ts3.23.1961.1990max_tmp.map,koeppen_classes.map)"
pcrcalc cru_ts3.23.1961.1990dtr_koeppen_tmp.map=
"areaaverage(cru_ts3.23.1961.1990dtr_tmp.map,koeppen_classes.map)"
pcrcalc cru_ts3.23.1961.1990_koeppen_aridityindex.map=
"cru_ts3.23.1961.1990sum_koeppen_pet.map/cru_ts3.23.1961.1990sum_koe
ppen_pre.map"
#-compute absolute, normalized differences
pcrcalc cru_ts3.23.1961.1990_pet_AND.map=
"abs(cru_ts3.23.1961.1990sum_koeppen_pet.map-
cru_ts3.23.1961.1990sum_pet.map)/cru_ts3.23.1961.1990sum_koeppen_pet
.map"
pcrcalc cru_ts3.23.1961.1990_pre_AND.map=
"abs(cru_ts3.23.1961.1990sum_koeppen_pet.map-
cru_ts3.23.1961.1990sum_pre.map)/cru_ts3.23.1961.1990sum_koeppen_pre
.map"
pcrcalc cru_ts3.23.1961.1990_tmp_AND.map=
"abs(abs(cru_ts3.23.1961.1990avg_koeppen_tmp.map-
cru_ts3.23.1961.1990avg_tmp.map)/cru_ts3.23.1961.1990avg_koeppen_tmp
.map)"
pcrcalc cru_ts3.23.1961.1990_dtr_AND.map=
"abs(cru_ts3.23.1961.1990dtr_koeppen_tmp.map-
cru_ts3.23.1961.1990dtr_tmp.map)/cru_ts3.23.1961.1990dtr_koeppen_tmp
.map"
pcrcalc cru_ts3.23.1961.1990_aridityindex_AND.map=
"abs(cru_ts3.23.1961.1990_koeppen_aridityindex.map-
cru_ts3.23.1961.1990_aridityindex.map)/cru_ts3.23.1961.1990_koeppen_
aridityindex.map"
#-select the best 5 per Koeppen class on the basis of temperature,
temperature range and precipitation and aridity index
pcrcalc temp.map=
cru_ts3.23.1961.1990_tmp_AND.map+cru_ts3.23.1961.1990_dtr_AND.map+cr
u_ts3.23.1961.1990_pre_AND.map+cru_ts3.23.1961.1990_aridityindex_AND
.map
```

```
pcrcalc temp2.map= "areaorder(temp.map,koeppen_classes.map)"
pcrcalc koeppen_classes_selectedorders.map= "if(temp2.map le
5,temp.map)"
pcrcalc koeppen_classes_selectedpoints.map= "ordinal(if(temp2.map le
5,temp2.map))"
pcrcalc koeppen_classes_selected.map= "if(temp2.map le
5,koeppen_classes.map)"
map2col koeppen_classes_selectedorders.map
koeppen_classes_selectedorders.txt
map2col koeppen_classes_selectedpoints.map
koeppen_classes_selectedpoints.txt
map2col koeppen_classes_selected.map koeppen_classes_selected.txt
rm temp.map temp2.map
echo 'done!'
```

III CROP CALENDARS, SW_0 AND IRRIGATION SCHEDULE

Crop calendars/ cycles. AquaCrop comes with two kinds of crop input files that differ in the way how crop calendars are determined. This can either be by growing degree days (GDD) or by a fixed number of calendar days for each growing phase. For the simulations in this study, the input files using GDD were used. It is stated in the input files for AquaCrop how many GDD are required for every growing phase of the crop. Using the climate data and GDD, Aquacrop calculates the number of calendar days of every phase of a crop cycle. For maize in the Cfb climate, the crop input file applying a fixed crop calendar was used. The GDD method yielded a crop cycle that proceeds throughout 16 months because there are not enough GDDs for the plant to grow to maturity within one season. The calendar days version of the crop file provided by AquaCrop was made for Davis, California, where the prevailing climate is Csb, which is summer dry instead of fully humid as in Cfb. Therefore, the number of calendar days was corrected according to data from Chapagain & Hoekstra (2014). Because the way in which these data is given in the corresponding document (see Figure 14) is not the way it is required for the crop input file, some assumptions were made and calculations were performed to convert it to the right information.

Table 6 Conversion of growing phase lengths for maize in Cfb climate

	In the crop file	In Chapagain & Hoekstra (2004)		Conversion calculation	Rounded from calculation: calendar days in in the new crop file
From sowing to mergence	6	Initial stage	30	(6/107)*120 =	7
From sowing to maximum root depth	108	Development stage	40	(108/107)*120=	121
From sowing to start of	107	Middle stage	50	30+40+50=	120

canopy senesence					
From sowing to maturity	132	Late stage	30	120+30=	150
From sowing to flowering	60			(60/132)*150 =	68
Length of flowering	13			(13/132) *150 =	15

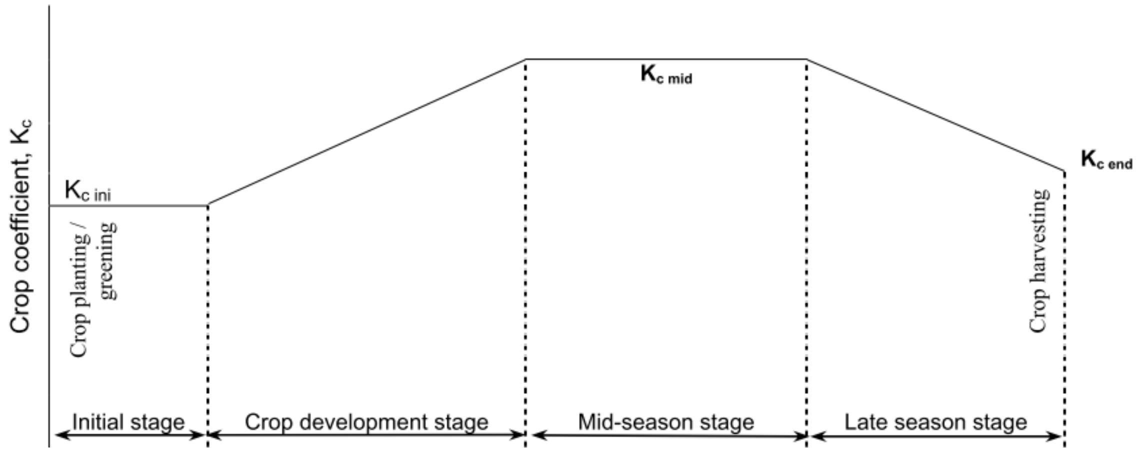


Figure 14 Development of crop coefficient Kc throughout crop cycle of wheat grown in India.

AquaCrop requires the start date of the simulation phase as an input. This is the sowing date or start of the crop cycle. As a reference for these data, the data portal of the FAO Global Agricultural Zones (GAEZ) was used (FAO, 2016 a)). This data portal provides world maps showing the first month of the growing season of a crop that leads to highest attainable yields. These starting dates of crop calendars result from calculation procedures of GAEZ Module II (Crop-specific agro-climatic assessment and water-limited biomass/yield calculation) (FAO, 2016 a)). The starts of growing seasons used in this study were retrieved for high input level, rain fed agriculture for the average climate during the base line period of 1961-1990. High input level was selected because as mentioned in chapter 1, ideal conditions are assumed for crop growth throughout this study. Rain fed cultivation was selected as water supply while retrieving starting dates, because a minimum irrigation requirement is most likely to be reached when water supply by precipitation is most favorable. Some of the selected locations showed as “unsuitable” in the starting date maps for some of the selected crops. If this was the case, the month that was displayed closest and/ or most abundant in the vicinity of the location.

To ensure that the moisture conditions at the start of the crop cycle is as favorable as possible, a precipitation criterion was used in the dryer climates (Aw and Bsh) to determine the starting date within the month of the crop cycle in AquaCrop. This criterion encompasses that in the 10 days before the starting date, precipitation was at least 0.5 times ETo in that period. This was only done for the WFs modeled under average climate conditions that were used to determine the WFBs. For the time series of WFs modeled to investigate climate variability this was not possible as Aquacrop can only apply a precipitation criterion for the first year of the simulation and uses the same sowing date for all consecutive years.

Initial soil water content SW0. As average climatic conditions are used to derive WFBs, ideally also initial soil water content (SW_0) is average soil water content (SWC) at onset of a growing season. To calculate these average SW0 conditions for onsets of all growing seasons for all soil types – climate combinations is time consuming. An alternative is to assume comparable initial conditions for each growing season-soil-climate combination. These initial conditions can either be permanent wilting point (PWP) or field capacity (FC), because SWC is known for each soil type under these conditions. The sensitivity of this choice on resulting WFs has to be known and either of these assumptions have to be proven valid.

Possible effects are 1) that blue WFs are larger for SW0=PWP, because more SW replenishment happens by irrigation instead of SW present from the beginning.

The sensitivity of the WF to SW0 is indeed low. In 128 of the 132 (97%) of the scenarios for maize, the differences between the WFs simulated with the extremes SW0=PWP or SW0=FC lay between -2% and +3% (see Figure 15). This is the case for both, dep % RAW=30 and dep % RAW=20. These differences are considered negligible. The expected effect that total WFs are larger for SW0=PWP than for SW0=FC is visible (see Figure 15), but also negligible. These results prove that it makes small enough of a difference if SW0 is PWP or FC to assume any value in between while making WFBs. There is one practical advantage of taking SW0=PWP for this research. This is related to the fact that at SW0=PWP, there is more SW replenishment by irrigation instead of SW present from the beginning. Hence, irrigation has more influence on the water balance than when SW0=FC. This brings out the differences better when comparing the WFs that result from different irrigation methods. This is useful while identifying best practice in irrigation method. For this advantage, PWP is taken as SW0 while simulating WFs that are used to identify WFBs.

Irrigation schedule. The longer the time intervals between irrigation events are, the more water stress occurs. As the WFB is defined as the lowest possible WF of a crop under unstressed conditions, the decision how to set the irrigation schedule should aim at low water stress (highest possible yield). The lower dep % RAW, the lower is the risk of water stress. Negligible water stress is achieved at dep % RAW = 20, hence 20% was used for all WF simulations. The decrease in dep % RAW can be an order of magnitude higher than the resulting increase in yield. Therefore, the effects of changing dep % RAW on the total WF were considered worth examining.

Possible effects of changing dep % RAW are 1) that the extent of the effect of changing dep % RAW is smaller on the total WF than on the blue WF, because irrigation water is applied more often with a smaller dep % RAW. 2) The extent of the effect of changing dep % RAW could be larger with SW0=PWP than SW0=FC. Irrigation has more influence on the water balance when SW0=PWP because more SW replenishment happens by irrigation instead of SW present from the beginning. This effect could be multiplied when looking at blue WF. The values for dep % RAW for which these effects were examined are 20% (negligible water stress) and 30% (almost negligible water stress). Once these effects are examined, the same dep % RAW will be used for WF simulations in all scenarios.

The sensitivity of the total WF to dep % RAW is negligible under both tested SW0. The expected higher sensitivity when SW0=PWP is visible, but the difference is negligibly small. Figure 15 show that in 93% of the scenarios for maize, the differences between dep % RAW=20 and dep % RAW=30 lay between 0 and +0.5% for SW0=FC and between -0.5% and +1% for SW0=PWP. Appendix B shows a more detailed analysis of these findings.

For future research, it may be interesting to examine the effects of changing dep % RAW on the blue WF. Also the effect on yield in comparison to the effect on runoff is interesting, because the latter may increase substantially at dep % RAW=20. This is due to increased irrigation, which causes the soil to be wetter. Although, runoff is not included in the WF, it plays a role in the short term availability of irrigation water because runoff is not used by the crop and lost from the irrigation water reservoir, unless it is reused.

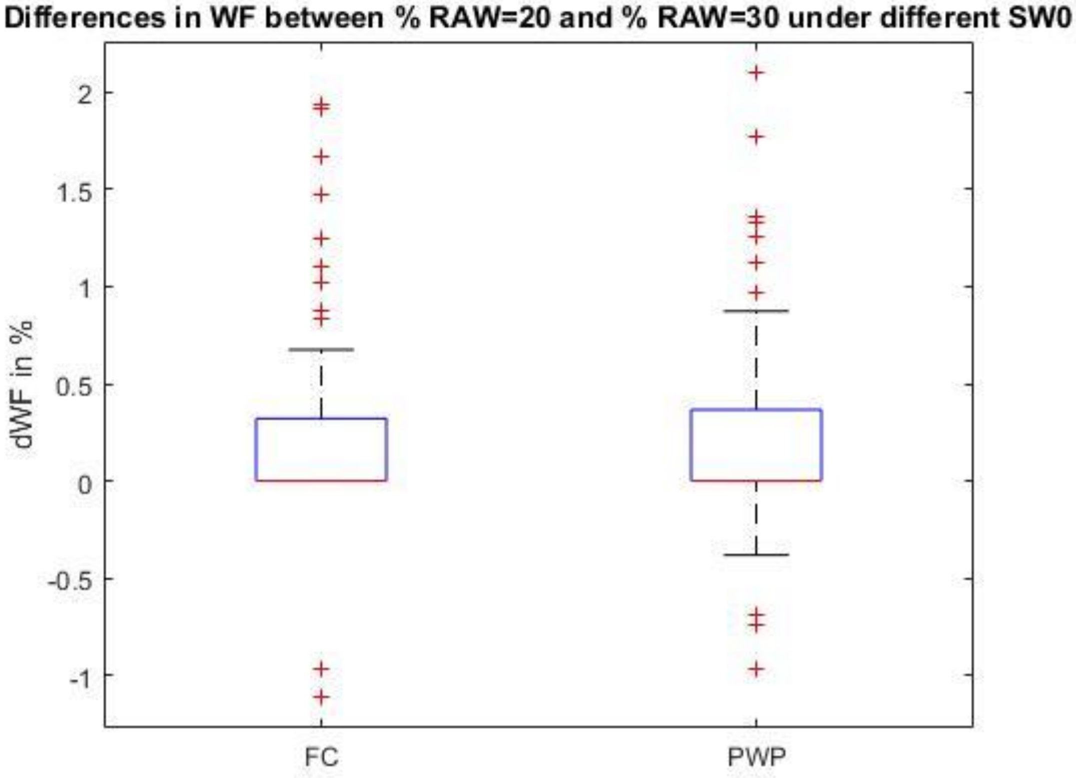
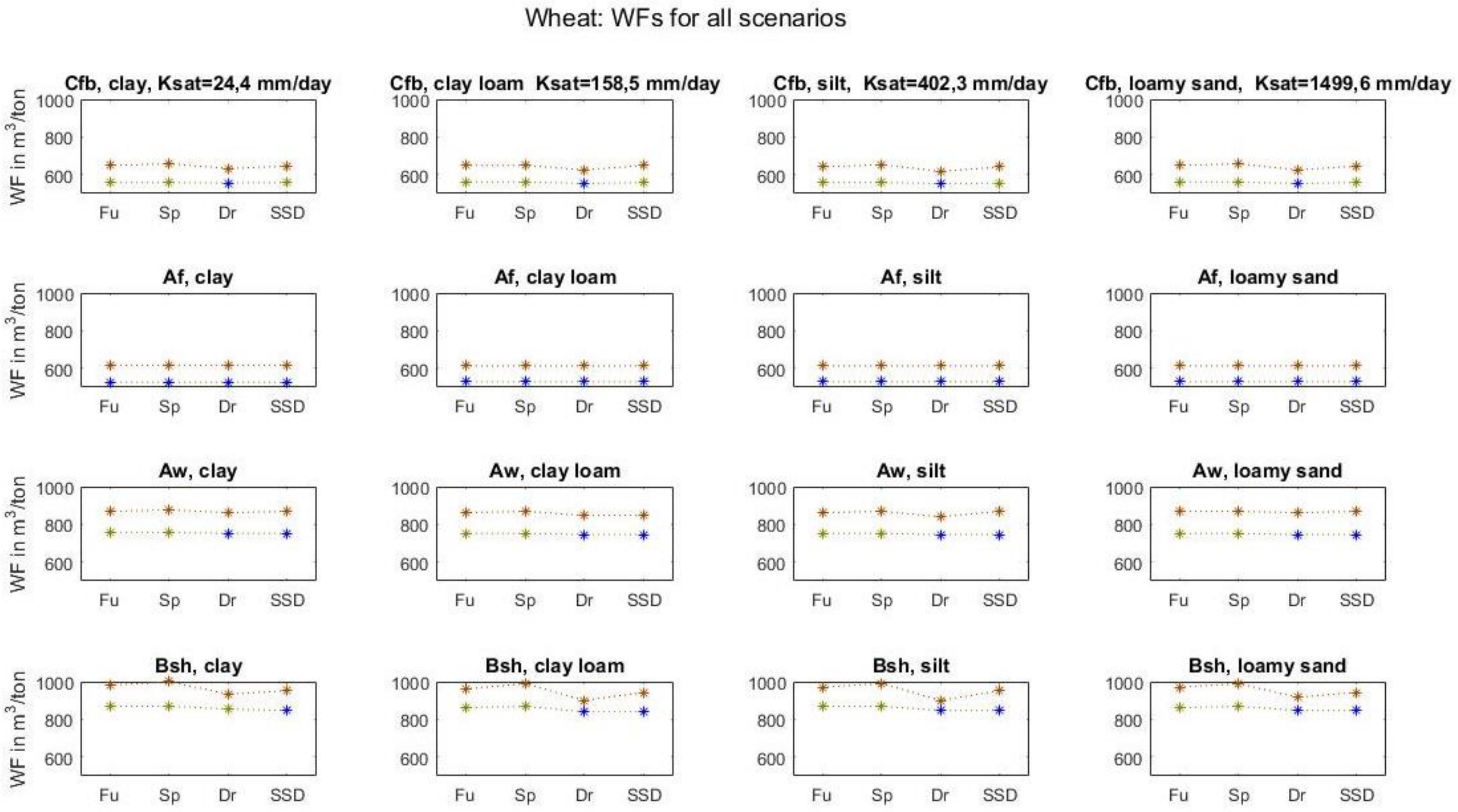


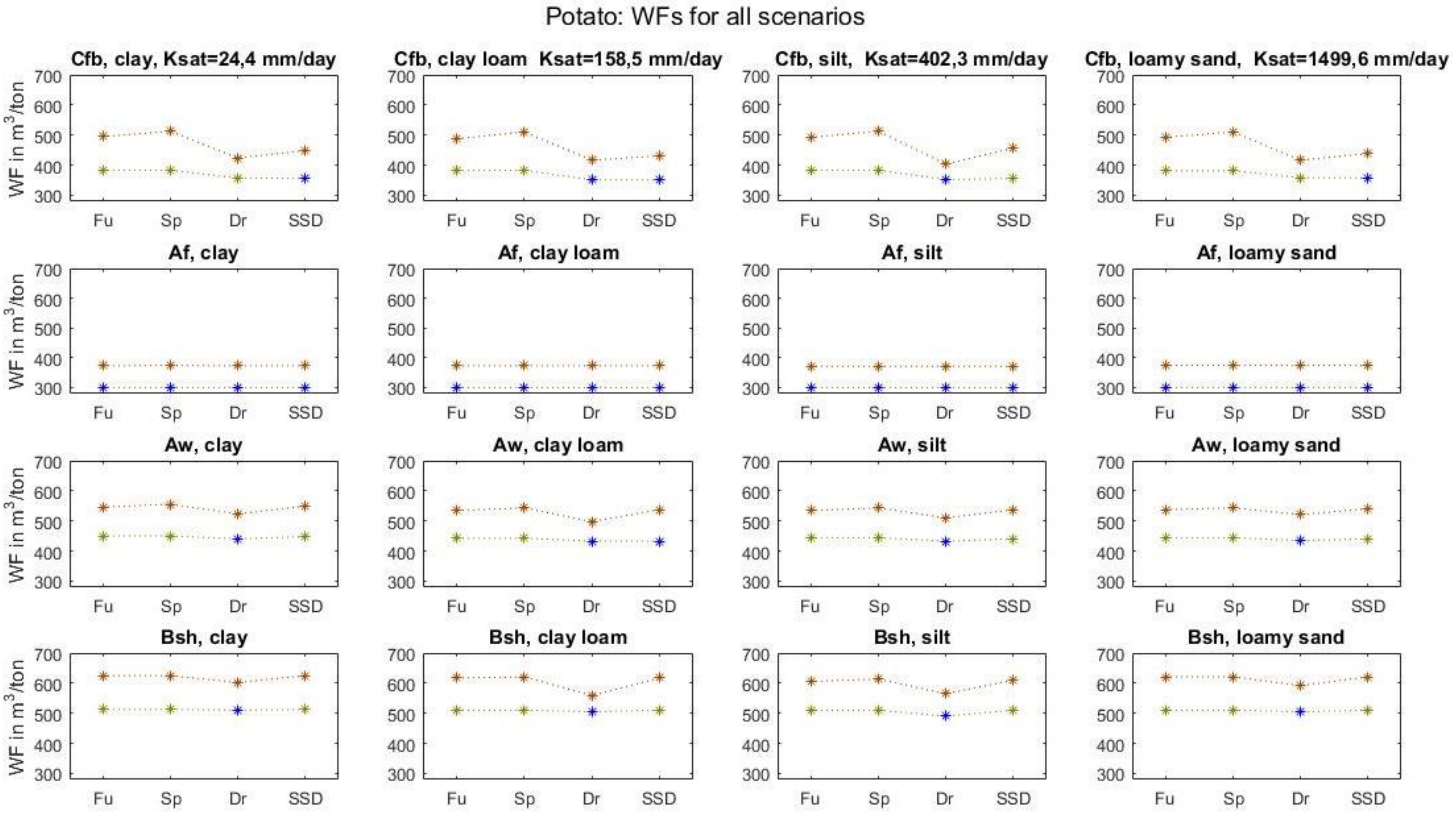
Figure 15 Differences in WF between %RAW=20 and % RAW=30 under different SW0

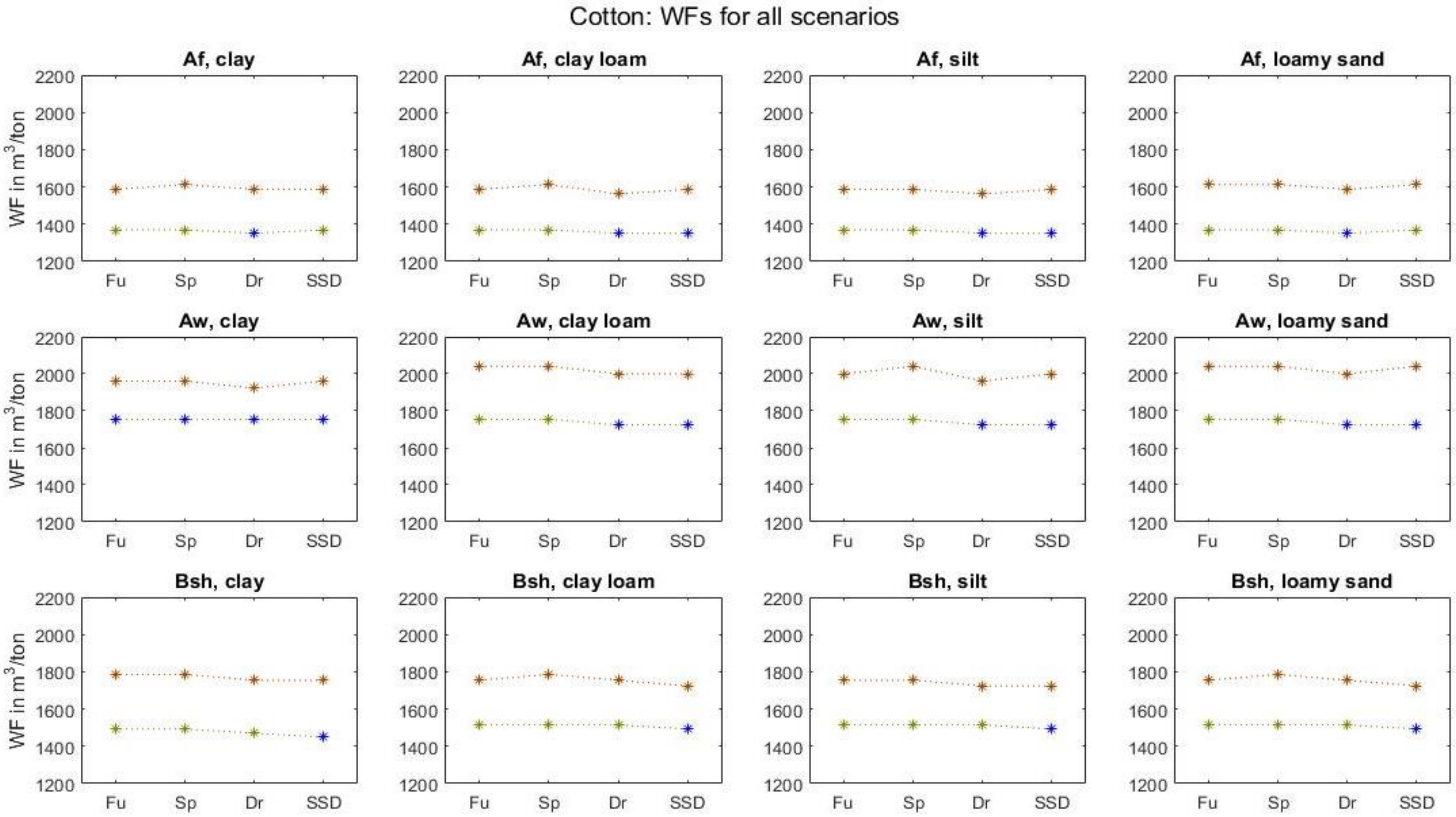
IV WFS FOR ALL IRRIGATION-METHOD-MULCHING COMBINATIONS IN ALL SCENARIOS

WFs for each crop-climate-soil-scenarios under all irrigation methods and mulching in the most average growing season.

The blue asterisks indicate the WFs obtained under best practice, which is used to determine the WFBs. The brown asterisks indicate the WFs that were obtained without mulch, the green asterisks indicate the WFs that were obtained with mulch.


Wheat: WFs for all scenarios
Cfb, clay, Ksat=24,4 mm/day
Cfb, clay loam Ksat=158,5 mm/day
Cfb, silt, Ksat=402,3 mm/day
Cfb, loamy sand, Ksat=1499,6 mm/day
Af, clay
Af, clay loam
Af, silt
Af, loamy sand
Aw, clay
Aw, clay loam
Aw, silt
Aw, loamy sand
Bsh, clay
Bsh, clay loam
Bsh, silt
Bsh, loamy sand
WF in m^3/ton
1000
800
600
Fu
Sp
Dr
SSD


Potato: WFs for all scenarios
Cfb, clay, Ksat=24,4 mm/day
Cfb, clay loam Ksat=158,5 mm/day
Cfb, silt, Ksat=402,3 mm/day
Cfb, loamy sand, Ksat=1499,6 mm/day
Af, clay
Af, clay loam
Af, silt
Af, loamy sand
Aw, clay
Aw, clay loam
Aw, silt
Aw, loamy sand
Bsh, clay
Bsh, clay loam
Bsh, silt
Bsh, loamy sand
WF in m³/ton
700
600
500
400
300
Fu
Sp
Dr
SSD


Cotton: WFs for all scenarios
Af, clay
Af, clay loam
Af, silt
Af, loamy sand
Aw, clay
Aw, clay loam
Aw, silt
Aw, loamy sand
Bsh, clay
Bsh, clay loam
Bsh, silt
Bsh, loamy sand
WF in m3/ton
2200
2000
1800
1600
1400
1200
Fu
Sp
Dr
SSD

V TEMPERATURE STRESS IN MAIZE IN THE CFB CLIMATE

Yearly output data from Aquacrop for Maize in Cfb in a clayloam soil. Temperature stress is highlighted.

Year	Cycledays	GDD	Total ET	Tr	E	Total Biomass	Yield	HI	**Temp. stress**
1961	137	872.2	334.1	292.4	41.7	17.31	8.31	48	**100**
1962	137	687.5	311.6	279.4	32.2	13.23	6.35	48	**100**
1963	137	809.2	323.9	289.6	34.3	17.94	8.61	48	**100**
1964	137	952.5	355.2	318.1	37.1	20.9	10.03	48	**100**
1965	137	758.8	296.6	262.8	33.8	15.56	7.47	48	**100**
1966	137	870.8	329.9	295.5	34.4	18.91	9.08	48	**98**
1967	137	902.8	340.6	307.3	33.3	19.23	9.23	48	**100**
1968	137	877.1	314.1	277.4	36.7	17.56	8.43	48	**100**
1969	137	966.6	352.6	316.2	36.4	20.46	9.82	48	**97**
1970	137	936.1	349.9	318.7	31.2	20.35	9.77	48	**100**
1971	137	922.4	340.6	309	31.6	19.39	9.31	48	**100**
1972	137	783.2	298.3	264.4	33.9	15.74	6.82	43.3	**100**
1973	137	925.3	344.2	310.2	34	20.31	9.75	48	**100**
1974	137	819	320.9	284.3	36.6	17.01	8.17	48	**99**
1975	137	929	349.4	318.9	30.5	18.72	8.98	48	**100**
1976	137	1112.8	439.2	408	31.2	23.63	11.34	48	**100**
1977	137	819.4	318.2	283.8	34.4	17.53	8.42	48	**100**
1978	137	792	329.9	297.5	32.4	16.71	8.02	48	**100**
1979	137	817.3	308.9	275.1	33.8	18.17	8.72	48	**100**
1980	137	849.6	344.9	308.5	36.4	18.35	8.81	48	**100**
1981	137	876.2	295.1	264.1	31	19.31	9.27	48	**100**
1982	137	1007.6	363.7	330.5	33.2	23.34	11.2	48	**100**
1983	137	1004.8	350.6	317.7	32.9	20.17	9.68	48	**100**
1984	137	800.3	299.8	266.3	33.5	15.42	7.4	48	**100**
1985	137	857.7	320.7	287.5	33.2	18.44	7.76	42.1	**100**
1986	137	904.3	364.5	332.2	32.3	20.51	9.85	48	**100**
1987	137	828.6	300.8	261.5	39.3	15.68	7.53	48	**99**
1988	137	911.3	315.2	276.3	38.9	19.93	9.57	48	**100**
1989	137	1035.1	395.4	361.6	33.8	23.46	11.26	48	**100**