WaterPIP
Water Productivity Improvement in Practice

Water Productivity Comparison using AquaCrop & WaPOR

A Case Study of the CropMon Project in Kenya

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Prepared by Wageningen University and Research in partnership with MetaMeta and IHE Delft Institute for Water Education.

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Acronyms

AETI	actual evapotranspiration and interception
CCo	initial canopy cover
EOS	end of season
E	evaporation
ET_a	actual evapotranspiration
ET_{ref} (or ET_o)	reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
fAPAR	fraction of absorbed photosynthetically active radiation
GDD	growing degree day
ha	hectare
HI	harvest index
HI_o	reference harvest index
HI_{adj}	adjusted harvest index
ISWC	initial soil water content
LCC	land cover classification
LST	land surface temperature
NDVI	normalized difference vegetation index
NPP	net primary production
P	precipitation
RMSE	root mean square errors
SOS	start of season
T	transpiration
TAHMO	Trans-African HydroMeteorological Observatory
WaPOR	FAO portal to monitor Water Productivity through Open access of remotely sensed derived data
WP	water productivity
WP_B	biomass water productivity
WP_y	yield water productivity

1 Introduction

Water productivity (WP) is an important performance indicator for agricultural land management and evaluation at a continental scale (Wesseling & Feddes, 2006). The Dutch Government started using the WP concept as indicator to evaluate the status and influence of Dutch-funded water projects in Africa. One of the key policy priorities by the Dutch Government was to increase WP by 25% in Dutch Development Cooperation projects (Ministry of Foreign Affairs of the Netherlands, 2013). As such, it intends to contribute to Sustainable Development Goal 6.4 on improved water use efficiency.

The Food and Agriculture Organization of the United Nations (FAO), with support from the Dutch government and in collaboration with IHE Delft Institute for Water Education and the International Water Management Institute, launched the FAO portal to monitor Water Productivity through Open access of Remotely sensed derived data (WaPOR). The database monitors the water productivity in Africa and the Middle East since 2009 at spatial resolution of 250 meters (whole continent), 100 meters (selected countries and river basins) and 30 meters (currently 8 areas).

The WaPOR database is the only database providing both above-ground biomass production and actual evapotranspiration (ET_a). Since the launch of WaPOR v1.0, a number of validation studies have been implemented (e.g., FAO and IHE Delft, 2019; Blatchford et al., 2020; Weerasinghe et al., 2020), focusing mainly on ET_a comparison at large scale or point scale (flux towers). Very limited validation has been done up to now in agricultural land, for which the database was primarily developed. In addition, validation of the WaPOR biomass with observed yield data requires conversion factors which vary place to place and year to year (e.g., harvest index).

This study aims to evaluate the WaPOR data by comparing with data collected from the field and the AquaCrop model for selected farms of the CropMon project in Kenya. AquaCrop is a crop growth model developed by the FAO to address food security and assess the effect of the environment and management on crop production (www.fao.org/aquacrop/en/). This water-driven model is designed for simulating green canopy and root growth under governing environmental conditions (Steduto et al., 2009). With a limited number of input requirements, AquaCrop simulates daily water balances in the root zones and crop development. The comparative analysis will provide a better insight into the reliability of remote sensing data, in particular for using WaPOR for water productivity assessments.

1.1 Project Description

The CropMon project was a four year project (2015-2019), funded by the Geodata for Agriculture and Water facility. CropMon aims to develop and provide information to farmers, including smallholders, to improve farm management practices during the growing season. The project leader was SoilCares Research BV in the Netherlands. Project partners were Spring BV (Netherlands), NEO BV (Netherlands), Weather Impact BV (Netherlands), Cereal Growers Association (Kenya), Coffee Management Services Ltd (Kenya), Equity Group Foundation (Kenya), KALRO Sugar Research Institute (Kenya) and SoilCares Ltd. (Kenya). The project focuses on the crops of coffee, maize, wheat, grass and sugarcane in both irrigated and rainfed agriculture. The CropMon project provides twice weekly messages on weather forecast and crop development on the basis of satellite image interpretation. The final target for the project is to make this information available to 150,000 farmers. There are 120 "model" farms with a database on production and farm inputs which could serve as a basis for WP analysis. Out of these farms, two large and three smaller farms were selected for the AquaCrop and WaPOR analyses.

1.2 Crop Production System and Challenges

Kenya has a total land surface of approximately 580,000 km^2 and a population of 44.5 million people, including 30 million people considered part of the agricultural sector (Mendes, & Paglietti, 2015). Agriculture is the key sector in the rural economy as it accounts 24 percent of the GDP and 65 percent of the total export earnings in 2014.

Smallholder farmers with land sizes averaging one hectare dominate Kenya's agricultural sector. The land tenure system in Kenya is predominantly executed that all married sons inherit an equal piece of land (Cross, 2002). This means that the agricultural land surface per family per generation is decreasing.

Kenya depends largely on rainfed agriculture. Almost 80% is located in an arid landscape with annual average rainfall varying between 200 and 600 mm/year. The higher situated areas (between 800 and 1,800 meters in elevation) are part of the semi-arid region with an average annual rainfall of 500-1,000 mm/year.

Kenya has 5.5 million hectares of arable land, but only 17% is suitable for rainfed agriculture. So in most parts of the country, rainfall is inadequate to meet crop water requirements for more than a single crop per year. That is why the largest potential stated by the FAO in 2014 is the development of irrigation management, water storage and high-tech efficient equipment for irrigation (Mendes, & Paglietti, 2015).

Soil fertility-related issues are a major concern to Kenya. As attested by the 'Strategy to Revitalize Agriculture' policy document of the Government of Kenya, 'low and declining fertility of the land' is one of the factors that continue to limit the growth of agriculture' (Government of Kenya cited in Gicheru, 2012). After the rapid growth of agriculture due to high-yielding varieties and land expansion during 1970s and 1980s, Kenya has experienced a persistent decline in agricultural growth, with the rate of increase reducing throughout the years. This has led Kenya to low crop productivity, chronic food shortages, and rising poverty levels country (Gicheru, 2012). However, the use of fertilizer is low due to its high prices and only 24.3% of farmers use manure to improve soil fertility (GoK, 2010).

1.3 Objective

The objective of this report is threefold; first, to shed light onto the agronomic factors that affect yield production and water productivity (i.e., the diagnostic analysis), second, to facilitate a comparison between the results of AquaCrop and those of WaPOR; and third, to investigate possible causes of discrepancies between WaPOR and AquaCrop results. The WaPOR database is based on satellite images and the AquaCrop simulation is based on validation of in-situ data. This way, the reliability of WaPOR data, and thus its analysis, can be assessed. Additionally, when the results of the AquaCrop and WaPOR are similar, the use of AquaCrop can be complementary to WaPOR in order to explain the influence of different stresses in low or high water productivities. In this report, this is referred to as the diagnostic analysis.

2 Method and Data

In order to meet the objectives of this report, AquaCrop simulations and WaPOR analyses were conducted for five rainfed farms of the CropMon project. Two of the farms are growing wheat commercially and the other three farms are growing maize for subsistence purposes. The five farms are located in Narok, Uasin Gishu and Nakuru Counties.

In order to compare the data and results of WaPOR analysis with AquaCrop, the following indicators were either obtained or calculated from AquaCrop and WaPOR for the five farms: i) evaporation (E), ii) transpiration (T), iii) actual evapotranspiration (ET_a), iv) reference evapotranspiration (ET_{ref}), v) above-ground biomass (BM), vi) harvest index (HI), vii) yield production and viii) yield water productivity (WP_y). The methodological framework to compare WaPOR and AquaCrop analyses is presented in Figure 2-1.

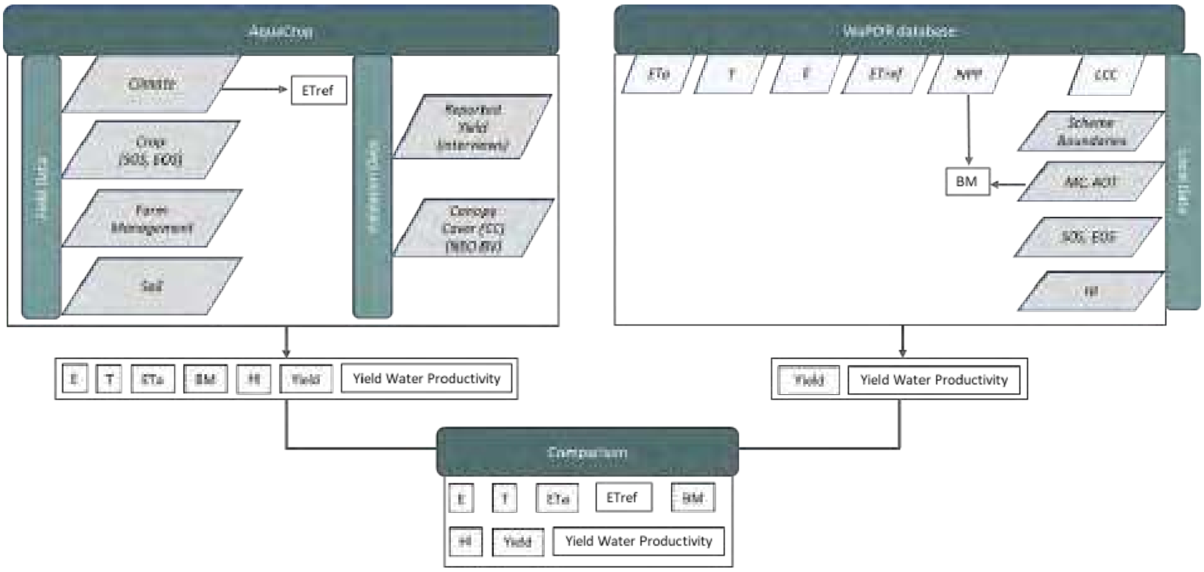


Figure 2-1: Methodological framework for comparison between AquaCrop and WaPOR analyses

In the following two sections, the methodology and data used for AquaCrop (Section 2.1) and WaPOR (Section 2.2) are discussed in further detail.

2.1 AquaCrop Model

AquaCrop is a crop growth model developed by the FAO to address food security and assess the effect of the environment and management on crop production (www.fao.org/aquacrop/en/). This water driven model is designed for simulating green canopy and root growth under governing environmental conditions (Steduto et al., 2009). With a limited number of input requirements (rainfall, reference evapotranspiration (ET_o), air temperature, and CO_2 concentration), AquaCrop simulates daily water balances in the root zones and crop development. To calculate the crop biomass and yield production, AquaCrop separates the evapotranspiration into soil evaporation (E) and crop transpiration (T). This separation makes sure that non-productive (soil evaporation) water consumption is not taken into account in the calculations for yield and biomass production.

2.1.1 AquaCrop Simulation Steps and Influence on the Harvest Index (HI)

AquaCrop is based on 4 main steps, as seen in Figure 2-2. In the first step, the canopy cover growth is simulated. Water, air temperature, soil fertility and salinity stresses may affect leaf expansion and result in early canopy senescence and reduction of the maximum canopy cover. Green canopy development proportionally affects the crop transpiration, and thus the second step of the simulation process is simulating crop transpiration. In this step, water and cold stress and water logging are considered. There is a lower and an upper threshold for shortage and excess of water in the root zone, respectively. If water in the root zone drops below the lower threshold, stomatal closure will occur, preventing the crop to transpire. If water in the root zone exceeds the upper threshold, deficient aeration affects crop transpiration. In the third step, the biomass that is produced is simulated as a proportion of the cumulative amount of water transpired. Lastly, in the fourth step, the yield is simulated based on the reference harvest index (HI_o), the adjusted harvest index (HI_{adj}) and the biomass produced. The HI_{adj} is dependent on water and temperature stresses during the growth cycle. The HI_o is a crop specific characteristic that is only adjusted when severe water stress has caused early senescence, preventing building up of the maximum harvest index and yield formation (see Figure 2-3).

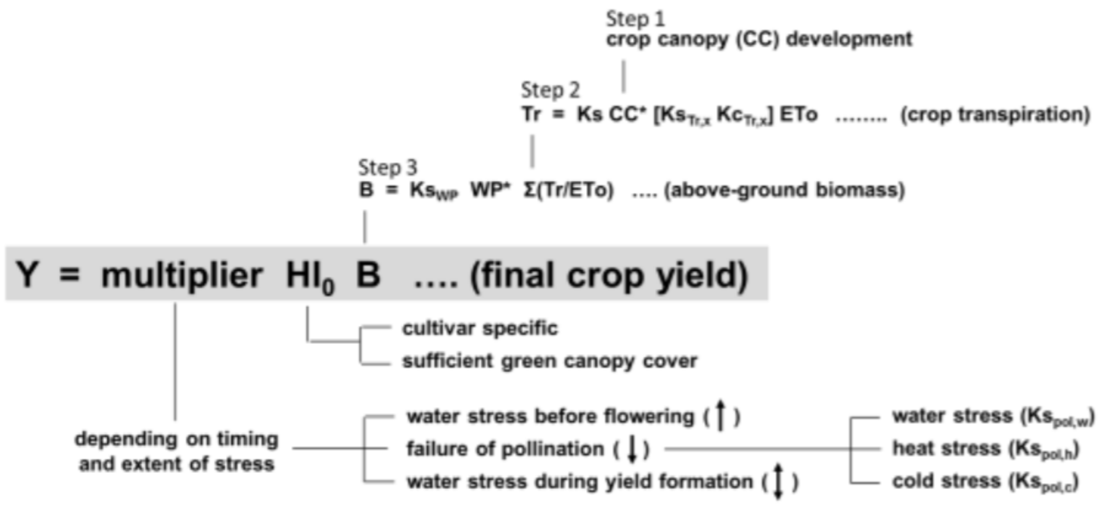


Figure 2-2: AquaCrop Simulation Steps, Source: FAO, 2017

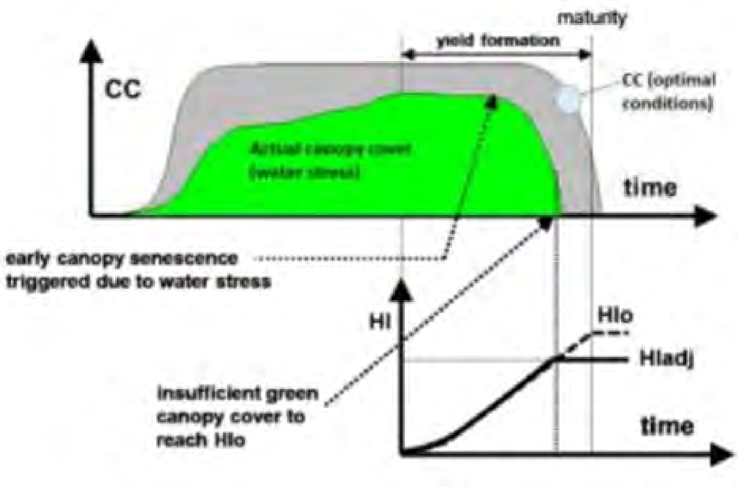


Figure 2-3: Adjustment of HI_o under insufficient green canopy cover (Source: FAO, 2017)

As seen below, the harvestable biomass depends on the timing and extend of water and temperature stress. In general, there are three phases of plant growth: vegetative growth, flowering and reproductive phase and lastly, senescence and maturity. The phase between flowering and maturity is when yield formation takes place. During the vegetative growth and before the reproductive phase, water stress can positively affect the harvest index since the crop has spent less energy in its vegetative growth. During flowering, water, cold and heat stresses might cause a reduction of the harvest index due to failure of pollination. However, when vegetative growth is possible in the flowering phase, a mild water stress can positively affect the harvest index due to the decrease of competition between leaf growth and reproductive growth. In determinant crops, the vegetative growth is possible up until the peak of the flowering (mid-flowering), while for indeterminant crops, vegetative growth can occur up until the senescence. As such, in determinant crops, stresses up until mid-flowering can affect the actual maximum canopy cover. During yield formation, the harvest index builds up and water stresses can negatively affect harvest index if stomatal closure is reached. If water stress is severe and permanent wilting point is reached, a 100% reduction of the harvest index will occur. In general, the impact of stresses (heat, cold, water, fertility stress) in the plant growth and production depends on the timing and intensity of the stress. An overview of how stresses affect the harvest index is presented in Figure 2-4.

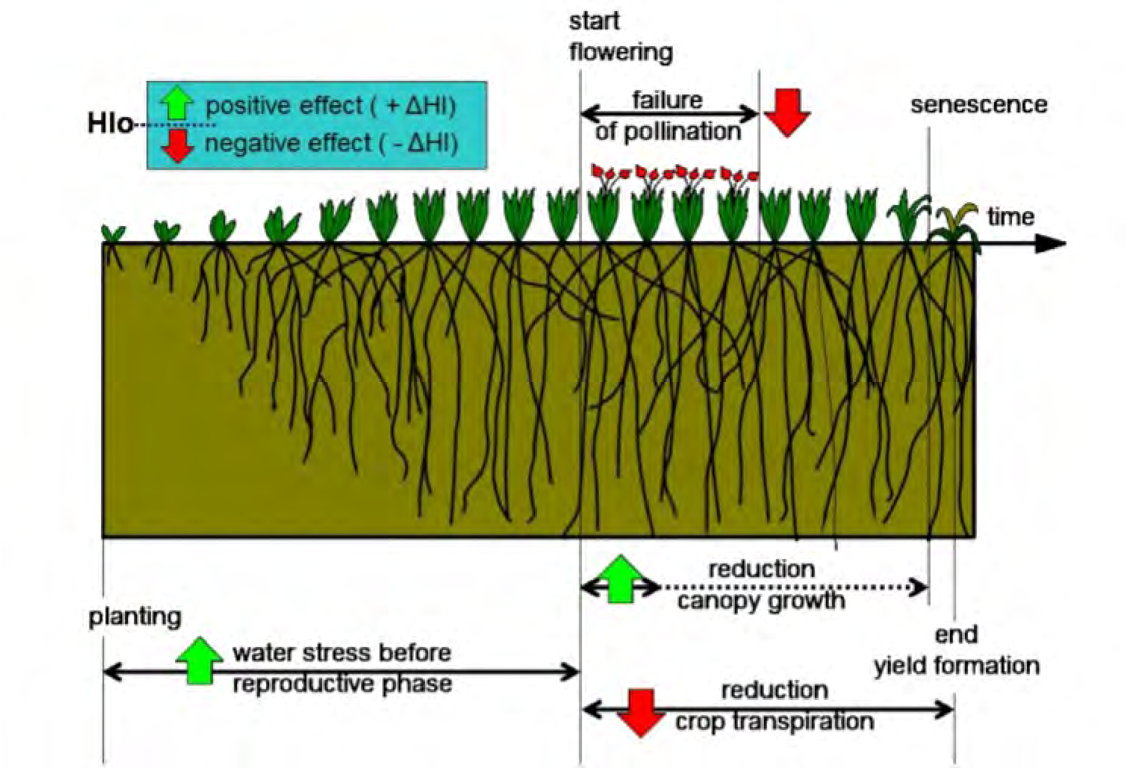


Figure 2-4: Effect of stresses in different crop growing stages (Source: FAO, 2017)

2.1.2 Crop Growth Simulation - Growing Degree Days and Calendar Days

Crop growth simulation is the basic feature of AquaCrop. AquaCrop provides default values for the crop development of different crops either through calendar days or through growing degree days (GDDs). However, these default crop growth values need to be calibrated and validated for each variety as they may vary significantly among varieties. Since crop growth stages are critical parameters for the simulations, reliable and accurate data are required in order to validate and/or calibrate the (default) growth stage settings accordingly.

GDDs are based on the concept of heat units (ºC), which are expressed in growing degree days (GDDs). GDDs are the number of days that are required by the crop to pass from one growing stage into the next (emergence, maximum canopy growth, senescence and maturity) under the prevailing climate conditions.

GDDs are calculated by subtracting the base temperature (T_{base}) from the average air temperature (T_{avg}) (Equation 2-1). T_{base} is the temperature below which no heat units can be accumulated and thus the crop development is zero. There is also a maximum temperature above which thermal units cannot be accumulated. Both base and maximum temperatures are crop conservative characteristics. T_{avg} depends on the climate file and the air temperature.

$$0 \leq GDD = T_{avg} - T_{base}$$

Equation 2-1

The main advantage of expressing the crop calendar in GDDs is that temperature stress is expressed more accurately since GDDs provide an indicator for temperature stress during the canopy development stages. When running with calendar days, temperature stress is taken into account for its effect on i) crop transpiration and ii) pollination (failure of pollination or not, that affects the HI). Using GDD ensures the canopy simulation is dynamically responsive to the climatic conditions governing the simulated context.

In theoretical terms, GDDs can also capture the effect of water stress in the development of the canopy, since water stress will increase the GDDs and thus the plant will go faster through growth stages which in turn will reduce the biomass production. This is a natural reaction of the plant to water stress. AquaCrop does not consider dynamic feedback of the water stress on GDDs. In order to assess the influence of water stress to GDDs, GDDs were calculated from CropSyst and AquaCrop model for one farm. The comparison of the two methods resulted in similar GDDs; CropSyst method resulted in a faster accumulation of GDDs by only 3-4 days. This influence was considered limited and thus GDDs as calculated by AquaCrop were used for all the simulations.

2.1.3 Simulating CropMon Farms with AquaCrop - Data

In order to simulate the five farms, data were obtained from the field regarding the climate of each farm, the crop cultivated, the management of the farm and the classification of the soil (Figure 2-5).

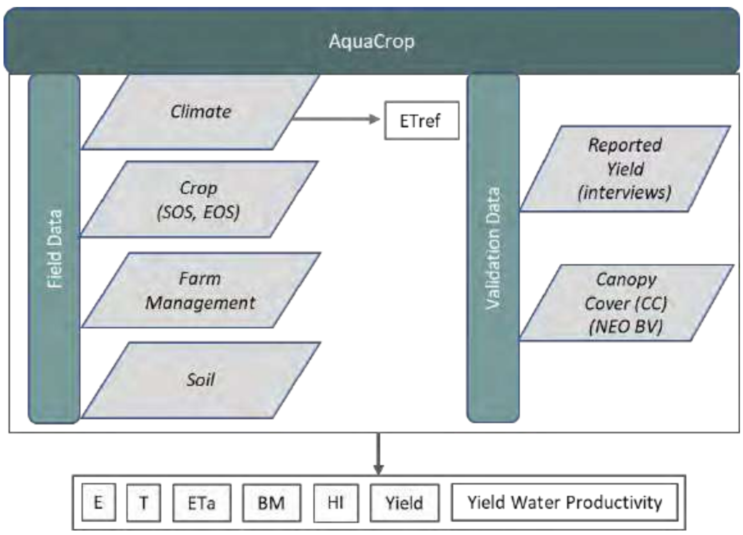


Figure 2-5: AquaCrop methodology

Weather data on daily humidity (%), precipitation (mm), pressure (kPa), radiation (W/m^2), min- max- and mean temperature (°C), wind direction and wind speed (m/s) were obtained from the meteorological stations of Trans-African HydroMeteorological Observatory (TAHMO). This data was also used for the calculation of ET_{ref}, based on the Penman-Monteith method.

The majority of TAHMO weather stations had incomplete weather data for 2018 (January to December), while at least one weather station around each farm had weather data for the complete year. In order to produce a full weather profile for each county, a climate file was created as the average of the different weather stations in the county. In the case of Uasin Gishu County, weather data were averaged from the three closest weather stations which are located outside the county (Figure 2-6). For the weather data of Narok County, an additional weather station outside of the borders of the county was used. As such, farms located in the same county have the same climate file. Using the average of the different weather stations involves some uncertainties regarding the accuracy of the daily weather data (Kusters, 2019). In Annex 1, the distance between each farm and the used weather stations is presented. In some cases, the distance between the farms and the used weather stations can be fairly large, over 40 km, which is significant. This represents an uncertainty factor, as the accuracy of the climate data, although based on the closest available data, cannot be verified with an on-farm station.

The farm and the weather station locations are shown in Figure 2-6.

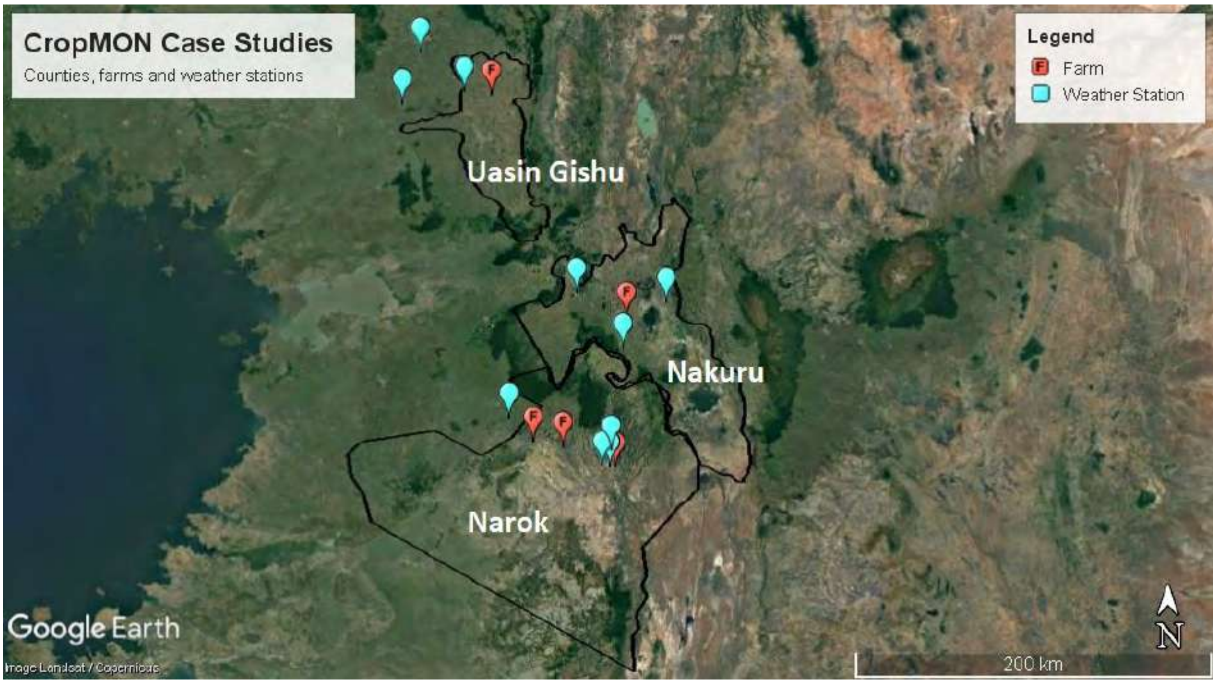


Figure 2-6: CropMon counties, farm and weather station locations

For one farm, an additional AquaCrop simulation was done. This simulation was run with WaPOR climate data (daily precipitation and daily ET_o) in order to determine the sensitivity of AquaCrop and WaPOR simulation outputs to variances in the climate input data (Section 5.1.1).

Crop data on the planting date (start of the season, SOS), the harvesting date (end of the season, EOS), planting density and specific crop cultivated (wheat or maize) were also obtained from interviews with the farmers. Canopy cover development data were obtained from the company NEO BV. Through satellite images with a 10x10m resolution, normalized difference vegetation index (NDVI) values were obtained for 38 dates over 2018. Canopy cover data before or after the growing season were not used, resulting in having 11 to 24 canopy cover data for each farm throughout the growing season. As such, the canopy cover data obtained from NEO BV were point values of % of canopy cover in particular dates.

In general, accurate canopy cover data that are obtained in the field (e.g., from drones) are critical for the calibration of AquaCrop and the adjustment of the crop growth stages. Since the NEO BV canopy cover data are obtained through satellite images, there are inaccuracies expected related to clouds and weed infestation, and canopy data cannot be linked to specific crop growth stages apart of SOS and EOS. For this reason, NEO BV data are used exclusively for validation purposes.

Soil data were obtained from the soil map of Kenya, developed in 1980 as used by Kusters (2019).

Farm management data regarding soil fertility and weed infestation levels were only qualitatively obtained in the field through observations. Moreover, soil fertility and weed infestation levels were adjusted based on the farming type (i.e., commercial and subsistence) and were used as a way to validate observed yield and canopy cover data (NEO BV). Observed yield data for the farms was obtained through interviews with farmers and it was used only for validation.

2.2 WaPOR Dataset

The WaPOR portal provides data on key parameters of land and water use for agricultural production (Figure 2-7) since 2009 for Africa and the Near East. The data can be used to estimate land and water productivity in agriculture.

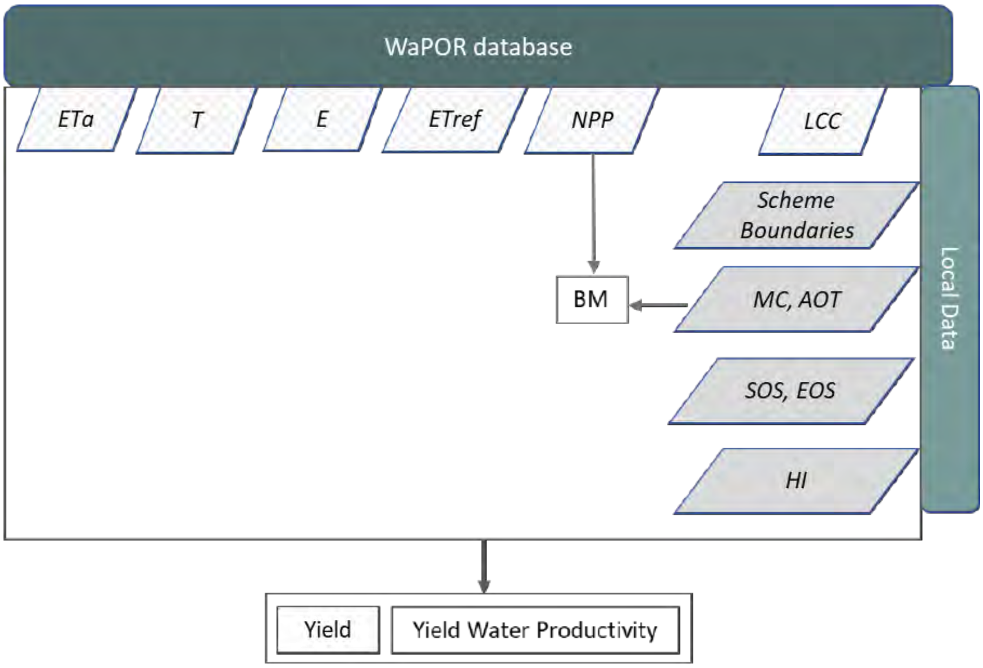


Figure 2-7: WaPOR methodology

WaPOR provides data on actual evapotranspiration and interception (AETI)[1], transpiration (T), precipitation (P), reference evapotranspiration (ET_{ref}), land cover classification (LCC) and net primary production (NPP). The spatial resolution of the satellite images for the above mentioned parameters is shown in Table 2-1.

[1] AETI data is considered to be the same as ET_a.

Table 2-1: WaPOR derived data

Remote sensing layers	Description/ Spatial resolution	Temporal Resolution
Actual evapotranspiration (AETI)	100 m (level 2)	Dekadal (2018)
Transpiration (T)	100 m (level 2)	Dekadal (2018)
Evaporation (E)	100 m (level 2)	Dekadal (2018)
Net primary production (NPP)	100 m (level 2)	Dekadal (2018)
Precipitation (P)	5 km (level 1)	Daily (2018)
Reference evapotranspiration (ET_{ref})	25 km (level 1)	Daily (2018)

The CropMon case study only collected field data in 2018 and thus the WaPOR was used for the seasonal analysis of the same year. As such, the above-mentioned parameters derived from WaPOR were aggregated to seasonal values using Equation 2–2 (example for estimating seasonal evapotranspiration):

$$ET_{a,s} = \sum_{SOS}^{EOS} ET_a$$

Equation 2-2

where ET_a is the actual evapotranspiration that includes evapotranspiration and interception, $ET_{a,s}$ is seasonal actual evapotranspiration in mm/season, SOS and EOS are starting and ending of the crop season. In the CropMon case study, the start of the season is set to be the date of planting while the end of the season is considered the date of harvest.

The biomass production (BM) is calculated from the seasonal net primary production (NPP) provided by WaPOR, based on Equation 2-3, where AOT is the ratio of above ground over total biomass, f_c is the light use efficiency correction factor of C3 and C4 crops and MC is the moisture content of fresh biomass. These parameters vary depending on the cultivated crop. The values used in the analyses are presented in Table 2-2. As such, there are different values for the wheat and maize farms.

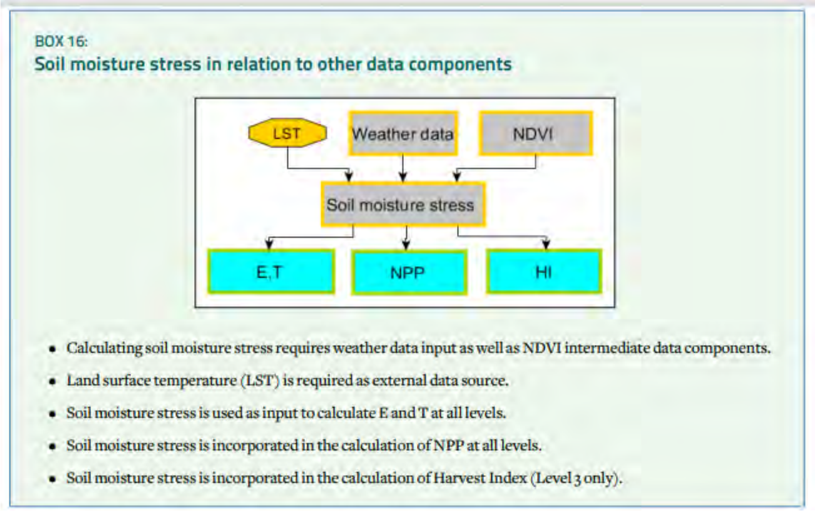
$$BM = AOT * f_c * \frac{NPP * 22.222}{1 - MC}$$

Equation 2-3

Table 2-2: WaPOR parameters

Parameters	Wheat	Maize
f_c	0.89	1.6
MC	0.15	0.26
AOT	0.85	0.93
HI (WaPOR manual, FAO, 2020)	0.48	0.48
HI* (WaPOR portal)	0.48	0.35

WaPOR addresses the different stresses in the calculation of NPP, based on different parameters. NPP is calculated by multiplying the maximum primary production (NPP_{max}) with several stress factors. NPP_{max} is climate limited by radiation, CO_2 concentration and temperature. The stress factors are combined in several parameters, the fraction of absorbed photosynthetically active radiation (fAPAR), light use efficiency of C3 crops and soil moisture stress (Veroustraete et al., 2002; Myneni and Williams, 1994; FAO, 2018). Soil moisture stress is an important parameter regarding biomass production and evapotranspiration (FAO, 2020). WaPOR considers soil moisture stress through land surface temperature (LST), the weather data and the vegetation cover (derived from NDVI) (Figure 2-8). Thus, the variation in NPP across pixels is due to a combination of noises in the remote sensing observations (e.g., distortion due to gap filling as a result of cloud cover), and stressed induced by water, nutrient, pests and diseases.


BOX 16:
Soil moisture stress in relation to other data components

- Calculating soil moisture stress requires weather data input as well as NDVI intermediate data components.
- Land surface temperature (LST) is required as external data source.
- Soil moisture stress is used as input to calculate E and T at all levels.
- Soil moisture stress is incorporated in the calculation of NPP at all levels.
- Soil moisture stress is incorporated in the calculation of Harvest Index (Level 3 only).

Figure 2-8: WaPOR methodology for soil moisture parameter, adopted from FAO (2020)

3 AquaCrop Analysis

3.1 Basic Assumptions

In order to run AquaCrop for the five farms, the following assumptions were made:

Assumption 1: Since the wheat farms were commercial farms, the soil fertility and weed infestation were considered to be relatively good. In the absence of hard data on these aspects, it was assumed that soil fertility stress in the wheat farms was around 15% while the weed infestation was around 10%. For the case of the maize farms, that are all subsistence farms, the soil fertility stress was assumed to be around 40% and the weed infestation around 15%. These assumptions were used in the initial runs of AquaCrop. Later, soil fertility levels were validated based on the reported yield (farmers' interviews) and canopy cover data (NEO BV). When validation was satisfactory, AquaCrop default settings for the growth stages could be used without further calibration. However, this was not the case for all the farms. Especially for two maize farms, slight adjustments of the growth stages were done for validation purposes even though calibration was not done. In these cases, more detailed data on canopy development and crop growth stages are required to conduct a proper crop-file calibration in AquaCrop.

Assumption 2: Crop growth is very sensitive to water stresses during the planting and the first days towards emergence. For this reason, the initial soil water content (ISWC) is very important for the simulations. When the ISWC is not defined by the user, AquaCrop assumes that the ISWC at the beginning of the simulation is at field capacity. This is the ideal situation for plant growth since there is no water stress (neither shortages nor excess) and it ensures that there is enough water in the root zone for germination. In this analysis, all simulations were initially run with ISWC at field capacity. Even if this approach might result in an overestimation of yield, this was later subject to change in order to simulate the reported yield (farmers' interviews) and canopy development (NEO BV). Another argument for assuming the ISWC at field capacity is the fact that farmers are aware of the importance of soil water during the first days of development and thus plant their crops based on experience after the first rains that have restored the soil moisture.

Assumption 3: The time of maturity in relation to the harvesting date are very important indicators in order to have realistic simulations. Maturity as a growth stage defines the time (length) of the building up of the HI, since AquaCrop creates a linear and gradual increase of the HI up until maturity. As such, if green canopy development is hampered too much due to physiological stresses (water and heat), insufficient photosynthetic assimilation capacity (biomass production) is available during the yield formation stage and maximum HI cannot be reached, causing a decrease in the simulated yield. This attribute can be adjusted by increasing the time between senescence and maturity and validating using the reported yield. However, when increasing the date of maturity, attention should be paid on the harvest date and the fact that maturity is reached before harvesting. Farmers in Kenya are known to leave their crops standing in the field (up to three months)[2] to dry after maturity is reached and then harvest (e.g., to obtain favourable low moisture contents before storage). As such, having in mind the crop calendar, the risk for calibrating for yield but having a maturity date that is after the observed harvest is avoided. In this analysis, harvest date data are available and thus they are used to make a realistic canopy development simulation.

3.2 Wheat Farms

Both wheat farms are located in Narok County (Figure 3-1). Climate data were averaged between the four weather stations of Figure 3-1. As such, the two farms have the same climate conditions. Moreover, both farms grow the same variety of wheat (kingbird) which implies the same growing stages in the crop-file.

[2] Alakonya et. al. (2008)

However, the two farms have different planting densities and planting dates (Table 3-1) and thus a different canopy cover development is expected due to different stresses.

Figure 3-1: Commercial wheat farms in Narok County

Table 3-1 shows all the input variables for the wheat farms, with the different planting and harvest dates. Plant density was calculated based on field data on sowing rate (kg seed/ha). Based on the plant density the initial canopy cover (CC_o) was calculated. The rooting depth was set at 1 meter based on the FAO publication of rooting depths[3].

Table 3-1: Simulation input for wheat farms

		Farm	
		I	II
General Farm Information	Crop type	Wheat	Wheat
	Variety	Kingbird	Kingbird
	County	Narok	Narok
	Root Depth (m)	1.0	1.0
	Plant density (plants/ha)	1,845,000	2,227,500
	Cropped Area (ha)	40.4	34.3
	CC_o (%)	2.77	3.34
	Max Canopy Cover (%)	96	96
	Soil Classification	L20	L20
	Field Capacity at top layer (%)	39	39
	Field Capacity at bottom layer (%)	54	54
	Dry yield production (reported) (ton/ha)	3.34	4.45
Crop Calendar	Planting date	11/03/2018	28/03/2018
	Harvest date	05/08/2018	30/07/2018

[3] Source: http://www.fao.org/3/y5749e/y5749e0j.htm

3.2.1 Farm I

3.2.1.1 Results

Table 3-2 shows the default and the validated settings of AquaCrop for Farm I. For the validation of Farm I, only the initial CC_o (available field data on kg seed/ha) and the soil fertility stress were changed.

Table 3-2: AquaCrop validation for Farm I

		Default	Validated
	CC_o	6.75	2.71*
	CGC** (%/day)	9.1	10.9***
	CC_{max}(no stress) (%)	96	96
	CDC (%/C-day)	0.4	0.4
Growing Cycle (GDD)	Emergence	150	150
	Max CC	1186	1186
	Senescence	1700	1700
	Maturity	2400	2400
Yield formation (GDD)	Length of building up of HI	1100	1100
	Duration of flowering	200	200
	Begin of flowering	1250	1250
Root depth	Max effective rooting depth (m)	1.5	1
	Max depth (GDD)	864	864
Soil Fertility	Biomass production (%)		85
	Max CC (%)		81
	canopy decline		medium
	reduction of canopy expansion (%)		10
	Avg. decline canopy cover (%/GDD)		0.08
	Reduction on WP (%)		8
	Harvest Index, HI (%)	48	

** The CC_o setting is automatically adjusted by AquaCrop on the basis of the sowing density input parameter (kg/ha of seed), which represents a management factor.*
*** CGC is the canopy growth coefficient.*
**** As the canopy growth coefficient (CGC) is expressed in calendar days and not GDD, the value is automatically adjusted to the prevailing climatic conditions, and the interpolation of the CC_o and CC_{max} values.*

In Table 3-3, the results of the simulations are presented, while in Figure 3-2 the graphic illustration of the results is shown.

Table 3-3: Simulation results for Farm I (*Observed canopy data were cleaned, see evaluation of simulation)

	Results
*Correlation (r)	0.76
*Root Mean Square Error (RMSE) (% CC)	17.5
*Average of Observed CC (%)	41.9
*Average Simulated CC (%)	40.5
Evaporation, until maturity (mm)	126.3
Evaporation, until harvest (mm)	172.2
Transpiration (mm)	204.2
Evapotranspiration until harvest (ET_a) (mm)	376.4
Reference Evapotranspiration until harvest (ET_o) (mm)	587.5
Rainfall until harvest (mm)	296.6

Table 3-3: Simulation results for Farm I (*Observed canopy data were cleaned, see evaluation of simulation)

Dry yield production (simulated) (ton/ha)	3.48
Dry yield production (reported) (ton/ha)	*3.34*
Harvest Index (adjusted) (%)	43.6
Potential Biomass (ton/ha)	15.814
Actual Biomass (ton/ha)	7.994
WP (kg yield/m^3 ET)	1.05
Temperature (transpiration) stress (%)	-
Canopy expansion stress (%)	21
Stomata Closure stress (%)	29
Weed infestation stress (%)	10
Soil fertility stress (%)	25

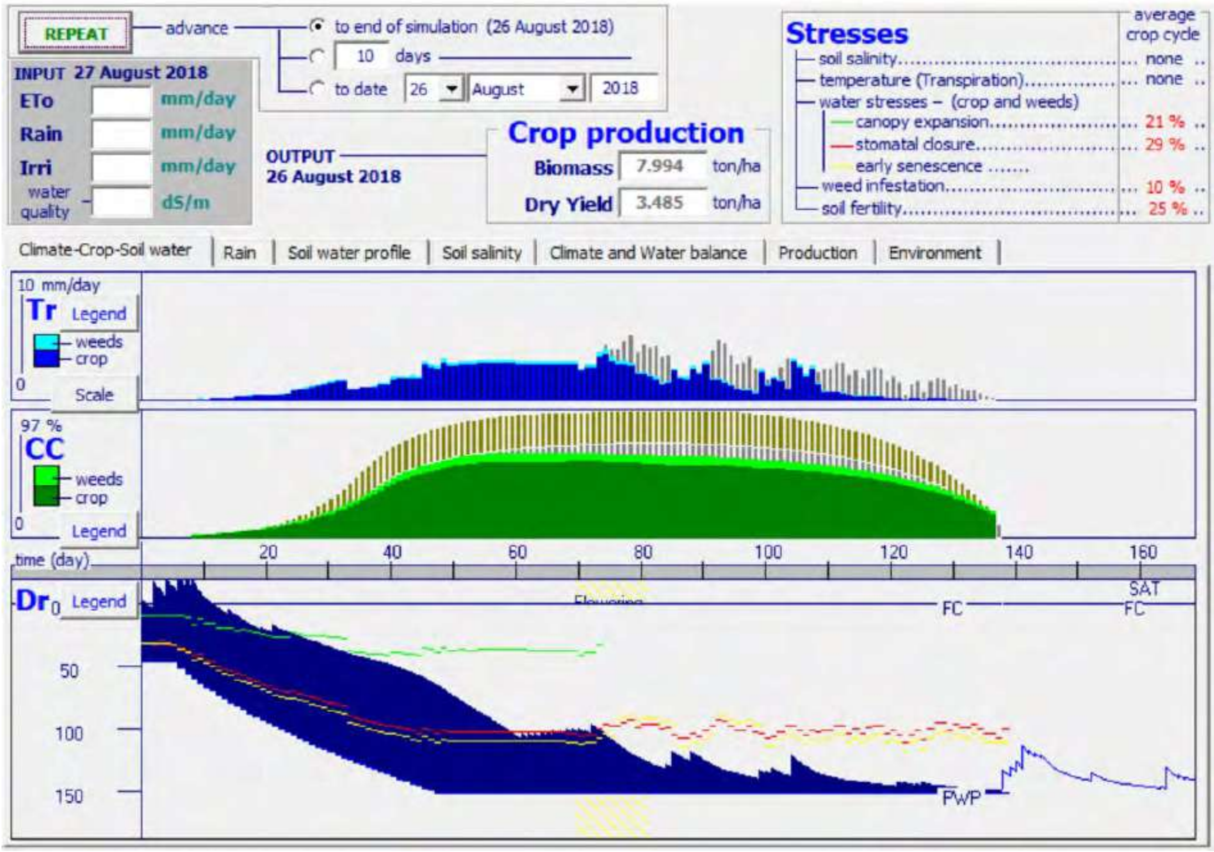


Figure 3-2: AquaCrop results for Farm I

3.2.1.2 Evaluation of Simulations

Stresses

During the first 10 days of the growing cycle, there is excess water in the root zone that exceeds the upper threshold for saturation (Dr graph in Figure 3-2). In this stressing condition, E is higher than T, and water logging conditions result in a transpiration stress. After this initial small transpiration stress, the water in the root zone decreases gradually and moves below the threshold for canopy expansion (green line). In effect, this is a mild water stress that affects the turgor of the plant and inhibits canopy growth due to the lack of sufficient turgor pressure. During the beginning of yield formation (day 75), the water level decreases further and stomatal closure occurs (red line). From this point onwards, the transpiration of the plant is restricted (Tr graph) while water stress can be seen in the CC graph (white lines) along the fertility stress (brown lines). AquaCrop calculates that water stress due to stomatal closure was at 29% while due to canopy expansion at 21%. Soil fertility stress of 25% provided the best simulation in line with the canopy cover data obtained from Neo BV and the reported yield. Flowering normally reaches half of its duration when maximum canopy cover is developed. However, for Farm I, flowering occurs after maximum canopy cover development takes place. This is due to the water stress that prematurely stunts the canopy development.

Influence of Harvest Index

As discussed above, severe water stress takes place during the yield formation. This has a negative impact on the HI which is calculated at 43.8% (see Table 3-3). In Table 3-4, the growing cycle of the crop is presented.

Table 3-4: Growing cycle for Farm I

	Default	Validated	Corresp. Days
Emergence (GDD)	150	150	9
Max CC (GDD)	1,186	1,186	65
Senescence (GDD)	1,700	1,700	95
Maturity (GDD)	2,400	2,400	138
Harvest			147

Reflection on Observed CC data (NEO BV)

The canopy cover data from NEO BV were cleaned as an outlier was found. The satellite canopy cover data for 11/6/2018 increased and decreased over 20% from the previous reading in less than a month (Figure 3-3). For this reason, the observed canopy data were cleaned and the outlier was not used (Figure 3-4). The correlation between the simulated and cleaned observed canopy cover data improved (from r=0.69 to r=0.76). It is generally recognized that satellite images might be affected by clouds, which are evident during rainy days. However, in the case of Farm I, many canopy cover data are taken during raining days without resulting in more outliers. As such, conclusions regarding the nature of this outlier cannot be made.

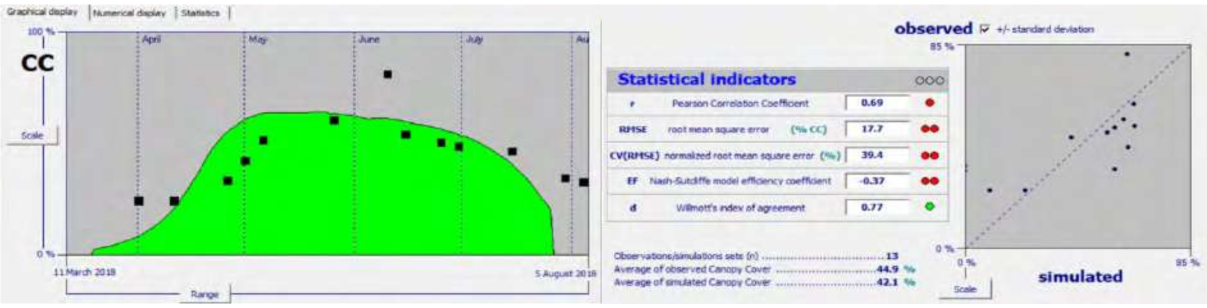


Figure 3-3: Correlation between uncleaned observed and simulated canopy cover data for Farm I

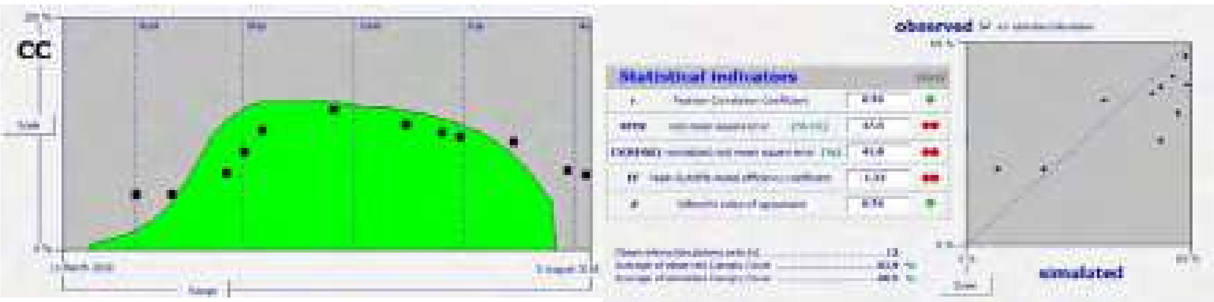


Figure 3-4: Correlation between cleaned observed and simulated canopy cover data for Farm I

3.2.2 Farm II

3.2.2.1 Results

Table 3-5 shows the default and the validated settings of AquaCrop for Farm II. For the validation of Farm II only the initial CC_o (available field data on kg seeds/ha) and the soil fertility stress were changed.

Table 3-5: AquaCrop validation for Farm II

		Default	Validated
	CC_o	6.75	3.34
	CGC (%/day)	9.1	10.9
	CC_{max} (no stress) (%)	96	96
	CDC (%/C-day)	0.4	0.4
Growing Cycle (GDD)	Emergence	150	150
	Max CC	1,186	1,186
	Senescence	1,700	1,700
	Maturity	2,400	2,400
Yield formation (GDD)	Length of building up of HI	1,100	1,100
	Duration of flowering	200	200
	Begin of flowering	1,250	1,250
Root depth	Max effective rooting depth (m)	1.5	1
	Max depth (GDD)	864	864
Soil Fertility	Biomass production (%)		85
	Max CC (%)		78
	Canopy decline		medium
	Reduction of canopy expansion (%)		11
	Avg. decline canopy cover (%/GDD)		0.09
	Reduction on WP (%)		1
	Harvest Index, HI (%)	48	

In Table 3-6, the results of the simulation are presented, while in the Figure 3-5 graphic illustration of the results is presented.

Table 3-6: Simulation results for Farm II (*Observed canopy data were cleaned, see evaluation of simulation)

	Results
*Correlation (r)	0.85
*Root Mean Square Error (RMSE) (% CC)	13.3
*Average Observed CC (%)	57.4
*Average Simulated CC (%)	56.8
Evaporation (mm)	91.8
Transpiration (mm)	235.8
Evapotranspiration (ET_a) (mm)	327.6
Reference Evapotranspiration (ET_o) (mm)	566.5
Rainfall (mm)	198.4
Dry yield production (simulated) (ton/ha)	3.999
Dry yield production (reported) (ton/ha)	4.45
Harvest Index (adjusted) (%)	45.7
Potential Biomass (ton/ha)	16.343
Actual Biomass (ton/ha)	8.748
WP (kg yield/m^3 ET)	1.23
Temperature (transpiration) stress (%)	-
Canopy expansion stress (%)	17
Stomata Closure stress (%)	26
Weed infestation stress (%)	10
Soil fertility stress (%)	15

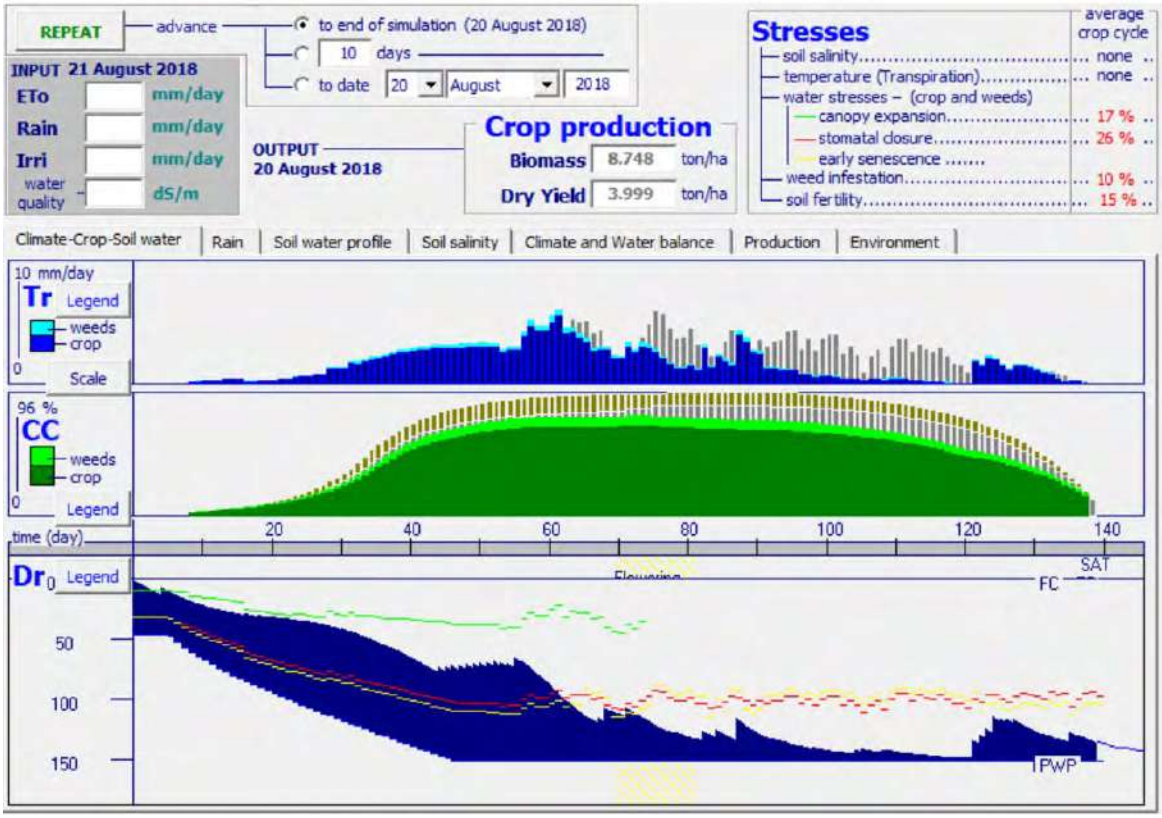


Figure 3-5: AquaCrop results for Farm II

3.2.2.2 Evaluation of Simulations

Stresses

Planting in Farm II happens around 20 days after planting for Farm I. As such, it is clear that there is less water in the root zone. However, since the initial water stress due to excess water is avoided in Farm II, the overall water stresses causing stomatal closure is at the same levels in the two farms (27% for Farm I and 26% in Farm II). Due to water stress, flowering takes place after maximum canopy cover has been reached. Transpiration is restricted when water levels decreases beyond the threshold for stomatal closure but recovers during the last days of the yield formation (days 120-139, see Tr and Dr graph in Figure 3-5) thanks to later rainfall. Since this happens during the yield formation and not the vegetative growth stage, no new canopy is developed but the yield increases.

Influence of Harvest Index

For Farm II, the crop parameter of physiological maturity is set at day 139 (2,400 GDD, the same as for the same variety used in Farm I). This is later than the reported harvest date at day 124 (Table 3-7). Even if this goes against Assumption 3 (see Section 3.1), this date was kept in order to simulate the reported yield as closely as possible, and we had no other information available to adjust these settings.

When the maturity date is decreased (less than 2,400 GDDs) the simulated yield decreases as well. This happens due to the fact that there is more water stress during the yield formation period, since the last rains (between days 120-139) are not taken into account. As such, even if the HI_o reaches its maximum, the HI_{adj} is reduced, causing a reduction in the simulated yield. On the other side, when maturity is increased (over 2,400 GDDs), the simulated yield decreases because there is not sufficient green canopy growth to reach maximum HI_o. For this reason, it seems that this date is around a sweet spot for simulating both the reported yield and adjusted canopy cover data, as discussed below. Moreover, the simulation of Farm I, which used the same variety of wheat as Farm II, provided a good validation of the GDD setting for the crop's maturity, thus providing no indication for a changed setting in the simulation of Farm II.

Table 3-7: Growing cycle for Farm II

	Default	Validated	Corresp. Days
Emergence (GDD)	150	150	9
Max CC (GDD)	1,186	1,186	66
Senescence (GDD)	1,700	1,700	96
Maturity (GDD)	2,400	2,400	139
Harvest			124

Reflection on Observed CC Data

Observed canopy cover data were cleaned for Farm II. When all the data points obtained from NEO BV were used, the correlation between observed and simulated results was poor (r=0.61, Figure 3-6). The 1st canopy cover reading was considered as an outlier and was removed from the dataset (Figure 3-7). This way the correlation between observed and simulated canopy cover after data cleaning was improved (from r=0.61 to r=0.85)

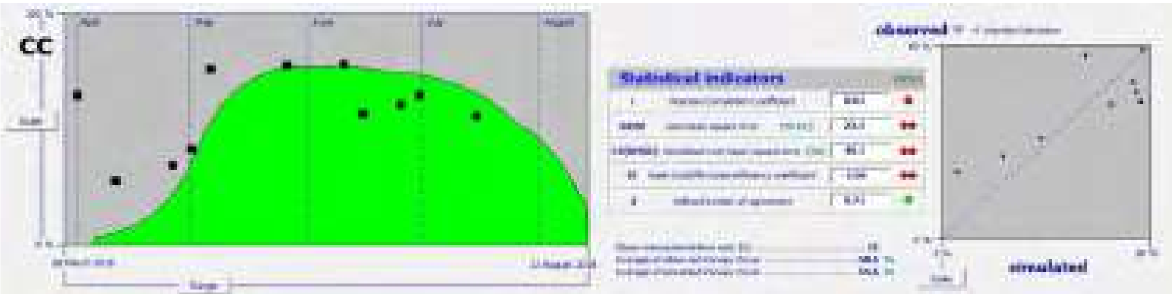


Figure 3-6: Correlation between uncleaned observed and simulated canopy cover data for Farm II

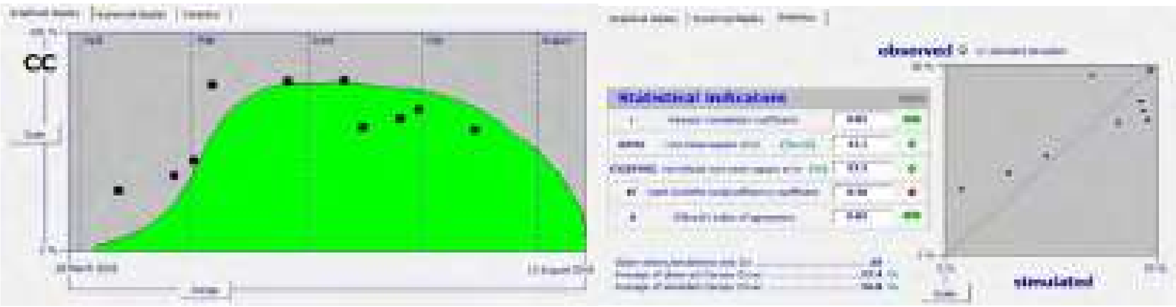


Figure 3-7: Correlation between cleaned observed and simulated canopy cover data for Farm II

3.3 Maize Farms

All maize farms are located in different counties; in Uasin Gishu, Narok and Nakuru Counties for Farms B, A and M, respectively (Figure 3-8). All maize farms grow different varieties with different planting dates in different climatic conditions and thus a different canopy cover development is expected due to different stresses. Table 3-8 shows all the input variables for the maize farms, with the different planting and harvest dates. For all farms, plant density was calculated based on field data on row planting (plant and row spacing). Since row planting is the same in all farms (0.25x0.75 m^2), the CC_o and plant density are also the same. The rooting depth was set at 0.9 meters based on the FAO publication of rooting depths[4].

Figure 3-8: Subsistence maize farms

Table 3-8: Simulation input for maize farms

		Farm B	Farm A	Farm M
General Farm Information	Crop type	Maize	Maize	Maize
	Variety	H6213	H516	H614
	County	Uasin Gishu	Narok	Nakuru
	Root Depth (m)	0.9	0.9	0.9
	Plant density (plants/ha)	53,333	53,333	53,333
	Cropped Area (ha)	5.3	2	1.2
	CC_o (%)	0.35	0.35	0.35
	Max Canopy Cover (%)	96	96	96
	Soil Classification	L24	Pd1	Pv8
	Field Capacity at top layer (%)	39	32	31
	Field Capacity at bottom layer (%)	48	39	39
	Dry yield production (reported) (ton/ha)	6.60	4.5	6.2
Crop Calendar	Planting date	22/03/2018	15/01/2018	10/03/2018
	Harvest date	20/11/2018	15/09/2018	02/11/2018

[4] Source: http://www.fao.org/3/y5749e/y5749e0j.htm

3.3.1 Farm B

Farm B is located in Uasin Gishu County and weather data were obtained from the three closest weather stations (Figure 3-9).

Figure 3-9: Subsistence maize farm, Farm B in Uasin Gishu County

3.3.1.1 Results

Table 3-9 shows the default and the adjusted settings of AquaCrop for Farm B. In order to get a better fitting between the simulated and reported yield, the maturity date was extended by 100 GDDs from the AquaCrop default settings. Moreover, the initial CC_o (available field data on plant and row spacing) and the soil fertility stress were changed.

Table 3-9: AquaCrop adjustment for Farm B

		Default	Validated
	CC_o	0.49	0.35
	CGC (%/day)	14.4	15.1
	CC_{max} (no stress) (%)	96	96
	CDC (%/C-day)	1	1
Growing Cycle (GDD)	Emergence	80	80
	Max CC	705	705
	Senescence	1,400	1,400
	Maturity	*1,700*	*1,800*
Yield formation (GDD)	Length of building up of HI	750	847
	Duration of flowering	180	180
	Begin of flowering	880	880
Root depth	Max effective Rooting depth (m)	2.3	0.9
	Max depth (GDDs)	1,409	1,409
Soil Fertility	Biomass production (%)		60
	Max CC (%)		80

Table 3-9: AquaCrop adjustment for Farm B

		Default	Validated
	Canopy decline		medium
	Reduction of canopy expansion (%)		10
	Avg. decline canopy cover (%/GDD)		0.04
	Reduction on WP (%)		56
	Harvest Index, HI (%)	48	

In Table 3-10, the results of the simulation is presented, while in Figure 3-10 the graphic illustration of the results is presented.

Table 3-10: Simulation results for Farm B

	Results
Correlation (r)	0.57
Root Mean Square Error (RMSE) (% CC)	39.2
Observed CC (%)	55.3
Simulated CC (%)	28.8
Evaporation, until maturity (mm)	257.8
Evaporation, until harvest (mm)	537.2
Transpiration (mm)	331.7
Evapotranspiration until harvest (ET_a) (mm)	868.9
Reference Evapotranspiration until harvest (ET_o) (mm)	1,255.4
Rainfall until harvest (mm)	1,571.9
Dry yield production (simulated) (ton/ha)	6.63
Dry yield production (reported) (ton/ha)	***6.6***
Harvest Index (adjusted) (%)	45
Potential Biomass (ton/ha)	31.574
Actual Biomass (ton/ha)	14.733
WP (kg yield/m^3 ET)	1.12
Temperature (transpiration) stress (%)	2
Canopy expansion stress (%)	3
Stomata Closure stress (%)	14
Weed infestation stress (%)	10
Soil fertility stress (%)	40

3.3.1.2 Evaluation of Simulations

Stresses

In general, there is enough water in the root zone for the crop growth in Uasin Gishu County. Looking at the main output screen of AquaCrop in Figure 3-10, it is clear that there is, however, aeration stress due to excessive rainfall (see Dr_0 graph). The crop suffered mild water stress during the first stages of growth (between days 2-15) where the water in the root zone was below the threshold for canopy expansion but over the threshold for stomatal closure. A similar small water shortage takes place around day 50. AquaCrop calculated that the water stress for canopy expansion is mild, at 3%. Additionally, there is some mild water stress during days 15-50, where the water in the root zone exceeded field capacity, however without any severe impact for plant growth.

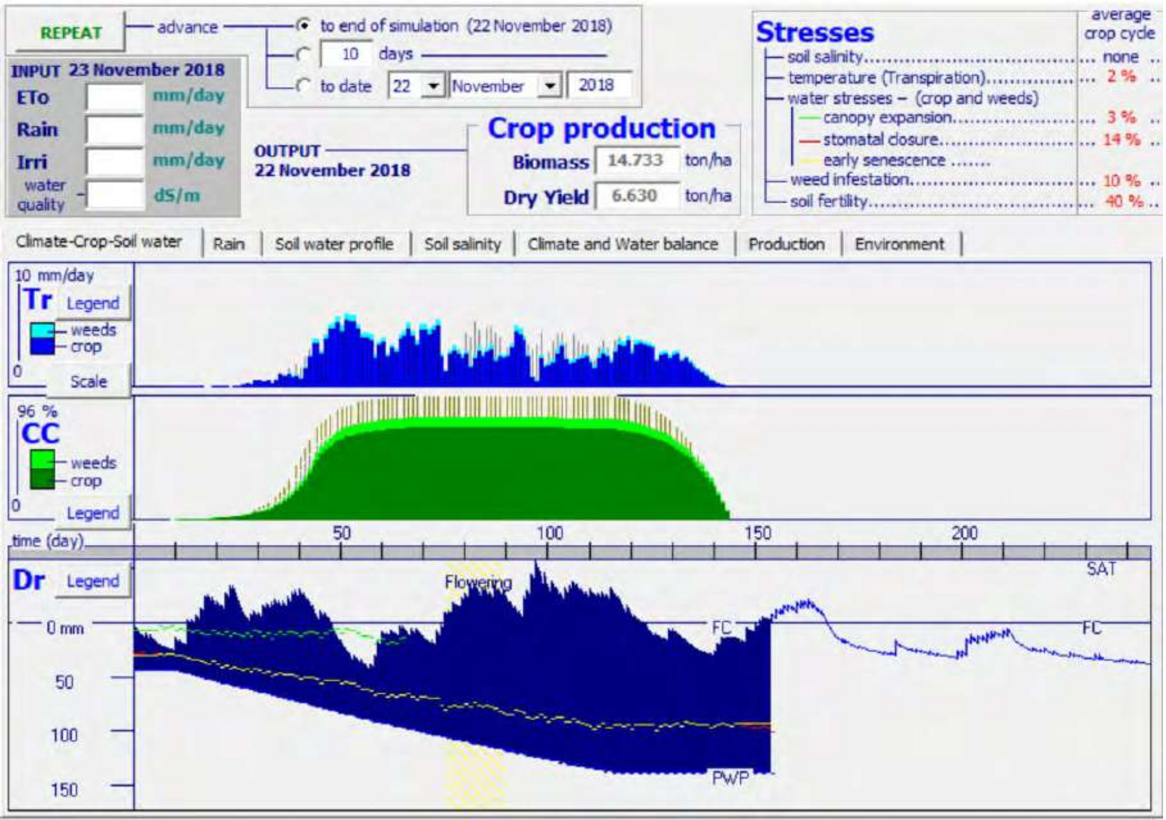


Figure 3-10: AquaCrop results for Farm B

Regarding the transpiration stress induced by excessive water in the root zone, AquaCrop calculates that excessive water caused transpiration stress due to stomatal closure to amount to 14%. Around day 95, soil water exceeded the field capacity and reached saturation for a limited amount of time. The effect of excess water is clear in the Tr graph, where one can observe that transpiration is reduced during the period when saturation is reached.

Influence of Harvest Index

Table 3-11 shows the crop calendar that was used for the simulation. The only difference from the default settings of AquaCrop is the extended maturity (100 GDDs). This was necessary in order to simulate the reported yield. This difference decreases the simulated yield by creating an insufficient green canopy cover and thus the crop cannot build up the maximum HI. This is why the HI is calculated at 45% (and not 48%). The consequence of this is that the crop growing cycle is terminated prematurely (around day 145, CC graph) due to a lack of green canopy.

Table 3-11: Growing cycle for Farm B

	Default	Adjusted	Corresp. Days
Emergence (GDD)	80	80	7
Max CC (GDD)	705	705	61
Senescence (GDD)	1,400	1,400	117
Maturity (GDD)	1,700	1,800	154
Harvest			243

Based on the simulation, maturity takes place at day 154. However, based on field data, harvest takes place at day 243. This means that the crop is left standing in the field for almost three months. Based on Alakonya et al. (2008), it is possible that some farmers leave maize to dry for such an extended period but there is an increased chance for ear rotting due to second rains. In Uasin Gishu County, there were rains after the simulated maturity (Figure 3-11). As such, for Farm B, it might be that the maturity of the plant was reached later on (signifying higher yield) but the reported yield was lower due to the rotting of the maize ears, caused by the extended drying out. However, data for the observed canopy cover suggest that the growth cycle of the crop is higher than what AquaCrop's default values assumes (see following sub-section).

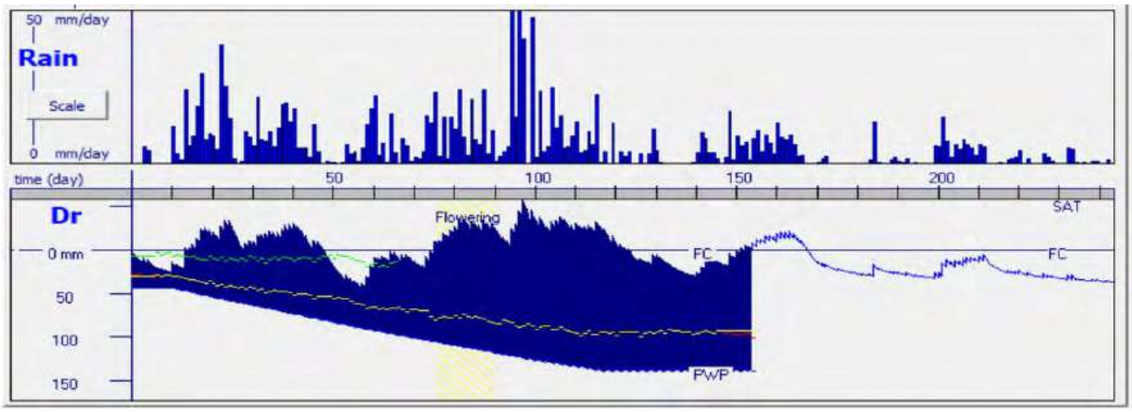


Figure 3-11: Rain pattern in Uasin Gishu County in relation to planting and crop root development

Reflection on Observed CC Data

The fitting between the simulated and observed canopy cover is relatively poor for Farm B (Figure 3-12). The data from NEO BV seem to have a consistent pattern, despite the noise during the first days after planting (higher canopy cover than expected). AquaCrop's default settings for crop growth seem to not match the observed canopy cover data. However, in absence of more accurate and reliable data on canopy development, calibration of AquaCrop was not possible. Since AquaCrop does not differentiate between crop varieties, a possible explanation for such differences between observed and simulated canopy cover is the differences in the growth cycle of the default crop variety and the variety used in the field.

Figure 3-12: Correlation between observed and simulated canopy cover data for Farm B

3.3.2 Farm A

Farm A is located in Narok County and weather data were obtained from the four closest weather stations (Figure 3-13).

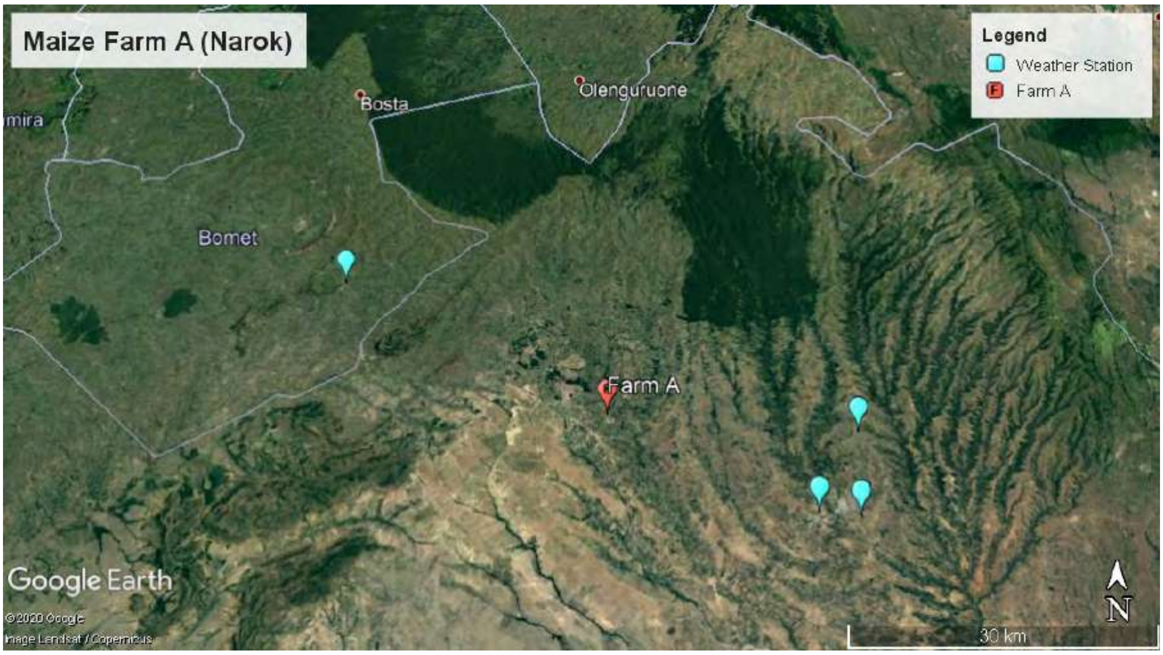


Figure 3-13: Subsistence maize farm, Farm A in Narok County

3.3.2.1 Results

Table 3-12 shows the default and the adjusted settings of AquaCrop for Farm A. In order to get a better fitting between the simulated and reported yield, the maturity was extended by 500 GDDs from the AquaCrop default settings. Moreover, the initial CC_o (available field data on plant and row spacing) and the soil fertility stress were changed.

Table 3-12: AquaCrop adjustment for Farm A

		Default	Validated
	CC_o	0.49	0.35
	CGC (%/day)	*13.3	13.9
	CC_{max} (no stress) (%)	96	96
	CDC (%/C-day)	1	1
Growing Cycle (GDD)	Emergence	80	80
	Max CC	705	705
	Senescence	1,400	1,400
	Maturity	*1,700*	*2,200*
Yield formation (GDD)	Length of building up of HI	750	1211
	Duration of flowering	180	180
	Begin of flowering	880	880
Root depth	Max effective Rooting depth (m)	0.9	0.9
	Max depth (GDDs)	1,409	1,409
Soil Fertility	Biomass production (%)		60
	Max CC (%)		80
	Canopy decline		medium
	Reduction of canopy expansion (%)		10
	Avg. decline canopy cover (%/GDD)		0.04
	Reduction on WP (%)		56
	Harvest Index, HI (%)	48	27

** This parameter is affected by the GDDs for maximum canopy cover. Even if default GDDs are used, the rate of canopy growth per day may differ between different farms based on the climate conditions. This explains the CGC differences in the default values between the farms.*

In Table 3-13 the results of the simulation is presented, while in Figure 3-14 the graphic illustration of the results is presented.

Table 3-13: Simulation results for Farm A

	Results
Correlation (r)	0.61
Root Mean Square Error (RMSE) (% CC)	36.7
Observed CC (%)	56.7
Simulated CC (%)	30.8
Evaporation, until maturity (mm)	186.2
Evaporation, until harvest (mm)	299
Transpiration (mm)	268.5
Evapotranspiration until harvest (ET_a) (mm)	567.5
Reference Evapotranspiration (ET_o) (mm)	1069
Rainfall until harvest (mm)	553.6
Dry yield production (simulated) (ton/ha)	4.28
Dry yield production (reported) (ton/ha)	*4.5*
Harvest Index (adjusted) (%)	27
Potential Biomass (ton/ha)	34.862
Actual Biomass (ton/ha)	15.92
WP (kg yield/m^3 ET)	0.94
Temperature (transpiration) stress (%)	5
Canopy expansion stress (%)	9
Stomata Closure stress (%)	8
Weed infestation stress (%)	10
Soil fertility stress (%)	40

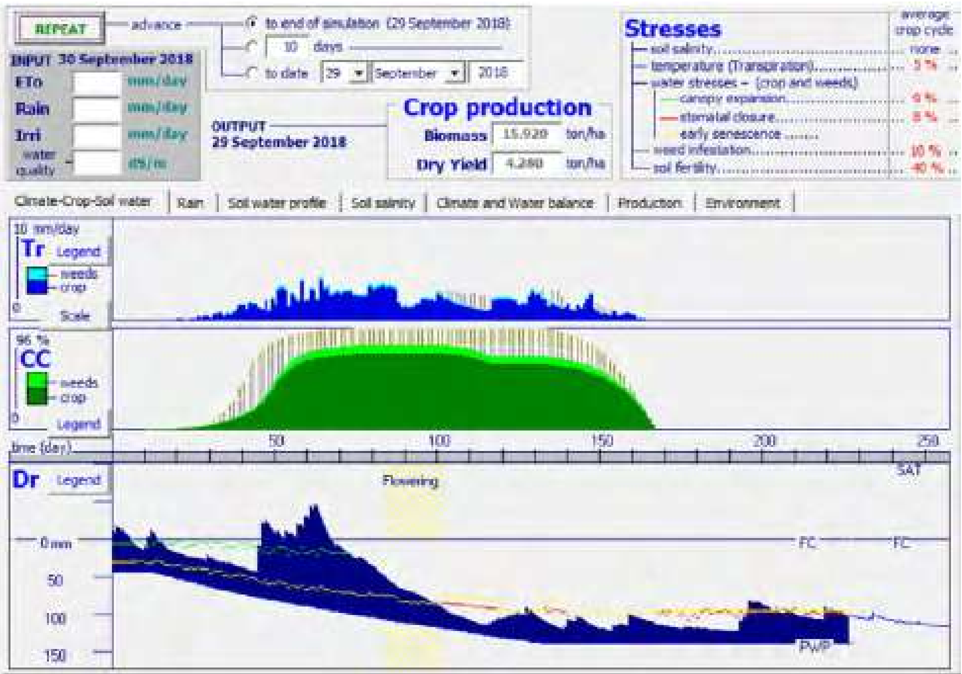


Figure 3-14: AquaCrop results for Farm A

3.3.2.2 Evaluation of Simulations

Stresses

Farm A is in water stress (as well as the other two wheat farms located in Narok County). Looking at Figure 3-14, there is water stress that gradually moves from below the threshold for canopy expansion to stomatal closure (Dr graph). During the initial days, water stress seriously affected the canopy development (white line in CC graph). It is also observed that that during stomatal closure, transpiration is reduced significantly (Tr graph). AquaCrop calculates temperature stress at 5% while water stress for canopy expansion and stomatal closure is at 9% and 8% respectively (Figure 3-14).

Influence of Harvest Index

Despite the reduction of canopy cover due to water stress in the initial stage, the HI_{adj} is not affected. As discussed in Section 2, water stress during the initial stages might be beneficial for the crop as it consumes less energy in the vegetative growth. However, the HI_o is highly reduced (from 48% to 27%) due to the adjustment of the maturity date. In order to validate the data on yield and observed canopy cover, the default AquaCrop setting regarding the time of maturity was extended by 500 GDDs (Table 3-14). This resulted in not sufficient green canopy cover development which in turn caused the pre-mature termination of the growth cycle, reducing the harvest index and the yield production.

Table 3-14: Growing cycle for Farm A

	Default	Adjusted	Corresp. Days
Emergence (GDD)	80	80	8
Max CC (GDD)	705	705	66
Senescence (GDD)	1,400	1,400	134
Maturity (GDD)	1,700	2,200	227
Harvest			243

Reflection on Observed CC Data

The fitting of the simulated canopy data is poor for Farm A (r=0.61). Looking at the observed data for the canopy cover (Figure 3-15), it is observed that during the initial growth stages there is noise in the observed data. Later on in the growth cycle, the observed data seems to follow a more realistic pattern of canopy development. Similar to Farm B, better fitting is possible by changing the default AquaCrop settings. However, informed changes in the default settings require more detailed data that were not available.

Figure 3-15: Correlation between observed and simulated canopy cover data for Farm A

3.3.3 Farm M

Farm M is located in Nakuru County and weather data were obtained from the two closest weather stations (Figure 3-16).

Figure 3-16: Subsistence maize farm, Farm M in Nakuru County

3.3.3.1 Results

Table 3-15 shows the default and the validated settings of AquaCrop for Farm M. For the validation of farm M only the initial CC_o (available field data on plant and row spacing) and the soil fertility stress were changed.

Table 3-15: AquaCrop validation for Farm M

		Default	Validated
	CC_o	0.49	0.35
	CGC (%/day)	12.4	12.9
	CC_{max} (no stress) (%)	96	96
	CDC (%/C-day)	1	1
Growing Cycle (GDD)	Emergence	80	80
	Max CC	705	705
	Senescence	1,400	1,400
	Maturity	1,700	1,700
Yield formation (GDD)	Length of building up of HI	750	750
	Duration of flowering	180	180
	Begin of flowering	880	880
Root depth	Max effective Rooting depth (m)	2.3	0.9
	Max depth (GDDs)	1,409	1,409
Soil Fertility	Biomass production (%)	-	54
	Max CC (%)		80
	Canopy decline		medium
	Reduction of canopy expansion (%)		10
	Avg. decline canopy cover (%/GDD)		0.02
	Reduction on WP (%)		57
	Harvest Index, HI (%)	48	

Table 3-16 presents the results of the simulation while Figure 3-17 presents the graphic illustration of the results.

Table 3-16: Simulation results for Farm M

	Results
Correlation (r)	0.96
Root Mean Square Error (RMSE) (% CC)	13.8
Observed CC (%)	60.5
Simulated CC (%)	54.6
Evaporation, until maturity (mm)	293.5
Evaporation, until harvest (mm)	332.5
Transpiration (mm)	361.4
Evapotranspiration until harvest (ETa) (mm)	693.9
Reference Evapotranspiration, (ETo) (mm)	1,059.1
Rainfall, until harvest (mm)	981.7
Dry yield production (simulated) (ton/ha)	6.598
Dry yield production (reported) (ton/ha)	*6.2*
Harvest Index (adjusted) (%)	48
Potential Biomass (ton/ha)	32.825
Actual Biomass (ton/ha)	13.747
WP (kg yield/m^3 ET)	1.01
Temperature (transpiration) stress (%)	30
Canopy expansion stress (%)	-
Stomata Closure stress (%)	-
Weed infestation stress (%)	15
Soil fertility stress (%)	46

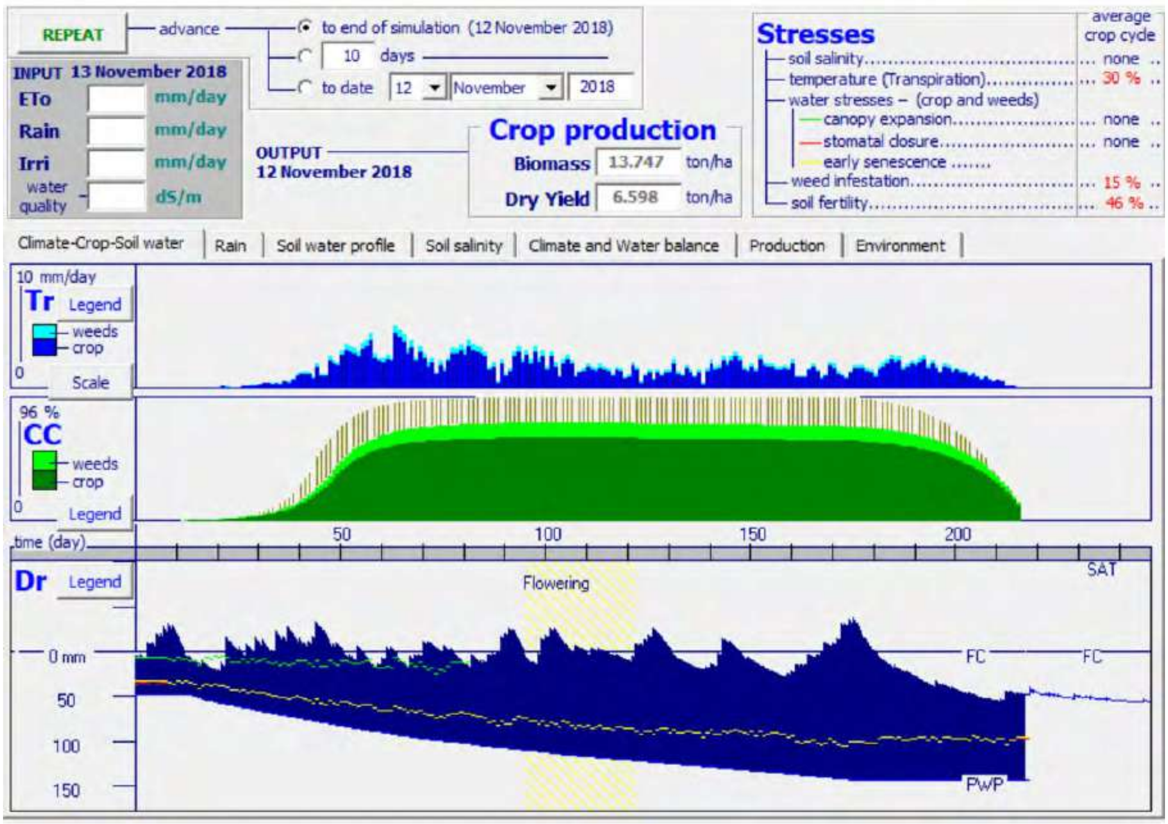


Figure 3-17: AquaCrop results for Farm M

3.3.3.2 Evaluation of Simulation

Stresses

Looking at Figure 3-17, it is clear that there is no water stress for Farm M. However, there is a temperature stress (Figure 3-18) of 30% (see Figure 3-17). This is a cold stress (T<10ºC) occurring from June onwards that affected crop transpiration. Soil fertility stress is assumed before simulating and this assumption is confirmed.

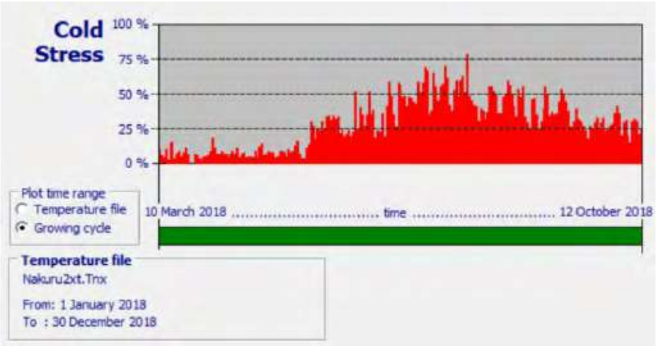


Figure 3-18: Cold temperature stress for Farm M

Influence of the Harvest Index

For Farm M, the green canopy growth was sufficient to reach the maximum HI_o. Moreover, since there wasn't any water stress there was no changes in the HI_{adj}. As such, the total HI is 48% and the crop was left drying in the field for 20 days (Table 3-17).

Table 3-17: Growing cycle for Farm M

	Default	Validated	Corresp. Days
Emergence (GDD)	80	80	9
Max CC (GDD)	705	705	71
Senescence (GDD)	1,400	1,400	176
Maturity (GDD)	1,700	1,700	217
Harvest			237

Reflection on Observed CC Data

The simulated CC has a very good fit with the observed canopy data (Figure 3-19). This indicate that the default AquaCrop settings reflect what is seen on the ground. Having in mind that AquaCrop does not allow for different default parameters for different varieties, it is highly likely that the variety used in Farm M has a similar growth cycle with the default settings of AquaCrop.

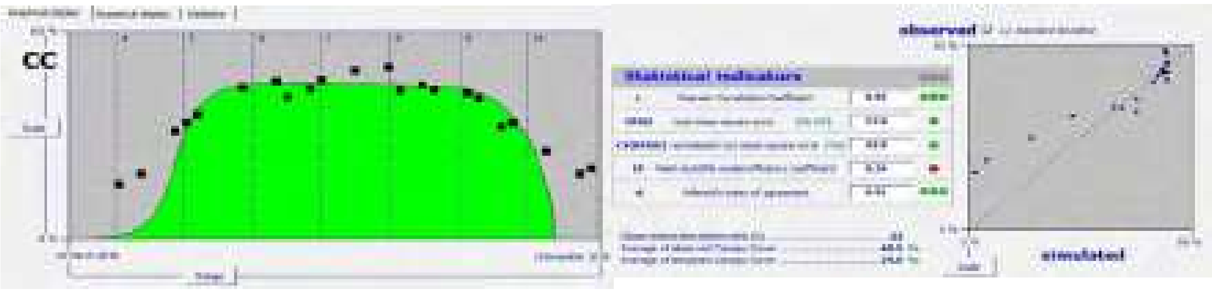


Figure 3-19: Correlation between observed and simulated canopy cover data for Farm M

3.4 Overall Evaluation of AquaCrop Results

The result of the simulations of all the five farms are presented in Table 3-18. For all farms, ET_o was calculated by the in-build ET_o calculator in AquaCrop based on the FAO Penman-Monteith equation and the climatic data. Following, the results of the simulations for the wheat farms (Section 3.4.1) and the maize farms (Section 3.4.2) are shortly discussed.

3.4.1 Wheat Farms

AquaCrop default settings produced relatively good results in the case of the two wheat farms. The fitting of simulated and reported yield and canopy cover is satisfactory with relatively low root mean square errors (RMSE< 18%, Table 3-18). Both farms were using the same wheat variety, which corresponded well to the crop default settings applied in AquaCrop. Additionally, wheat farms are both commercial farms, where better management is evident compared to subsistence farming of maize. The AquaCrop simulation indicate growing conditions in the wheat farms were similar.

3.4.2 Maize Farms

Regarding the maize farms, the simulations were more complicated than the ones for wheat. This is due to the fact that different varieties were used. The default crop settings for maize only provided a good fit for one maize variety (the oldest one) in one farm setting (Farm M). Farms A and B would require a more detailed calibration of the crop settings in AquaCrop to produce a better fit between the simulated and observed canopy and yield data. In the absence of detailed canopy cover and crop development stage data, adjustments were made on the crop maturity settings of the crop-file to obtain a reasonable fit in both canopy and yield. As a consequence, though reasonable in final fit, the resulting simulation outcomes in terms of seasonal ET_a and biomass for Farms A & B are, in the absence of a detailed calibration, less confident and prone to a margin of error. The RMSE for the observed and simulated canopy cover was relatively high (RMSE> 35%). Simulated yield produced by the AquaCrop default calendar settings was improved by extending the time of maturity. This affected the HI and thus the simulated yield.

The growing conditions across the three maize farms have been very different, subjecting the maize crops to different stress factors affecting the transpiration, biomass accumulation and yield. For all three farms, a severe soil fertility deficit (40% for A & B, 46% for M) had to be assumed to obtain a reasonable fit between AquaCrop simulations and observed data. These levels of fertility stress are, however, not uncommon in rainfed subsistence farming conditions in East Africa. As evident from the simulation runs in AquaCrop (Figure 3-10, Figure 3-14 and Figure 3-17), these deficits in soil fertility had a direct impact upon the reduced canopy development, and in effect, the reduced photosynthetic efficiency of the green canopy (e.g., less intense green leaves). The overall result is a reduced biomass accumulation that is reflected in a lower biomass water productivity (WP_B).

Table 3-18: AquaCrop results for all farms

	Wheat		Maize				
	Farm I	Farm II	Farm B		Farm A		Farm M
			*Default	Validated	*Default	Validated	
Correlation (r)	0.76	0.85	0.57	0.57	0.6	0.61	0.96
Root Mean Square Error (RMSE) (% CC)	17.5	13.3	39.2	39.2	37.1	36.7	13.8
Observed CC (%)	41.9	57.4	55.3	55.3	56.7	56.7	60.5
Simulated CC (%)	40.5	56.8	28.8	28.8	30.5	30.8	54.6
Evaporation, in growing cycle (mm)	126.3	91.8	251.6	257.8	184.1	186.2	293.5
Evaporation, until harvest (mm)	172.2	-	553.4	537.2	309.4	299	332.5
Transpiration (mm)	204.2	235.8	331.7	331.7	268.5	268.5	361.4
Evapotranspiration in growing cycle (ET_a) (mm)	330.5	327.6	583.3	589.5	452.6	454.7	654.9
Evapotranspiration until harvest (ET_a) (mm)	376.4	327.6	885.1	868.9	577.9	567.5	693.9
Reference Evapotranspiration until harvest (ET_o) (mm)	587.5	566.5	1,255.4	1,255.4	1,069	1,069	1,059.1
Rainfall until harvest (mm)	296.6	198.4	1,571.9	1,571.9	553.6	553.6	981.7
Dry yield production (simulated) (ton/ha)	3.48	3.999	7.071	6.63	7.625	4.28	6.598
Dry yield production (reported) (ton/ha)	*3.34*	*4.45*	*6.6*		*4.5*		*6.2*
Harvest Index (adjusted) (%)	43.6	45.7	48	45	48	27	48
Potential Biomass (ton/ha)	15.814	16.343	31.574	31.574	34.862	34.862	32.825
Actual Biomass (ton/ha)	7.994	8.748	14.733	14.733	15.92	15.92	13.747
**WP_y (kg yield/m^3 ET_a)	1.05	1.23	1.21	1.12	1.68	0.94	1.01
**WP_B (kg biomass/m^3 ET_a)	2.42	2.67	2.53	2.50	3.52	3.50	2.10
**WP_B (kg biomass/m^3 T_a)	3.91	3.71	4.44	4.44	5.93	5.93	3.80
Temperature (transpiration) stress (%)	-	-	2	2	8	5	30
Canopy expansion stress (%)	21	17	3	3	9	9	-
Stomata Closure stress (%)	29	26	14	14	8	8	-
Weed infestation stress (%)	10	10	10	10	10	10	15
Soil fertility stress (%)	25	15	40	40	40	40	46

* Default values refer to the calendar days. CC_o, root depth and soil fertility were changed according to field data

** These are calculated based on ET_a in growing cycle

3.5 Diagnostic Analysis

3.5.1 Wheat Productivity Diagnostics

The AquaCrop simulations of the two wheat farms, that return a day-by-day water balance and crop growth simulation, provide a diagnostic capacity to relate the achieved levels of production and water productivity to specific physiological stresses occurring during the growth season. In both farms, the default crop settings of AquaCrop (defining the growth stages in GDD) worked well, allowing to adjust the management parameters (e.g., weeds and fertility management) to obtain a reasonable to good fit between the observed canopy (Neo BV remote sensing data) and simulated canopy, and between reported yields and simulated yields. In both cases, the simulation indicates the wheat crops were subdued due to a number of physiological stresses that delimited their production and productivity. These are discussed in more detail below:

- The water related stresses are threefold: (i) aeration stresses due to excess rainfall occurred at the start of the season which resulted in a reduction of crop transpiration and therefore, a reduction in photosynthetic biomass accumulation, leading to a reduced canopy development; (ii) mild water stress occurred in the vegetative growth stage, leading to a "canopy expansion stress" that further reduced canopy growth and future photosynthetic capacity (biomass accumulation) of the crop; (iii) severe water stress leading to stomatal closure occurred during the second half of the growing season, from the onset of flowering to harvest, affecting crop transpiration, biomass accumulation and yield formation (e.g., reduction of HI). All three stresses occurred in both Farm I and II but, differed slightly in severity due to differing timing of the growth season in relation to the climate (e.g., late sowing of Farm II).

- Soil fertility stress is set to be mild to medium (25% for Farm I and 15% for Farm II), in order to achieve a better fit between simulated and Neo-observed canopy cover data. Fertility stress reduces the photosynthetic efficiency of green canopy cover, leading to a reduced biomass accumulation rate reflected in a lowering of the WP ratio. The immediate apparent effect of fertility stress is a reduced canopy cover, reduced biomass production, and reduced transpiration rate. Yield is affected accordingly. Theoretically, this reduced production/productivity level can be fairly easily addressed by supplying more and sufficient fertilisers (preventing stress from occurring). The immediate effect of this is a more rigorous canopy development during the vegetative growth stage (see Annex 2) that, due to higher initial crop transpiration rates, will lead to a more pronounced water stress during the later crop stages as more water has been depleted from the soil during the vegetative stage. Overall production and productivity is slightly better thanks to fertility, but still well below potential in the absence of favourable rains in the yield formation period. This also illustrates how the cost-benefit ratio of additional fertilization in rainfed cereal crops can be rather low or negative, which explains its rather low uptake.

- The flowering and yield formation periods are sensitive growth stages in which water and temperature stresses can lead to yield penalties; i.e., through a reduction of the HI in the simulation. In both wheat farms, we see this effect occurring due to water stress in this period, which reduces the HI from a default setting of 48% to around 43% and 45%, respectively.

The AquaCrop simulation for the two wheat farms permits a detailed diagnostic of the multiple stresses to which the rainfed crops have been subdued during the growing season. It also makes clear that most of these are climate induced (temperatures and water stress) that cannot be tackled through agronomic management. Soil fertility management is one component that could be managed but, as shown in the optimal simulation (Annex 2), only with marginal effect on production/productivity. This is due to more rigorous vegetative growth in the early season which leads to more severe water stress (and associated yield penalties) later in the season. Management options are thus severely restricted under prevailing climatic conditions. Another remarkable outcome of the AquaCrop diagnostic is the pronounced effect of mild water stress in the first half of the season that significantly restricts the canopy development (and progressive photosynthetic capacity) of the crop.

3.5.2 Maize Productivity Diagnostics

The maize crops are subjected to multiple stresses, including fertility, cold temperature, mild water stress induced canopy expansion stress, severe water stress (limited), and aeration stress (excess rainfall). Of these, the soil fertility stress is the most pronounced, and simultaneously the theoretically most easily addressed through management interactions. There is, however, a noted difference in growing conditions between Farms B and M. Fertility management may be a good option as the rainfall patterns are favourable (there is high soil moisture replenishment during the second half of the season) which would provide enough water for a vigorous growing crop (optimising the effect of good soil fertility). For Farm A, this is not the case. Here soil moisture depletion is already pronounced with fertility stress and adding fertiliser to the crop will only increase these water stress levels further during the yield formation period as more water will have been consumed during the more vigorous vegetative stage. The other stresses are climate induced, and may not be altered by management actions, except for changes in sowing date, which are difficult to anticipate beforehand.

The reported yield for Farm A is exceptionally low, given the biomass simulated in AquaCrop. Adjustments had to be made in the maturity settings of the crop file in order to approach this reported yield, resulting in an adjusted HI of 27 percent. In the absence of more detailed data that would allow a proper calibration of the crop growth parameters in the crop-file, this result becomes speculative. As explained, the widespread practice to leave the crop standing in the field well beyond physiological maturity (as a means to dry the cereal) may well provide a different explanation. Yield reduction may thus well have occurred during drying, making the default setting of AquaCrop a possible outcome for physiological maturity of Farm A, which would imply that a higher yield could be obtained by earlier harvesting. In the absence of supporting data, however, we have no means to verify this.

4 WaPOR Analysis

Knowing the scheme boundaries of the five different farms, WaPOR Level 2 data (100 meter resolution) were downloaded for all the five farms for the year 2018. However, because of the small size of the farms few pixels fully covered the farms, which affects the reliability of the analyses. The wheat farms are commercial farms of 40.4 and 34.3 hectares for which the number of pixels available for these farms is over 15. The maize farms are subsistence farms of 5.3, 2, and 1.2 ha and thus the number of available pixels for these farms is starkly reduced (Farm B is 4 pixels and Farms A and M are only 1 pixel each). Additionally, the pixels of the satellite data do not necessarily overlap the contours of the different fields, especially when the size of the field is small. For the wheat farms, there is a relatively good coverage of the farms (Figure 4-1) while for the maize farms, the coverage is poor (Figure 4-2). For this reason, WaPOR derived data and water productivity calculations should be taken with caution in particular for small fields, as derived values will be largely influenced by the area/crops surrounding the field as a result of "pixel noise".

Figure 4-1: Field coverage of WaPOR satellite images for wheat farms: Farm I (left) and Farm II (right)

Figure 4-2: Field coverage of WaPOR satellite images for maize farms: Farm B (left), Farm A (central) and Farm M (right)

4.1 WaPOR Results

In order to analyse the five farms against the different agronomic indicators (i.e., E, T, ET_a, ET_{ref}, biomass, HI, yield production and WP_y), WaPOR was used with two different methods: the point time series and the area time series method. For the point time series method, a point in the center of each farm was selected and the different agronomic indicators were derived from the pixel values of this particular point. For the area time series method, the different agronomic indicators were derived from the average values of all the pixels that were included in the farm's boundaries. ET_a was obtained through both methods. Based on the field data regarding the start of the season and the harvest date, daily and decadal WaPOR E, T, ET_{ref} and ET_a values were aggregated to seasonal values. Moreover, the time of the crop's physiological maturity based on the AquaCrop simulation is also used to aggregate E, T and ET_a values and assess the sensitivity of WaPOR to the end date of analysis. The results of the WaPOR analysis under the two different methods are presented in Table 4-1.

Comparing the ET_a values obtained through the two methods, some small differences are observed; 6% for Farm I[5] and 1-3% for the rest of the farms. Area time series method provides the average values of all the pixels that are inside the boarders of the investigated area, while the point time series method provides the value of the pixel of a specific point. As such, values obtained through point time series in larger farms with many pixels are expected to be in a range of values that is centered around the value obtained through area time series method. That is indeed the case for Farm I; the area ET_a is in between the range of values created from the two points of point ET_a . For the small maize farms and especially for Farms A and M where there is only one pixel that describes the agronomic parameters, it would be expected that values of the two methods would exactly match as there is only one pixel. However, the differences are very small (1-3%) and can be considered negligible.

Table 4-1: WaPOR results for all farms

		Wheat			Maize		
		Farm I		Farm II	Farm B	Farm A	Farm M
		Central Point	South edge Point				
Point Time Series Analysis (WaPOR)	Evaporation (mm), in growing cycle*	40.8	52.6	30.7	43.7	72.1	48.3
	Evaporation (mm), until harvest**	43.3	55.6	30.7***	70.1	92.6	57.4
	Transpiration (mm), in growing cycle	155	105.7	251.4	253.1	254.2	470.4
	Transpiration (mm), until harvest	165.5	114.7	251.4***	457.9	339.2	502.5
	Interception (mm), in growing season	13.2	7.1	27.7	30.4	17.8	35.5
	Interception (mm), until harvest	13.2	7.1	*	42.5	18.8	36.6
	Evapotranspiration (ET_a) (mm), in growing cycle	209	165.4	309.8	327.2	344.1	554.2
	Evapotranspiration (ET_a) (mm/season), until harvest	235	188.4	309.8***	570.5	450.6	596.5
	Reference Evapotranspiration (ET_o) (mm), until harvest	449.1	449.1	451.9	859.3	834.4	733.4
	Rainfall (mm), until harvest	954	897.7	659.6	1,205	1,191	1,281
Area Time Series Analysis (WaPOR)	Evapotranspiration (ET_a) (mm/season), until harvest	198.76		313.84	590.88	461.40	608.98
	NPP season mean [gC/m^2/season]	311.54		518.12	922.14	714.98	881.02
	Biomass (ton/ha) (NPP formula)	6.13		10.19	41.21	31.91	39.37
	Dry yield production (ton/ha) (WaPOR manual HI, FAO, 2020)	2.94		4.89	19.78	15.32	18.90
	Dry yield production (ton/ha) (WaPOR portal HI)	2.94		4.89	14.42	11.17	13.78
	WP_y (kg yield/m^3 ET)	1.47		1.56	3.35	3.32	3.10
	WP_y (kg yield / m^3 ET) (portal)				2.44	2.42	2.26
Field Data	Dry yield production (reported) (ton/ha)	3.34		4.45	6.6	4.6	6.2

** Growing cycle refers to the period starting from the beginning of planting until the date of simulated maturity of the plant.*
*** The period until the harvest refers to the period starting from the beginning of planting until the reported harvest.*
**** Reported harvest is before the simulated maturity of the plant. Thus, reported harvest was disregarded and harvest was considered to take place at the moment of crop's maturity.*

[5] This refers to the average of the two ET_a values obtained from the two points.

4.1.1 Point Time Series Comparison

To obtain evaporation E, T, ET_a and ET_{ref}, WaPOR data were downloaded manually using the analysis tool for the specific coordinates of each farm for 2018 (point time series method). A central point for each of the farms was selected and analysis was performed based on the pixel values for this point. However, different points located inside the borders of the farm might show different values, especially in cases of large farm sizes. In order to assess such differences between different pixel values, two points (central and south edge point) were selected for one of the large wheat farms; Farm I. As seen in Table 4-1, differences between the two points regarding climate data; ET_o and precipitation, are minimal (0% and 6% respectively). Considering that the spatial resolution of WaPOR for climate data is 20 km for ET_o and 5 km for precipitation, Farm I is located within a single pixel for ET_o while there are two pixels for precipitation. E and ET_a values show considerable differences of around 20%. T values show the greatest variation between the two points; around 30%. In the calculation of ET_a, WaPOR incorporates E, T and interception values. As seen in Table 4-1, ET_a for the point time series is the summation of E, T and interception.

Based on the point series WaPOR results, ET_a continues to accumulate after the physiological maturity of the plant (as simulated with AquaCrop), which increases the seasonal ET_a (Annex 3). In the WaPOR analysis, the time of physiological maturity is not directly assessed but maturity is indirectly captured through the fAPAR and values of daily E and T reflect the senescence of the crop. This is verified in this analysis and a decline of E, T, and ET_a values is observed after the simulation with AquaCrop physiological maturity (see Annex 3). However, T accumulation is continuing until the (manually entered) end of the season. In reality, this is unlikely since after full senescence, no more transpiration should occur. Since the time of physiological maturity is not reported upon or monitored in the field, the harvest date is used as a proxy for the end of the season. This results in increases of the seasonal E, T and ET_a values. As such, the longer the period between the time of physiological maturity and the end of the season (harvest date), the more the over-attribution of E, T and ET_a in WaPOR will be. We observed that the results of WaPOR values for E, T and ET_a are affected by the end date of the WaPOR analysis, but an accurate detection of physiological maturity (e.g., full senescence) through fAPAR should only result in a minimal effect. Such increases are visible in all farms except Farm II, as in this farm the end date for WaPOR analysis is the same as the maturity of the plant. This is more pronounced in the maize farms (Farm B, A and M) in which the period between maturity and harvest in longer.

4.1.2 Seasonal Values Comparison (based on area time series results)

To obtain biomass, ET_a, yield and water productivity, WaPOR data were derived using Python scripts developed by IHE Delft Institute for Water Education and the average pixel values were obtained for each farm (area time series method). Biomass was calculated based on Equation 2-3 (see Section 2.2) and the NPP data were obtained from WaPOR. Based on the crop cultivated in each farm, different assumptions about the HI, the moisture content, the light use efficiency and the above ground biomass were made (see Table 2-2). Then, the yield production and WP_y were calculated.

Based on the reported yield from the interviews with farmers, WaPOR yield analysis for wheat farms performed better than the maize farms. This is due to the larger size of the wheat farms compared to the maize farms. Differences in yield calculation for the wheat farms are around 12% and 10% for Farm I and II, respectively. Regarding the maize farms, WaPOR overestimated the yield production, resulting in significant differences. When using the HI of maize from the WaPOR manual (HI = 0.48, FAO, 2020), the differences between calculated and observed yield amount were 299%, 333% and 304% greater for Farm B, A and M, respectively. When the HI from the WaPOR portal (HI=0.35) was used, these differences were lowered to 218%, 243% and 222% for the three farms, respectively.

5 Comparison of AquaCrop and WaPOR Results

The AquaCrop and WaPOR results comparison was done for the crop season; i.e., the period from planting until the harvest. This section starts with a comparison between the results of the wheat farms (Section 5.1) and the maize farms (Section 5.2). In Section 5.3, the potential sources of deviation between AquaCrop and WaPOR results are discussed comprehensively.

5.1 Comparison for Wheat Farms

For the two wheat farms, the differences in evapotranspiration values vary (Table 5-1). Biomass of WaPOR is 23% smaller and 16% higher than that of AquaCrop for Farm I and Farm II, respectively. Resulting WP_y values are consequently different. For Farm I, the difference in WP_y value is 40%; 1.05 kg/m^3 ET_a of AquaCrop and 1.48 kg/m^3 ET_a of WaPOR. For Farm II, the difference in WP_y value is 26%; 1.23 kg/m^3 ET_a of AquaCrop and 1.56 kg/m^3 ET_a of WaPOR.

Table 5-1: AquaCrop – WaPOR comparison for wheat farms

	Farm I			Farm II		
	Aqua Crop	WaPOR	Difference	Aqua Crop	WaPOR	Difference
Evaporation (mm/season)	172.2	49.45	122.75	91.8	30.7	61.1
Transpiration (mm/season)	204.2	140.1	64.1	235.8	251.4	-15.6
Reference Evapotranspiration (ET_o) (mm/season)	587.5	449.1	138.4	566.5	451.9	114.6
Actual Evapotranspiration, until harvest (mm/season)	376.4	198.76	177.64	327.6	313.84	13.76
Precipitation, until harvest (mm/season)	296.6	925.85	-629.25	198.4	659.6	-461.2
Dry yield production (reported) (ton/ha)	3.34			4.45		
Dry yield production (ton/ha)	3.48	2.94	0.54	4	4.89	-0.89
Harvest Index (adjusted) (%)	43.6	48	-4.4	45.7	48	-2.3
Biomass (ton/ha)	7.994	6.13	1.864	8.748	10.19	-1.442
WP_y (kg yield/m^3 ET)*	1.05	1.48	-0.43	1.23	1.56	-0.33

** For the calculation of WP_y, AquaCrop uses ET_a values at the moment of physiological maturity of the plant while WaPOR uses ET_a values until the moment of harvest.*

For Farm I, the difference in ET_a is high; 199 mm of WaPOR, against 376 mm of AquaCrop (47% difference). Regarding the results for the yield, the 3.48 ton/ha yield simulated in AquaCrop is close to the 3.34 ton/ha reported yield (4% difference); the WaPOR yield of 2.94 ton/ha is 12% lower than the reported yield. ET_a for Farm I is underestimated despite the higher precipitation in WaPOR. The low ET_a values by WaPOR is difficult to attribute; as it could be pixel noise or LST noise in combination with a relative barren surrounding. This could explain the deviation, but we have no means to verify this. Interestingly, the biomass production is relatively high for the calculated corresponding ET_a, and reflected in less rigorous reduction in T_a (32% smaller). As such, WaPOR seems to overestimate biomass production despite the fact that in absolute values, biomass seems to be underestimated; 7.994 ton/ha from AquaCrop against 6.13 ton/ha from WaPOR. This overestimation of biomass also impacts the yield that is in turn overestimated for the corresponding ET_a values. The simulation in AquaCrop indicates that the prolonged water stress conditions the wheat crop faced, significantly affected the yield formation period; affecting thus the HI that was lowered from its potential 48% to 43.6%. WaPOR does currently not have the means to simulate these stress impacts on yield formation and, consequently, will return relative too high yield figures under these stress conditions leading to an elevated WP_y.

For Farm II, the 3.99 ton/ha yield simulated in AquaCrop is 10% lower than the 4.45 ton/ha reported yield while the 4.89 ton/ha yield of WaPOR is 9.9% higher than the reported yield. The difference in ET_a is low; 313.8 mm of WaPOR, against 327.6 mm of AquaCrop (4% difference). Farm II WaPOR analysis was closer to the AquaCrop results and the reported yield compared to Farm I. T and ET_a values for Farm II show a difference between AquaCrop and WaPOR analysis of only 6% and 4%, respectively. This happens because Farm II is the only farm in which the full senescence of the plant is at the same time of harvest and thus the accumulation of T takes place for the same time period for AquaCrop and WaPOR. Since maturity and senescence of crop growth are related to physiological performance of the crop and not monitored or reported in the field, it is not possible to obtain this information before modelling analysis of crop growth. As such, WaPOR analysis for Farm I was not adjusted to the date of senescence as the fAPAR correction factor should return a reduced T_a for full senescence of the canopy.

Farm II appears to give relatively good results between AquaCrop and WaPOR. The agreement in T values for Farm II signify a basis for the development of similar levels of biomass. However, WaPOR analysis does not consider T values for the calculation of biomass results. As such, biomass calculation are not similar due to similar T values. Biomass is calculated through the NPP and a set of assumptions, as seen in Equation 3 and Table 2-2. In turn, NPP is calculated through, among others, climate data. For Farm II (and Farm I), WaPOR data on ET_o and precipitation vary significantly from the local weather data of TAHMO. As such, despite the seemingly good comparison between T (6%) and biomass values (16%), it is expected that this agreement is coincidental as the climate data used in AquaCrop and WaPOR are significantly different. To test this hypothesis, an additional AquaCrop simulation for Farm II was run with WaPOR climate data (see Section 5.1.1).

5.1.1 Influence of Climatic Data for Farm II – Using AquaCrop with WaPOR climate data

To test if the deviations in results obtained through WaPOR, in comparison to those obtained through AquaCrop, originate from differences in the climatic parameters used by both programs (ET_o, P), we ran an AquaCrop simulation for Farm II with the climate data obtained from WaPOR instead of those from the TAHMO weather stations.

In order to look more in detail how the influence of precipitation is affecting the biomass production, a new AquaCrop simulation for Farm II was done. In this simulation, daily climatic data on precipitation and ET_o were obtained through WaPOR and replaced the TAHMO weather data. The results of this analysis are presented in Table 5-2.

In terms of ET_a, the difference between WaPOR and the new AquaCrop simulation results is 12%, which would be relatively acceptable but poorer when compared with the original AquaCrop (TAHMO) simulation. However, the partitioning of ET_a shows high differences. The E values are 75% higher with the new AquaCrop analysis compared to WaPOR values while the T values are 42% lower with the new AquaCrop analysis compared to WaPOR values. As such, despite the agreement in ET_a values, the transpiration and (thus) the biomass production show significant differences of 42% and 36%, respectively. These high WaPOR values for biomass are the more remarkable as the simulated values for seasonal ET_a seem in line with those of AquaCrop. This indicates that the partitioning of E and T in WaPOR is not working adequately. Partitioning of T and E are based on the 'light extinction factor' (a) for the net radiation and the 'leaf area index' (FAO and IHE Delft, 2019). Based on the WaPOR quality assessment, a values for cropland require additional improvements (FAO and IHE Delft, 2019).

Table 5-2: AquaCrop results for Farm II, with daily ET_o and precipitation data from WaPOR

	Farm II		
	AquaCrop	WaPOR	AquaCrop with WaPOR climate file (ET_o and P)
Evaporation (mm/season)	91.8	30.7	129.6
Transpiration (mm/season)	235.8	251.4	146.5
Reference Evapotranspiration (ET_o) (mm/season)	566.5	**451.9**	
Actual Evapotranspiration (mm/season)	327.60	313.84	276.1
Precipitation (mm/season)	198.40	**659.6**	
Dry yield production (reported) (ton/ha)	4.45		
Dry yield production (ton/ha)	4.00	4.89	3.258
Harvest Index (adjusted) (%)	45.7	48	48
Biomass (ton/ha)	8.748	10.19	6.793
WP_y (kg yield/m^3 ET)*	1.23	1.56	1.18
Correlation (r)	0.85		0.82
Root Mean Square Error (RMSE) (% CC)	13.3		24.3
Average Observed CC (%)	57.4		57.4
Average Simulated CC (%)	56.8		72.2
Temperature (transpiration) stress (%)	-		-
Canopy expansion stress (%)	17		-
Stomata Closure stress (%)	26		53
Weed infestation stress (%)	10		10
Soil fertility stress (%)	15		15

This discrepancy between ET_a and biomass (NPP) is the results of the separated simulation for the two parameters adopted in WaPOR; ET_a and NPP are separately simulated, whereas in AquaCrop these are physiologically interlinked. The high values of biomass in WaPOR suggest WaPOR is overestimating the NPP accumulation of the recorded canopy – in essence returning values for a non-stressed photosynthesis condition. This is inherent to the adopted methodology, whereby first the climatic potential T and NPP is calculated, and then adjusted for environmental factors as water stress and leaf greenness (eq. 24 and 34 of the WaPOR manual, FAO, 2020). As the water stress is solely based on the LST sensor with a resolution of 1 km, over- and under-estimations of water stress (or fAPAR of canopy) will directly affect the T and NPP output. In the case of Farm II this results in an under-estimation of (aeration induced) transpiration stress, leading to an overestimation of T. Looking at the water balance in the root zone (Figure 5-1), as simulated by AquaCrop, it is clear that there is a significant aeration stress that results in stomatal closure (53%). For this reason transpiration is inhibited despite the full canopy development. This is a physiological stress WaPOR may not be able to detect. Based on the 1 km LST sensor, WaPOR, when compared to the AquaCrop simulation, overattributes the partitioning of ET_a to T.

5.2 Comparison for Maize Farms

For the maize farms (Table 5-3), there are significant differences between AquaCrop and WaPOR. Regarding the ET_a, WaPOR differs from AquaCrop by 32% (591 mm from WaPOR against 869 mm from AquaCrop), 19% (461 mm from WaPOR against 567 mm from AquaCrop), and 12% (609 mm from WaPOR against 694 mm from AquaCrop) for Farms B, A, and M, respectively. Such differences are also evident in the partitioning of E and T, where WaPOR calculated T higher and E lower than AquaCrop (Table 5-3). Regarding biomass production, WaPOR values are 280%, 200% and 286% greater than AquaCrop values for Farms B, A and M, respectively. In turn, differences in yield are also significant as WaPOR results in higher levels of yield. Considering an HI for maize of 0.35 (WaPOR portal), WaPOR yields are 217%, 261% and 209% greater than those reported by AquaCrop for Farms B, A and M, respectively. When the higher HI of 0.48 (WaPOR manual, FAO, 2020) is used, these differences are even higher.

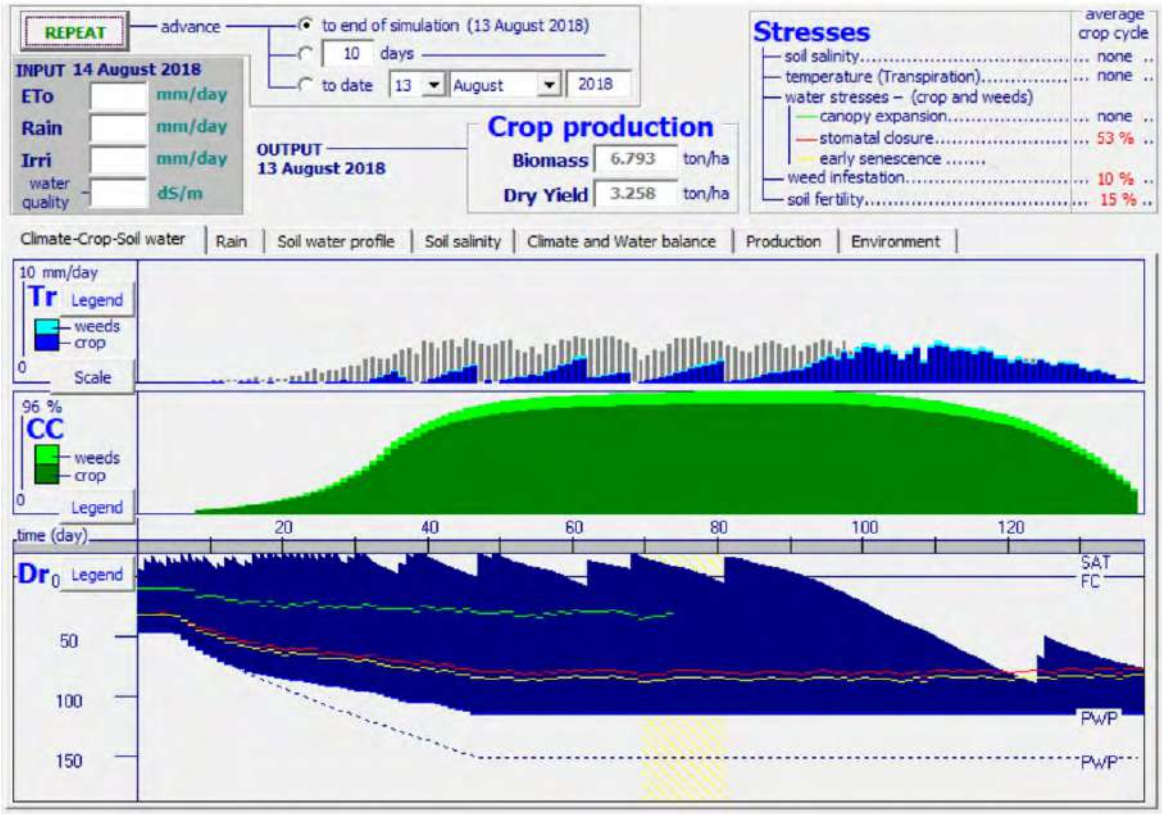


Figure 5-1: AquaCrop results for Farm II, with daily ET_o and precipitation data from WaPOR

As all three maize farms are small subsistence farms (1.2 to 5.3 ha), a substantive degree of noise resulting from a mismatch between satellite pixel and field boundaries may be expected. This degree of pixel noise is affecting the ET_a, biomass, and yield values for the maize farms. Even though a comparison between AquaCrop and WaPOR for the small maize farms cannot be done when there is not sufficient pixel coverage of the farms, the AquaCrop analyses show that the maize production is affected by certain stress factors (soil fertility, canopy expansion and temperature stress). The WaPOR database deals with these stresses in a very basic manner as described below. Soil fertility stress, which is set as high in the AquaCrop simulations, is a prime contender for deviating numbers. In WaPOR, the biomass is the product of the decadal accumulated NPP, which is based on temperature (radiation) and the green canopy fraction (photosynthetically active fraction of the canopy). Fertility stress will reduce the 'greenness' and photosynthetic efficiency of the canopy which should affect the fAPAR. Ideally, the daily NPP accumulation would have to be adjusted for fertility stress. The WaPOR outputs for the maize farms suggest this is not adequately achieved with the current fAPAR correction in the NPP equation (eq. 34 of manual, FAO, 2020). This is likely a result of sensor resolution and excessive "pixel noise" in small scale farms.

Canopy expansion stress, due to mild water stress in the vegetative growth stage, is only a limited factor for the maize crops, limited for Farm A and a bit (3%) for Farm B. Although unlikely to be captured in the WaPOR simulation of biomass, this is too small a factor in these cases to explain the discrepancy in output numbers.

Table 5-3: AquaCrop – WaPOR comparison for maize farms

	Farm B			Farm A			Farm M		
	AquaCrop*	WaPOR	Difference	AquaCrop*	WaPOR	Difference	AquaCrop*	WaPOR	Difference
Evaporation (mm/season)	537.2	70.1	467.1	299	92.6	206.4	332.5	57.4	275.1
Transpiration (mm/season)	331.7	457.9	-126.2	268.5	339.2	-70.7	361.4	502.5	-141.1
Reference Evapotranspiration (ET_o) (mm/season)	1255.4	859.3	396.1	1069	834.4	234.6	1059.1	733.4	325.7
Actual Evapotranspiration (mm/season)	868.9	590.88	278.02	567.5	461.4	106.1	693.9	608.98	84.92
Precipitation (mm/season)	1,571.90	1,205.20	366.7	553.6	1,191.30	-637.7	981.7	1,281.40	-299.70
Dry yield production (reported) (ton/ha)		6.66			4.5			6.24	
Dry yield production (ton/ha)	6.63	19.78/14.42	-13.15/-7.79	4.28	15.32/11.17	-11.04/-6.89	6.6	18.90/13.78	-12.3/-7.18
Harvest Index (adjusted) (%)	45	48/35	-3/+10	27	48/35	-21/-8	48	48/35	0/+13
Biomass (ton/ha)	14.73	41.21	-26.48	15.92	31.91	-15.99	13.75	39.37	-25.62
WP_y (kg yield/m^3 ET)**	1.12	3.35/2.44	-2.24/-1.32	0.94	3.32/2.42	-2.38/-1.48	1.01	3.10/2.26	-2.09/-1.25

** Only the validated values were used for the comparison between AquaCrop and WaPOR*

*** For the calculation of WP_y, AquaCrop uses ET_a values at the moment of physiological maturity of the plant while WaPOR uses ET_a values until the moment of harvest.*

Another stress factor occurring in Farms A and M is temperature stress. In both cases the AquaCrop simulation indicates the occurrence of cold temperature stress (9% for Farm A, and 30% for Farm M). In both cases, ambient temperatures fall below the optimum growing temperature (the crop specific base temperature) for maize, which in the AquaCrop simulation results in prolonged periods in which the temperatures are too low for the crop to accumulate GDD. In effect, it will stop growing and accumulate biomass. Although NPP rates in WaPOR will be low in these periods (due to climatic conditions), they may still be accumulated in the WaPOR simulation if not stopped by a threshold value.

5.3 Overall Comparison – Sources of Deviation between AquaCrop and WaPOR

Possible sources of deviation between WaPOR and AquaCrop are numerous. Firstly, the use of WaPOR in rainfed conditions might be problematic. During the wet season, the satellite readings of the different indicators might be affected by cloud cover, delimiting the useable data set of WaPOR that may affect the accuracy of its output.

Secondly, the influence of the pixel resolution and field coverage of WaPOR is obviously an issue, as the fewer number of pixels are assigned to each farm, or the more boundary pixels it contains, the less confidence can be given to the WaPOR output due to "pixel resolution noise". This is further compounded by the WaPOR Level 1 and 2 output dependence on the coarse 1 km resolution of the LST sensor, which determines the ET_a, partitioning into E and T, the water stress correction for ET, E and T, and the water stress correction factor for the biomass – essential output factors of WaPOR.

Thirdly, possible sources of discrepancies, provided by the detailed diagnostics of water productivity in AquaCrop, are fourfold:

i. The first stage of the growing season was characterised by excessive water, leading to aeration stresses that reduce crop transpiration and photosynthesis; WaPOR may not be able to pick these up as evaporation will be high relative to transpiration and, these stresses tend to be short term (shortly after intensive rainfall) and thus not be captured in-between two images; moreover, the stomatal closure due to aeration stress reduces the photosynthetic assimilation of biomass which does not seem to be picked up by WaPOR and may explain its relative high levels of biomass production for all cases in this study.

ii. The development stage of the growing season is characterised by a mild water stress situation leading to a pronounced "canopy expansion stress", with an accumulated seasonal value of 21%. This physiological stress represents a loss of turgor pressure in the leaves that inhibits the "mechanical" expansion of leaves inhibiting further biomass accumulation in the green canopy. WaPOR may not be able to detect this form of mild water stress, accounting thus full NPP values during this period whereas the crop does not have the means to store that production in its organs. Again, this would contribute to a relative over reporting of biomass by WaPOR.

iii. Apart from prolonged water stress (mild canopy expansion & stomatal closure), the AquaCrop simulation also indicates a significant degree of soil fertility stress. Physiologically this implies that the green canopy cover (GCC) will be less photosynthetically efficient (e.g., lighter green). As all the simulation in AquaCrop show (Section 3), soil fertility deficits are considerably constraining photosynthetic efficiency of a nutrient deprived canopy, resulting in reduced biomass accumulation, reduced canopy and reduced ET_a. In terms of the WaPOR modelling approach, this would require a fertility stress adjustment factor of the daily NPP accumulation rate. WaPOR seems to not be able to adjust these stresses in its stand-alone NPP simulation model to reflect the effects of soil fertility deficiencies and other stresses. In all farms, except Farm I, and especially in the maize farms, the biomass production from WaPOR is significantly higher than the one simulated by AquaCrop. For Farm I, the biomass production is also considered overestimated when assessed against the relatively low ET_a values. WaPOR does not seem to have the capability to adequately capture fertility stress in its fAPAR correction factor, leading it to return a relative overestimation of NPP and biomass accumulation in fertility stress conditions. To what extend this may be compensated by a lower NDVI (fAPAR) reading is still unclear and untested. The deviation in values for biomass between WaPOR and AquaCrop suggest, however, a tendency for overestimation of biomass in WaPOR as not all physiological stresses can be captured and modelled with its remote sensing approach. However, the WaPOR results obtained for the small maize fields cannot be considered reliable. This is due to the "noise" generated by the pixel coverage of the fields, which under Level 2 100 m resolution of WaPOR may not always results in a neat fit with field and crop boundaries on the ground.

iv. The difference between physiological maturity and harvest is not picked up by WaPOR, whereby WaPOR reported a further increase of T after physiological maturity (e.g., full senescence of wheat and maize crops) until harvest. Physiologically, this is not possible. This may be partially attributed to the coarse resolution of the LST sensor that is utilized in Level 1 and 2 datasets to partition ET in E and T, but should be corrected by the NDVI-based fAPAR values for green canopy cover (which are based on the higher resolution sensors of 100 and 250 m). The latter, apparently, is not working adequately, resulting also in this case in an overestimation of NPP and biomass by WaPOR.

Fourthly, yield formation is calculated through WaPOR analysis based on some assumptions; one of which including the utilisation of a fixed harvest index (HI) ratio.

Fifthly, AquaCrop and WaPOR analyses use different sources of climate data to calculate ET_o, which also influences the values of ET_a, biomass and thus yield. WaPOR uses satellite-based climate data with a 5 km resolution for precipitation and 20 km for reference ET, whilst AquaCrop is based on measured data from the average values of the nearest climate stations from the TAHMO school-based network with a similar or higher resolution (3-60 km).

6 Conclusions

6.1 CropMon AquaCrop Simulations & Diagnostics

Simulations in AquaCrop have been conducted for 5 rainfed farms in Kenya for the 2018 season (2 commercial wheat and 3 subsistence maize farms) with the use of weather data from TAHMO climate stations, canopy cover data derived from NEO BV crop monitoring programme and reported data by farmers (e.g., start of season, harvesting date, sowing density, and yield). These simulations provided the following results and insights:

6.1.1 Modelling Reliability

The simulations for the two commercial wheat farms (that used identical crop varieties) performed well, allowing simulations to be conducted with the default crop parameterization for wheat as provided by AquaCrop (e.g., GDD defined growth stages) and fitting of simulated and monitored canopy cover through adjustments of the fertility management.

The simulations for the three maize farms, turned out more complicated as three different varieties of maize were applied, of which only one (Farm M, with the oldest variety of maize) proved to perform well with the default crop settings of AquaCrop for maize. For the two other farms, adjustments were required in the crop parameterization for which we lacked the proper and detailed field observations of in-season canopy development and crop growth stages to perform a proper calibration of the crop parameters. This needs a more detailed set-up to perform well.

6.1.2 Agronomic Diagnostics

From both the wheat and maize simulations (with caveat for 2 of the maize farms), it became clear that the crops have been subjected to multiple and varying physiological stresses during the growing season that affected their agricultural water use and productivity. These range from:

- Mild (early season) water stresses that result in turgor stress that inhibits the crops from expanding their canopy and increase their photosynthetic assimilation capacity (and transpiration rate);
- Severe water stresses that lead to stomatal closure affecting both photosynthetic assimilation (biomass production) and the harvest index (yield formation); depending on the severity and timing of its occurrence;
- Waterlogging due to excessive rainfall which lead to aeration (transpiration) stresses that inhibit photosynthetic assimilation due to stomatal closure (biomass and transpiration reduction);
- Cold temperature stresses that inhibit plant growth (and thus transpiration and biomass accumulation);
- Fertility stresses (particularly severe in the subsistence maize) that affect photosynthetic assimilation and biomass, resulting in a decreased canopy and transpiration, and may affect the harvest index.
- The combination of these stresses leads to reductions in canopy development, biomass accumulation, seasonal transpiration and yield.
- The stresses are environmental and pose little to no options for management improvements. Fertility management (fertilizer application) may improve photosynthetic assimilation but, in

rainfed conditions may result in invigorated vegetative growth of the crop in the first half of the growing season with higher rates of transpiration that become off-set by more severe water stresses in a depleted soil; thus effectively offsetting all, or nearly all of the potential benefits of fertilizer application by enhanced water stress losses.

6.2 Comparison with WaPOR

Assessment of the water use and productivity of the same five plots through WaPOR Level 2 data yielded starkly different outputs and results in ET, partitioning of E and T, biomass production and yield, when compared to AquaCrop simulations and reported data in the field (ranging in 10% to 333% differences). Three of these plots are smaller than the WaPOR resolution, and are therefore likely to be affected by the pixel noise. The other larger plots were, up to a certain point, able to produce similar results, but failed to address all the observed stress factors.

Dealing with relative small farm plots (1-10 ha) WaPOR has to deal with "pixel resolution noise" that emanates from poor and partial coverage by remote sensing sensor pixels with the farm plot area, where partial cover of the area will affect the sensor value and WaPOR outputs for ET, E, T, biomass, and yield. Making the results less reliable than when a clean full cover of the sensor with cultivated area can be assured.

The differences in output, however, were also observed for the two wheat farms (40.4 and 34.3 ha), affecting results in ET, E & T, biomass and yield. Whereas some of these discrepancies may be attributed to inabilities of WaPOR to monitor mild physiological stresses (e.g., turgor, fertility, physiological maturity).

Despite the reasonable comparison, it is important to note that all parameters are affected by the coarse resolution of the underlying LST sensor that is used in ET_a, E, and T estimations and determine the water stress correction factor for the NPP biomass data. With a resolution of 1 km, this implies a minimal neat farm plot area of 100 ha is required to produce a noise free data output (which in practice can easily run up to 400 ha when pixels cross plot boundaries)

The data outputs suggest, in comparison with AquaCrop, a tendency of WaPOR to overestimate T in relation to E as T values over the total ET_a values are higher than what AquaCrop results show and a relative overestimation of biomass (and resulting derived yield). Numerous factors and reasons can be thought of that may explain this tendency.

Both AquaCrop and WaPOR outputs are highly sensitive to the climate input data when determining ET_{ref} and rainfall. In this comparative analysis, we observed a marked difference between WaPOR climate parameters and those derived from TAHMO weather stations for AquaCrop. These differences affect the different outcomes. This warrants a further assessment in future of the WaPOR climate parameters with ground weather stations.

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8 Annexes

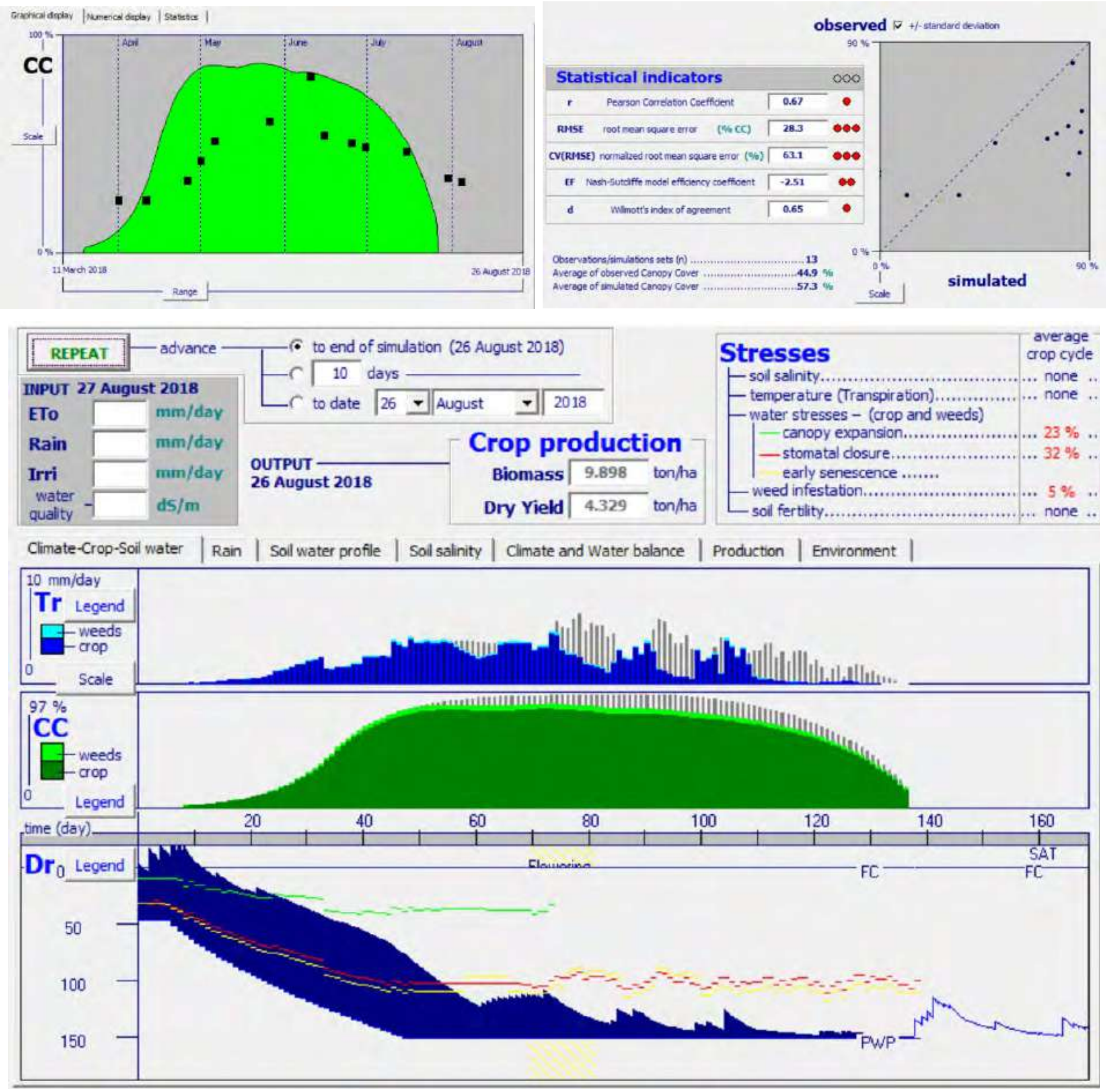
Annex 1 – Distance between weather stations and farm locations

County	Climate Data	Approximate Distance from Farm I (km)	Approximate Distance from Farm II (km)	Approximate Distance from Farm A (km)
Narok	Weather station 1	3	44	30
	Weather station 2	7	40	24
	Weather station 3	10	43	27
	Weather station 4	60	18	33

County	Climate Data	Approximate Distance from Farm B (km)
Uasin Gishu	Weather station 1	45
	Weather station 2	15
	Weather station 3	50

County	Climate Data	Approximate Distance from Farm M (km)
Nakuru	Weather station 1	16
	Weather station 2	22
	Weather station 3	30

Annex 2 - AquaCrop simulation results for Farm I (Wheat) with no soil fertility stress



Annex 3 – WaPOR point series data for Farm I (planting date: 11/3/2018, simulated maturity: 26/7/2018, harvest date: 5/8/2018 indicated by the vertical lines)