Simulating the water footprint of woodies in Aquacrop and Apex

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BE GREEN **READ ON SCREEN**

Summary

As the crop cultivation sector is the largest human water consumer, models that simulate its water use are important in global water studies. Within this sector, herbaceous plants and woody plants can be discriminated. Aquacrop is a plant simulation model very capable of simulating herbaceous plants, but the carry-over effects from one year to another, the large number of plant varieties and the more complicated evaporation and transpiration behaviour make the relative simple model not suited for the simulation of woodies. Apex is a model capable of simulating both herbaceous and woody plants, but the constant that drives biomass growth changes over the seasons and locations and loses its linearity in stress conditions. This study compares the Aquacrop and Apex in the simulation of woody plants. For this the yield, the evapotranspiration and the water footprint resulting from these are important.

From the plants with the largest harvested areas, the apple tree, the grapevine, the olive tree and the oil palm are selected as four important plants that will be simulated in this study. Each of these plants is simulated on a field level in the region where their core production is located. To make a comparison between the two very different models possible, the input and the processes in Aquacrop and Apex are harmonized. To allow for a simulation of woody plants, Aquacrop only simulates the yearly foliage development of an already full-grown tree. Apex can simulate the plant development in the first years that characterize woodies.

For a full-grown woody plant, Aquacrop and Apex show different yields and evapotranspiration rates because of differences in input, parametrization and model structure. Aquacrop and Apex show roughly the same yield patterns in irrigated conditions, but in rainfed conditions large differences can occur. The evapotranspiration rates are very similar in rainfed conditions, but in irrigated conditions they deviate a lot from each other. When we compare the yield with literature, both models in general overestimate the yield. The evapotranspiration is in accordance with literature values.

The climatic variability influences the yields and evapotranspiration rates. In both models the evapotranspiration responds very realistically to yearly climate fluctuations. The yield in Aquacrop also responds as expected, but the yield in Apex is dominated by a model processes that does not correspond to the climatic variability. The influence of the soil is limited in Apex, while it can have a large effect on especially the yield in Aquacrop.

The development phase of woody plants is important for the lifelong average yields, because the first years of a plants life are characterized by a rather low yield. The evapotranspiration rate also changes over the first years, but the effect of the development phase is negligible for the lifelong average evapotranspiration. When we take the development of yield into account for the calculation of the water footprint, it becomes visible that the water footprints in irrigated conditions are quite similar between the models, while in rainfed conditions they can differ quite a lot because of the difference in yield underlying the water footprint. Compared to the literature also large differences can occur.

Both models show their limitations. Because of this, additional research is required to compare the models under a wider scope. A case study can help to find more reliable estimates for the parameter values in the models. From this study alone, it cannot be concluded that one model is better than another. When simulating woodies, Aquacrop does not seem to be inferior to Apex, despite the fact that Aquacrop model is not designed for these plants.

Preface

A year ago I started working on my master thesis. The first few months where filled with the necessary preparations. My goal was simple: contribute to the tree simulation part of the Aqua21 modelling framework. How? That is what I tried to find out during these months. With civil engineering as my background, I dived into literature unfamiliar to me. I wrote the chapters of the literature report, revised them, threw parts completely overboard and finally came up with the literature report me and my supervisors found satisfying. Parallel to this I also constructed a research proposal, and similar repetitions led to a final version of this too.

After finishing these two reports, I started working on the actual thesis. Diving into one model, a second one and even a third for some time, I slowly got familiar with the models. Slowly, as this part took longer than expected. One model turned out to be unusable for the plans we had with it. A second one turned out to be difficult, because of the incomplete documentation and a complicated model structure. A third one was quite workable, but not all results could be explained with the documentation provided. But day-by-day I got more trusted with the models and finally the day came when I could produce results. Like a plant emerging from its seed, things started to develop. And not much later I'm writing this, as I finalized my project.

During the whole thesis my daily supervisor was Joep. Let me first say thank you. With the same background as me, he sensed the difficulties I had with the models. Being well informed in both models, he kept providing me with tips and answers for the questions I had. At the same time he showed great dedication by taking his time for the feedback and helping me keep my focus on the main issues.

During the thesis and at the beginning of the preparations, Martijn was my final supervisor. Thank you too. By taking his time for the feedback, with each typo and error noticed, he helped making the report much better. His general knowledge of the processes involved, while not having hand-on experience with the models themselves, helped me more than once to get a better understanding of the processes underlying the models.

Most important, the feedback of Joep and Martijn completed each other. By focussing on the same subject but having a different view on things, they helped getting the discussion going I needed to improve the study. For the feedback sessions, the phrase one plus one is three is truly applicable. I wish Joep all of luck with his PhD and his new born family. For Martijn nothing less of course. I hope you again find the time to travel the world.

Besides Joep and Martijn, I have many others to thank. I like to thank Arjen with his help in the preparation phase when Martijn was visiting New Zealand. I like to thank Abebe for sharing his knowledge of Apex and helping me whenever I experienced problems with the model. Furthermore, I like to thank La and Hatem for sharing their knowledge of simulating woodies with Aquacrop.

Mick
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symbol	*(Apex)*	*(Aquacr.)*	*description*	*unit*
Climatic input				
CO_2	$\mathrm{CO_2}$	$\mathrm{C_a}$	Atmospheric CO_2 conc.	$[ppm]$
ET_o	-	$\mathrm{ET_o}$	Reference evapotranspiration	$[mm]$
P	r	P	Precipitation	$[mm]$
R_sol	RA	-	Solar radiation	$[MJ/m^2]$
T_min	TMN	$\mathrm{T_n}$	Min. temperature	$[°C]$
T_max	TMX	$\mathrm{T_x}$	Max. temperature	$[°C]$
Soil input				
Δz	DZ	Δz	Thickness of soil layer	$[m]$
θ_fc	FC	θ_FC	Water content at field capacity	$[m^3/m^3]$
θ_sat	-	θ_SAT	Water content at saturation	$[m^3/m^3]$
θ_wp	WP	θ_WP	Water content at wilting point	$[m^3/m^3]$
cn	CN	CN	Curve number	$[-]$
K_sat	SC	$\mathrm{K_{sat}}$	Saturated hydraulic conductivity	$[mm/day]$
po	PO	-	Porosity	$[mm]$
Model parameters				
CC_max	-	$\mathrm{CC_x}$	Maximum canopy cover	$[m^2/m^2]$
CC_o	-	$\mathrm{CC_o}$	Initial canopy cover	$[m^2/m^2]$
CDC	-	CDC	Canopy decline coefficient	$[°C^{-1}]$
CGC	-	CGC	Canopy growth coefficient	$[°C^{-1}]$
HU_max	-	maturity	Max. amount of heat units for a plant	$[°C]$
HU_sen	-	senescence	Acc. heat units where senescense starts	$[°C]$
HUI_sen	$\mathrm{HUI_D}$	-	HUI when senescence occurs	$[°C/°C]$
$k_\mathrm{e,max}$	-	$\mathrm{Ke_x}$	Maximum evaporation rate	$[-]$
$k_\mathrm{tr,max}$	-	$\mathrm{Kc_{Tr,x}}$	Maximum transpiration rate	$[-]$
K_machine	HE	-	HI reduction for machine efficiency	$[-]$
K_pest	PSTF	-	HI reduction for pests	$[-]$
LAI_max	XLAI	-	Maximum leaf area index	$[m^2/m^2]$
LDC	ad	-	Leaf decline coefficient	$[-]$
LGC_1	ah1	-	First leaf growth coefficient	$[-]$
LGC_2	ah2	-	Second leaf growth coefficient	$[-]$
PHU	PHU	-	Potential heat units	$[°C]$
rd_1	ar1	-	First rooting parameter	$[-]$
rd_2	ar2	-	Second rooting parameter	$[-]$
T_base	TBSC	$\mathrm{T_{base}}$	Lower boundary of plant T range	$[°C]$
T_upper	-	$\mathrm{T_{upper}}$	Upper boundary of plant T range	$[°C]$
Model variables				
θ	ST	θ	Soil moisture content	$[m^3/m^3]$
B_root	RW	-	Root biomass	$[ton/ha]$
B_st	STL	B	Standing (aboveground) biomass	$[ton/ha]$
B_total	DM	-	Total biomass	$[ton/ha]$
CC	-	CC	Canopy cover	$[m^2/m^2]$
CC^*	-	CC*	Adjusted canopy cover	$[m^2/m^2]$

symbol	*(Apex)*	*(Aquacr.)*	*description*	*unit*
CDC_{ws}	-	$\mathrm{CDC_{adj}}$	Canopy decline coefficient in water stress	$[°C^{-1}]$
CGC_{ws}	-	$\mathrm{CGC_{adj}}$	Canopy growth coefficient in water stress	$[°C^{-1}]$
E	-	E	Evaporation	$[mm]$
ET_{p}	EO	-	Potential evapotranspiration	$[mm]$
F_{perc}	QV	D	Percolation or drainage	$[mm]$
F_{ro}	Q	RO	Surface runoff	$[mm]$
F_{uf}	UF	CR	Upward flow or capillary rise	$[mm]$
HI^*	HIA	$\mathrm{HI_{adj}}$	Adjusted harvest index	$[-]$
HU	HU	GDD	Heat units (or growing degree days)	$[°C]$
HU_{sum}	-	t	Accumulated amount of heat units	$[°C]$
HUI	HUI	-	Heat unit index	$[°C/°C]$
k_{tr}	-	$\mathrm{Kc_{Trx,sen}}$	Transpiration coefficient	$[-]$
K_{age}	-	$\mathrm{Kc_{Trx,adj}}$	Ageing correction on transpiration coef.	$[-]$
K_{cold}	FTM	-	Dormancy factor temperature	$[-]$
K_{day}	FHR	-	Dormancy factor daylength	$[-]$
K_{hi}	-	$\mathrm{f_{HI}}$	Adjustment factor for harvest index	$[-]$
K_{pol}	-	$\mathrm{Ks_{pol}}$	Adjustment for pollination	$[-]$
K_{sen}	-	$\mathrm{f_{sen}}$	Sen. correction on transpiration coef.	$[-]$
$K_{\mathrm{ws,ante}}$	-	$\mathrm{f_{ante}}$	Adjustment water stress before yield	$[-]$
$K_{\mathrm{ws,post}}$	-	$\mathrm{f_{post}}$	Adjustment water stress after yield	$[-]$
LAI	LAI	-	Leaf area index	$[m^2/m^2]$
P_{i}	RFI	-	Amount of intercepted precipitation	$[mm]$
$P_{\mathrm{i,max}}$	RIMX	-	Max. amount of intercepted precipitation	$[mm]$
PAR	PAR	-	Intercepted photosynthetic radiation	$[MJ/m^2]$
RUE	RUE	-	Radiation use efficiency	$[kg/ha \cdot (MJ/m^2)^{-1}]$
S_{as}	AS	-	Aeration stress coefficient	$[-]$
S_{biomass}	-	$\mathrm{Ks_b}$	Stress factor on biomass	$[-]$
S_{cdc}	-	$\mathrm{Ks_{sen}}$	Stress factor on CDC	$[-]$
S_{cgc}	-	$\mathrm{Ks_{exp,w}}$	Stress factor on CGC	$[-]$
S_{e}	-	Kr	Stress factor on evaporation	$[-]$
S_{min}	REG	-	Minimum stress factor	$[-]$
S_{root}	RGF	-	Minimum stress factor for roots	$[-]$
S_{strength}	SS	-	Root soil strength stress	$[-]$
$S_{\mathrm{tr,aer}}$	-	$\mathrm{Ks_{aer}}$	Aeration stress on transpiration	$[-]$
$S_{\mathrm{ts,root}}$	ATS	-	Root temperature stress	$[-]$
$S_{\mathrm{tr,sto}}$	-	$\mathrm{Ks_{sto}}$	Stomatal closure stress on transpiration	$[-]$
S_{ts}	TS	-	Temperature stress coefficient	$[-]$
S_{ws}	WS	-	Water stress factor	$[-]$
Tr	UW	Tr	Transpiration	$[mm]$
Tr_{p}	EP	-	Potential transpiration	$[mm]$
wt	T	-	Water tension	$[kPa]$
WP^*	-	WP*	Adjusted water productivity	$[ton/ha]$
Y	YLD	Y	Yield	$[ton/ha]$

Chapter 1

Introduction

This study compares the simulations of woody plants in the plant simulation models Aquacrop and Apex in the context of the water footprint. The meaning of this will become clear in this chapter.

1.1 Background

One of the main building blocks for a functioning human society is freshwater. Freshwater is used for drinking purposes, in industrial processes and for agricultural production. While freshwater is a renewable resource, it is finite. This means that at a certain location during a certain time the amount of freshwater is restrictive (*Hoekstra and Mekonnen*, 2011). Because of the many human functions for freshwater, in combination with the natural demand in a watershed, the distribution of this limited amount of freshwater is a complex puzzle.

From the total human freshwater consumption, 85 percent comes at the account of the agricultural sector (*Shiklomanov*, 2000; *Hoekstra and Chapagain*, 2007). Within the agricultural sector, the crop cultivation system and the livestock system can be discriminated. As 98 percent of the water consumption in the livestock system comes from the crop cultivation system in the form of food for livestock, the crop cultivation system is by far the most important sector when it comes to water consumption (*Mekonnen and Hoekstra*, 2012). In the crop cultivation system two types of plants can be discriminated, namely herbaceous plants and non-herbaceous, or woody, plants. All non-herbaceous plants, which are the trees and the shrubs, are perennial, while herbaceous plants can be both annual and perennial.

With the growing global population, the already high water demand from the agricultural sector will most likely increase considerably to meet the human food requirements (*Döll and Siebert*, 2002). However, the expected increasing demand from industry, electricity production and domestic use will leave little room for a higher water consumption of agriculture. And water users are already competing for the available freshwater. To deal with these increasing conflicting water demands, descent water management is required to limit the consequences (*OECD*, 2012). Global studies that trace water dependencies, water supplies and water demands can help to lay open vulnerabilities in these complex water dynamics. This study is conducted in the context of the Aqua21 modelling framework, a study that will combine global hydrology and water footprints to identify locations of water stress and to identify patterns in water consumption.

The water footprint in the Aqua21 modelling framework follows the line of the ecological footprint, and indicates both the direct and indirect water use of a country, product, consumer or any other study subject (*Hoekstra and Hung*, 2002; *Chapagain and Hoekstra*, 2004). In the agricultural sector, the water footprint of a crop is calculated by dividing the water consumption by the yield of the plant (*Hoekstra et al.*, 2011). The water footprint is thus expressed in volume of water consumption per unit of product. The water consumption of a plant is equal to the evapotranspiration during the growing season. For an annual plant, the water footprint can easily be calculated per year, as the plant is sowed and harvested in the same year. For a perennial as a tree or shrub this is more comprehensive, as the water footprint should be calculated from the yield and evapotranspiration over the complete life of the plant. This includes the first years of a plants life in which it is still developing its yield and years that the plant can be considered full-grown.

To calculate the water footprint of plants on a global scale, Aqua21 uses a plant simulation model. Such a model calculates the yield and evapotranspiration under the given environmental and management conditions. The plant simulation model currently embedded in the modelling framework has proved to be very capable of simulating herbaceous plants as wheat and maize under a wide range of conditions. How woody plants will be simulated within Aqua21 is not clear yet. This study is therefore concerned with the simulation of yield and evapotranspiration and the resulting water footprint for woody plants in a global context. While this is directly relevant for Aqua21, also other global water studies that simulate woody plants benefit from this study.

1.2 State-of-the-art

Over the years many studies have used plant simulation models to simulate woody plants, often on a global scale. Plant simulation models can be classified according to their plant growth component as either water-driven, solar-driven or carbon-driven (*Steduto*, 2006). In this first class, the plant growth is driven by the water consumption of the plant, while in the second class the plant growth is driven by incoming solar radiation. The third class relates biomass growth directly with the carbon assimilation in the plant.

The water-driven models often use a method described by *Allen et al.* (1998) for the calculation of the evapotranspiration. Here the evapotranspiration is derived from a reference evapotranspiration, which is the evapotranspiration from a normalized surface. A model that incorporates the principles of *Allen et al.* (1998) is Cropwat, a plant simulation model developed by the Food and Agriculture Organization (FAO) of the United Nations. *Hoekstra and Hung* (2002) used this model to estimate virtual water flows between countries and introduced with this the water footprint concept. Cropwat calculated the evapotranspiration, while the yield in this study was retrieved from the Faostat database. In the study 38 different plants were considered, including the woody plants oil palm, grapevine and citrus tree. *Chapagain and Hoekstra* (2004) continued on this study with a similar approach for yield and evapotranspiration. However, this study was much more comprehensive and included 164 different plants, with a minority being woody plants. *Mekonnen and Hoekstra* (2011) simulated 146 different plants on a global scale and combined the Cropwat model with an own grid-based dynamic water balance model. This model also used the principles described by *Allen et al.* (1998). In this study the yields were not taken from a database, but were calculated by their own model in order to account for processes as water stress. The model is a clear example of a water-driven model, as the yield is directly linked with the evapotranspiration. These yields were scaled to nation average yields. Cropwat is still used these days in large-scale studies (for example *Pfister and Bayer* (2014)).

Döll and Siebert (2002) simulated irrigation water requirements on a global scale with the Watergap model. This model was in its early stages capable of simulating two different types of plants; rice and nonrice. Watergap incorporated elements of Cropwat and calculated the irrigation requirements based on the evapotranspiration. The Watergap model has been used for multiple studies, among them a global water stress study to assess the impact of climate change (*Alcamo et al.*, 2007). *Siebert and Döll* (2008) improved Watergap to a model called GCWN. This model shows remarkable similarities in parametrization with Cropwat. With this new model, 26 different plants were distinguished, including some woody plants. These days the Watergap model is still used for global grid-based studies (*Schmied et al.*, 2016).

More recently, the Food and Agriculture Organization released a new plant simulation model called Aquacrop. This model can be considered as the successor of Cropwat. At its basis also lie the principles of *Allen et al.* (1998). The model has been developed for the simulation of herbaceous plants, but is used for the simulation of woody plants as well. *Hunink and Droogers* (2010) and *Hunink and Droogers* (2011) estimated the response of yield and water demand as a function of climate change. For Albania and Uzbekistan different plants were simulated, including the apple tree, the grapevine and the olive tree. *Zhuo et al.* (2016) simulated yield and evapotranspiration in China. In this study Aquacrop has been used to simulate 17 plants, also including the apple tree. Aquacrop is also the model currently embedded in the Aqua21 modelling framework for the calculation of the water footprint for herbaceous plants.

Besides these water-driven models, also solar-driven models are used for grid-based simulations of woody plants. The most common used solar-driven model is Epic, a model that has been developed for the simulation of soil productivity. The model Apex is an expansion of Epic, and allows for interaction between different points in a grid-based analysis through the water balance. Both Apex and Epic are distributed by Texas A&M AgriLife Research. The models are capable of simulating both herbaceous and woody plants. *Tan and Shibasaki* (2003), *Liu et al.* (2009) and *Balkovič et al.* (2013) used Epic for the simulation of plants on a large scale. However, each of these studies only simulate herbaceous plants. This in contrast with *Liu and Yang* (2010), who used Epic for a global simulation and included a number of woody plants as grapevine, oil palm and citrus tree. The model estimated the water consumption under both rainfed and irrigated conditions.

Next to the models based on *Allen et al.* (1998) and Apex and Epic, many other plant simulation models are found in literature. Often these models are solar-driven, such as Apsim (*Keating et al.*, 2003), Dssat (*Jones et al.*, 2003) and Stics (*Brisson et al.*, 2003), sometimes they are carbon-driven as Wofost (*Supit et al.*, 1994) and sometimes models allow the user to select one of multiple growth engines, such as Cropsyst (*Stöckle et al.*, 2003). However, most of these models are not frequently used in global studies.

1.3 Research gap

There are many large scale studies concerned with the yield and evapotranspiration of woody plants. Carbon-driven models are not widely applied in global studies. The solar-driven models Apex and Epic are used in global studies and have the advantage to explicitly discriminate between herbaceous and woody plants. They take into account the different processes that characterize these plants, such as the fact that a tree does not die at harvest but simply loses a parts of its biomass to fruits. Unfortunately, these models have the disadvantage that the constant that relates the solar radiation with the biomass growth, the radiation use efficiency, changes during the seasons and over different locations (*Adam et al.*, 2011). Furthermore, this relation loses its linearity in stress conditions (*Steduto*, 2006). What remains are water-driven models as Cropwat, Watergap and Aquacrop, which are indeed considered more stable under stress conditions (*Steduto*, 2006).

Aquacrop is the most recent water-driven model and is currently embedded in the Aqua21 modelling framework for the simulation of herbaceous plants. This model has also been used in grid-based studies to simulate woody plants. However, *Steduto et al.* (2012) stated that the relative simple modelling approach of Aquacrop make the model unsuitable for the simulation of woody plants. The carry-over effects from one year to another, the large number of plant varieties and the more complicated evaporation and transpiration behaviour cause complexities Aquacrop is not designed for. Current studies however do not take these complexities into account and treat woody plants as if they are herbaceous. Woody plants are parametrised similarly as other plants and studies with Aquacrop thus not discriminate between these two truly different kind of plants as Apex and Epic do. Also the other water-driven models Watergap and Cropwat apply the same simulation method to both herbaceous and woody plants, despite their complicated structure.

Non of the models is capable of simulating woody plants while still having a reliable structure under different conditions. Aquacrop is suppose to be stable under varying conditions but it does not discriminate between woody plants and herbaceous plants. Apex, which is a more comprehensive model than its sister model Epic, does discriminate between these different plant types, but suppose to be less stable. However, a different model set-up might allow Aquacrop to simulate full-grown woody plants, while Apex can simulate the development phase of the plants and might be more reliable than literature suggests. These two models will therefore be compared in this study for the simulation of woody plants as these two models are the most promising options for simulating woodies. As we are here concerned with studies on a global scale, it is important to analyse the response of the models to different conditions. Unexpected responses on certain conditions can make a model unsuitable for simulations in a global context.

For a woody plant a development period and a full-grown period can be distinguished. To calculate the water footprint, the lifelong average yield and evapotranspiration should be known, as the water footprint is calculated from the complete life. As Aquacrop will only be able to simulate the full-grown period, the effect of this development period for the full simulation should be known. Apex can simulate the development of the plant. By combining the results of the two models, the water footprint can be calculated for the full life of the plant.

Concluding, the water-driven model Aquacrop is currently used for the Aqua21 modelling framework, but the more complex behaviour of woody plants can make it unsuitable for the simulation of woodies. However, a different set-up might allow for the simulations of full-grown woody plants with Aquacrop. This can then be compared to Apex, which is already capable of simulating woody plants. By comparing the models under various conditions, the performance of the models can be analysed. To simulate the water footprint for these conditions, it is important that the influence of the development phase on the lifelong average yields and evapotranspiration rates is known.

1.4 Research goal and questions

The research goal of this study is directly derived from the research gap:

> Compare the yields and evapotranspiration rates of full-grown woody plants simulated with AquaCrop and Apex under various environmental conditions, and subsequently calculate the water footprint of woodies, considering the influence of the development phase on lifelong average yields and evapotranspiration rates.

The following research questions are asked with the goal:

1. What are the average yields and evapotranspiration rates of full-grown woody plants in the models Aquacrop and Apex?
2. How do environmental conditions affect yields and evapotranspiration rates of full-grown woody plants in Aquacrop and Apex?
3. What is the influence of the development phase on lifelong average yields and evapotranspiration rates and what is the resulting water footprint?

As there are many woody plants found all over the world and on top of this many cultivars, this study will not be able to cover the full range of woody plants. This study will therefore focus on only four important woody plants: the apple tree, the grapevine, the olive tree and the oil palm. The apple tree is simulated at three different locations, the rest of the plants at only one location. The different environmental conditions in this study are the climate and the soil. The total simulation period will be limited by the amount of available data. All of these aspects are explained in detail later in the report.

1.5 Reading guide

In chapter 2 the structure of the models, the underlying processes and the equations in the models are examined. Chapter 3 firstly explains the selection of interesting woodies and the collection of the corresponding data. This chapter also explains the method to simulate full-grown woody plants with Aquacrop and provides information on how a fair comparison between the models is done. Also the method is presented to answer each of the research questions. With this, the woodies can be simulated. The simulated yields and evapotranspiration rates and the resulting water footprint for Aquacrop and Apex are compared in chapter 4. In chapter 5 the methods and the models are discussed. Finally, chapter 6 gives the conclusions and recommendations resulting from this study.

Chapter 2

Plant simulation models

In this chapter the two plant simulation models Aquacrop and Apex are analysed in order to get a better understanding of the models. In section 2.1 the general structure of the two models is compared. Section 2.2 discusses the equations in the models. The model descriptions are based on the documentation belonging to the models. For Aquacrop this is given by *Raes et al.* (2012) and for Apex this is given by *Williams et al.* (2012). This study uses Aquacrop version 4 and Apex version 1501 revision 1604.

2.1 General structure

Aquacrop is a daily plant simulation model with a water-driven plant growth engine. Apex, on the other hand, is a daily watershed simulation model with a solar-driven growth engine. These two different principles, plant simulation model versus watershed simulation model and water-driven engine versus solar-driven engine, are explained below. But first, the input components of the models are shortly discussed.

In figure 2.1 the different input components of Aquacrop and Apex are shown. The model itself can be considered as a series of coupled equations that calculate the plant growth. It is the responsibility of the user to provide all the necessary data and parameters for these equations. To start with, this input consists of the location characteristics. These are climatic variables as temperature and precipitation, and soil characteristics as saturated hydraulic conductivity and soil depth. The models also require program parameters to be set. These are the parameters that generally not change for different plants or locations. Furthermore, the user provides a plant to the model, characterized by a certain combination of parameters. Finally, the model requires data that describes the management of the plant. This management includes for example planting dates and irrigation information.

From these input components the model calculates the plant growth. From the resulting output, the yield and evapotranspiration are most important in this study, as they are required for the water footprint calculation.

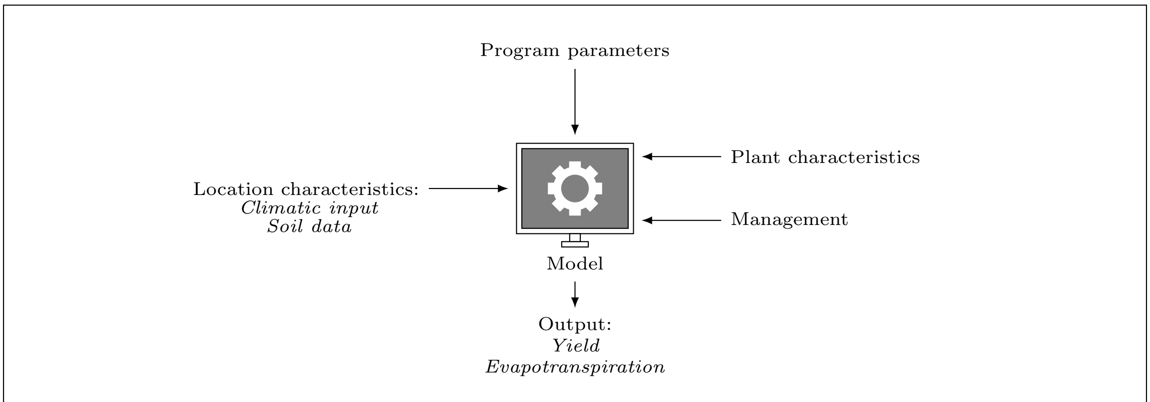
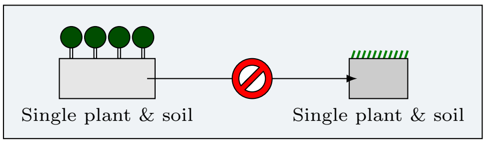
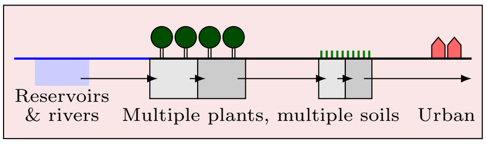


Figure 2.1: The input components of the plant simulation models Aquacrop and Apex.



(a) Aquacrop



(b) Apex

Figure 2.2: The simulation characteristics of Aquacrop and Apex. Aquacrop is a plant simulation model, capable of simulating on a field basis. Apex is a watershed simulator, with capabilities of simulating multiple watershed characteristics.

2.1.1 Plant simulation model vs. watershed simulation model

Aquacrop is a model developed by the Food and Agriculture Organization (FAO) of the United Nations. It is a plant simulation model, implying that it is developed specifically for the simulation of plants and that it does not take into account processes that are not directly related to plant growth. Apex, short for Agricultural Policy/Environmental eXtender, is distributed by Texas A&M AgriLife Research and is a watershed simulation model. This means that it is capable of simulating many different characteristics of a watershed, such as rivers, reservoirs, different soils, different plants and urban areas. The difference between the two is visualized in figure 2.2.

Being only a plant simulation model, Aquacrop is rather simple and can only simulate on a so-called field level. This means that the model can only do point simulations; only one plant and one underlying soil structure can be simulated in a single simulation run. To simulate an area with different plants and soil types, each of the different combinations should be simulated separately. There is no communication between the different simulation points. This can also be seen in figure 2.2a.

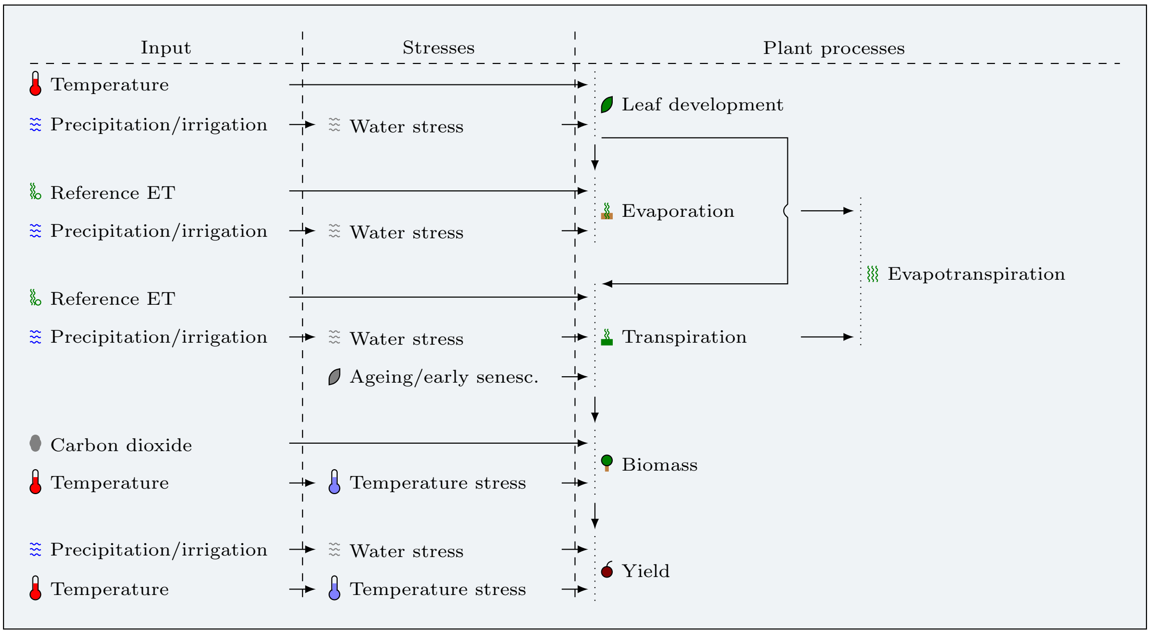
Where Aquacrop can only simulate on a field level, Apex is capable of simulating on a watershed level. Besides the fact that this opens the possibility to simulate the previously mentioned reservoirs, urban areas and more, this also implies that the model can simulate multiple plants and soil combinations within a single run. In this case Apex can be seen as a coupled-field model, as there are still different fields where plant growth takes place. However, these different fields communicate to each, the communication lines being the water fluxes in Apex. This opens the possibility to make a more realistic simulation of a composed area, but has the downside of a more complex model structure.

2.1.2 Water-driven engine vs. solar-driven growth engine

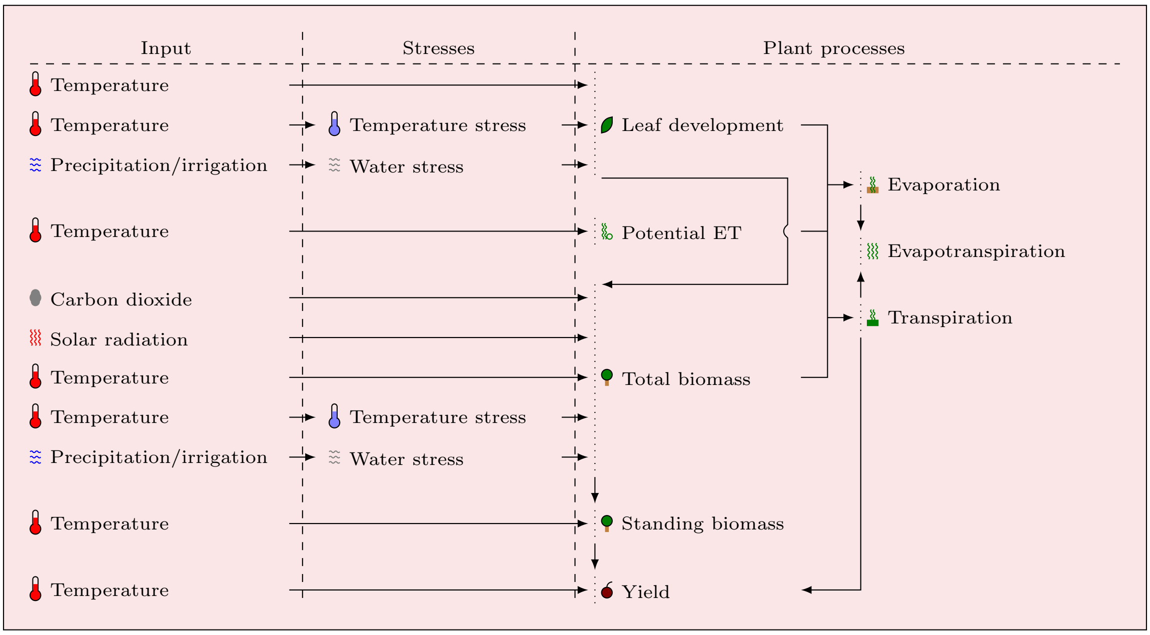
When we look at the growth engines of the simulation models, in this case Aquacrop and Apex but it is also applicable to other plant growth models, there are a few processes that can be found in both models. See figure 2.3. First of all leaf development is simulated, mainly driven by the temperature. There are growth limitations depending on the availability of building material, in this case only water as nutrients are not considered in this study. With leaves on the plant, the plant will start to transpire and with this the evapotranspiration is affected. The biomass growth depends on the type of model; in water-driven models this growth is a function of the water use of the plant, which is the transpiration. In solar-driven models it depends on the solar radiation reaching the plant. From this biomass a certain yield can be derived.

Let us see how this is implemented in each of the models. The structure of Aquacrop is found in figure 2.3a. The leaf development in the model is indeed driven by temperature, with water stress influencing the growth. From this leaf development, the evaporation and transpiration are calculated, together forming the evapotranspiration. Both of them depend on the input variable reference evapotranspiration, which is evapotranspiration from a normalized surface, forced by the local climate conditions. Also, the amount of water available influences the evaporation and transpiration. As can be seen in the figure, the biomass in Aquacrop is derived from the transpiration, from which it becomes, by definition, a water-driven model. The carbon dioxide concentration in the atmosphere influences, together with the temperature, the biomass accumulation. From this biomass, the yield is derived, affected by the temperature conditions and the water availability.

In Apex, the leaf development is also a function of the temperature and the water availability. This leaf development influences the biomass growth, but the biomass growth is also affected by the temperature, water availability, carbon dioxide and, very important, the solar radiation. It is this last one that makes Apex a solar-driven model. Note that Apex firstly calculates the total biomass (root weight plus aboveground weight), from which the aboveground biomass, or standing biomass, is derived. Parallel to this the temperature determines the potential amount of evapotranspiration that can take place. These three components, being leaf development, biomass growth and potential evapotranspiration, together determine the amount of evaporation and transpiration. From the standing biomass, the yield can be derived, which depends on, among others, the transpiration.



(a) Aquacrop



(b) Apex

Figure 2.3: The model structures of Aquacrop and Apex. Aquacrop is water-driven, as the biomass is a function of the transpiration. Apex is solar-driven, as the biomass is affected by the solar radiation. See the text for a more detailed explanation of the models.

2.2 Equations in the models

With this general structure of the models in mind, we take a closer look at the equations in the models. Below, Aquacrop and Apex are discussed separately.

2.2.1 Aquacrop

Aquacrop has a relatively simple model structure compared to Apex, caused by the fact that it only simulates plants and not a whole watershed. Here we focus only on the simulation components important for this study. To be able to simulate plant growth, the model requires the climatic variables daily minimum temperature (T_{min}), daily maximum temperature (T_{max}), daily precipitation (P), daily reference evapotranspiration (ET_{o}) and yearly atmospheric carbon dioxide concentrations (CO_2). For the soil profile, the most important parameters are the water content at saturation (θ_{sat}), the water content at field capacity (θ_{fc}), the water content at wilting point (θ_{wp}) and the saturated hydraulic conductivity (K_{sat}).

While having a relatively simple structure, Aquacrop is rather physical based resulting in a more complex simulation of processes compared to Apex. This is especially visible in the simulation of stresses. Water stress, for example, is not implemented in the model as one stress coefficient, but has many forms. While the application of water stress and other stresses will become clear in the explanation of the different model components, the general principle of stresses in Aquacrop is similar for all of them, see figure 2.4. In Aquacrop, the stress is simulated by a relative stress. If the model simulates water stress, plant parameters state at which water content water stress occurs and also state at which content the stress has reached its maximum. Within this range, the relative stress goes from zero to one. The value of the stress coefficient, the parameter actually applied in the model to simulate the stress, is related to this relative stress in a linear, convex or logistic way.

In Aquacrop, a certain growth stage occurs at a certain amount of accumulated heat units (or growing degree days). Each plant has, depending on its parameters, a certain temperature range that it flourishes best in. When the temperature is above a plants minimum threshold, the additional degrees are stored as heat units. In equation form this looks like

$$HU(i) = \frac{T_{\text{max}}(i) + T_{\text{min}}(i)}{2} - T_{\text{base}}; \quad 0 \leq HU(i) \leq T_{\text{upper}} - T_{\text{base}}, \tag{2.1}$$

in which $HU(i)$ [$^\circ C$] are the heat units acquired on day i, $(T_{\text{max}}(i)+T_{\text{min}}(i))/2$ is the mean temperature on day i, based on the maximum temperature $T_{\text{max}}(i)$ [$^\circ C$] and the minimum temperature $T_{\text{min}}(i)$ [$^\circ C$]. Furthermore, T_{upper} [$^\circ C$] and T_{base} [$^\circ C$] are plant properties describing the upper and lower boundary of the temperature range. From this, the accumulated amount of heat units are calculated with

$$HU_{\text{sum}}(i) = \sum_{n=0}^{n=i} HU(n) \quad HU_{\text{sum}}(i) \leq HU_{\text{max}}, \tag{2.2}$$

where $HU_{\text{sum}}(i)$ [$^\circ C$] is the accumulated amount of heat units on day i and HU_{max} [$^\circ C$] is a plant property that describes the maximum amount of heat units that can be accumulated for the plant. When this number of accumulated heat units is reached, the life of a plant is complete.

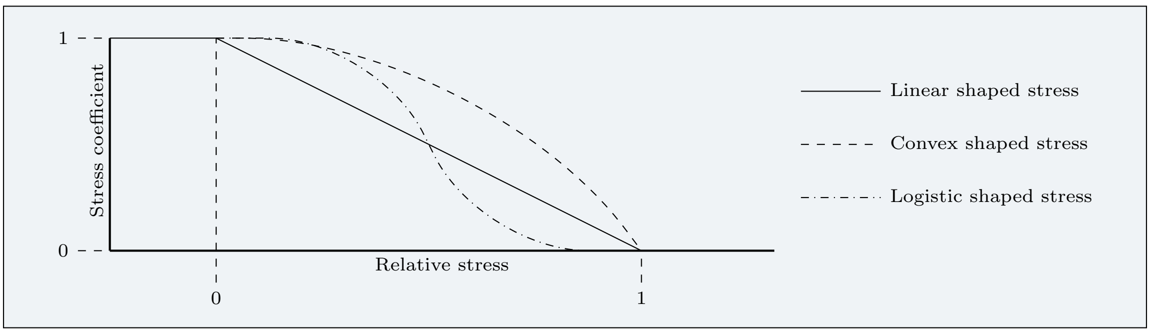


Figure 2.4: The general implementation of stress coefficients in Aquacrop.

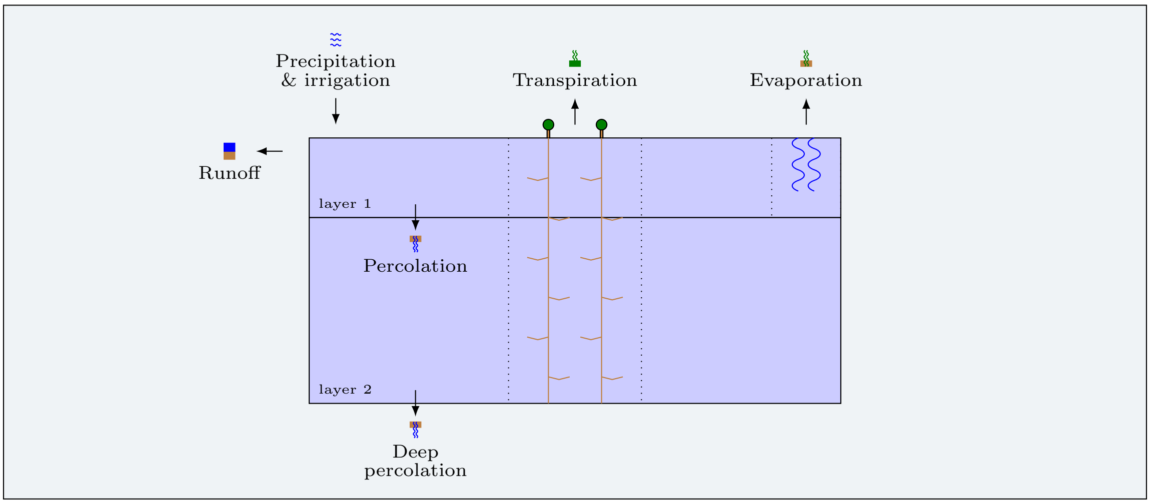


Figure 2.5: The components present in the soil water balance of Aquacrop.

Soil-water balance

The soil-water balance is one of the main model components in Aquacrop. The water content in this balance determines the water stress, which is very important for the plant growth. An overview of the different components in the water balance is found in figure 2.5.

In Aquacrop, the soil profile is split into multiple layers. In each of the layers, a certain amount of water content can be calculated for the end of the day by taking the water content at the beginning of the day and calculating the remain of the ingoing and outgoing fluxes. Aquacrop starts with the calculation of the outgoing flux percolation (or drainage). This is calculated by

$$F_{\text{perc}}(l,i) = f(K_{\text{sat}}(l), \theta_{\text{fc}}(l), \theta_{\text{sat}}(l), \Delta z(l), \theta(l-1, i-1)), \tag{2.3}$$

where $F_{\text{perc}}(l,i)$ $[mm]$ is the amount of percolation taking place from layer l on day i, $K_{\text{sat}}(l)$ $[mm/day]$ is the saturated hydraulic conductivity of layer l, $\theta_{\text{fc}}(l)$ $[m^3/m^3]$ the field capacity of layer l, $\theta_{\text{sat}}(l)$ $[m^3/m^3]$ is the soil moisture content at saturation of the layer, $\Delta z(l)$ $[m]$ is the thickness of the layer and $\theta(l-1, i-1)$ $[m^3/m^3]$ the soil moisture content of the layer above layer l on the beginning of day i.

After the calculation of the percolation, the ingoing flux infiltration is calculated. This is the irrigation, if applicable, and the precipitation minus a possible runoff. The runoff is calculated with

$$F_{\text{ro}}(i) = f(cn, P(i)), \tag{2.4}$$

where $F_{\text{ro}}(i)$ $[mm]$ is the runoff on day i, cn $[-]$ the curve number an $P(i)$ $[mm]$ the precipitation on day i. The infiltration water is distributed over the soil layers, depending on the maximum soil water content the layer accepts, the current soil water content and the saturated hydraulic conductivity.

With this updated amount of soil moisture content, the evaporation and transpiration are calculated. Evaporation occurs only from a small surface layer, while transpiration takes water from the root zone, which can cover the whole soil profile. More on evaporation and transpiration later. Aquacrop can also simulate capillary rise, but as there is no ground water table simulated in this study, this capillary rise is always zero.

Leaf development

Aquacrop simulates leaf development as canopy cover, which is defined as the percentage of soil area that is covered by the plant. The leaf development in the model is simulated by three equations; two that describe the canopy incline at the beginning of the season and one that describes the canopy decline at the end of the season. For the canopy incline, one equation describes a concave incline, whereas the second one describes a convex incline. See figure 2.6. Furthermore, the canopy cover is

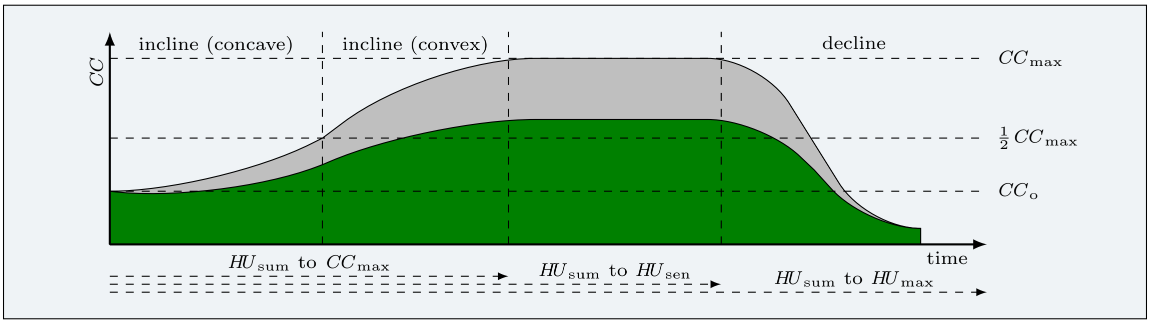


Figure 2.6: The development of the canopy cover in Aquacrop.

influenced by stress. The three equations are

$$CC(i) = \begin{cases} CC_{\text{o}} \cdot e^{HU_{\text{sum}}(i) \cdot CGC_{\text{ws}}(i)} & \text{if } HU_{\text{sum}}(i) \leq HU_{\text{sen}} \ \& \ CC(i) \leq \frac{1}{2}CC_{\max} \\ CC_{\max} - 0.25\frac{(CC_{\max})^2}{CC_{\text{o}}} \cdot e^{-HU_{\text{sum}}(i) \cdot CGC_{\text{ws}}(i)} & \text{if } HU_{\text{sum}}(i) \leq HU_{\text{sen}} \ \& \ CC(i) > \frac{1}{2}CC_{\max} \\ CC_{\max} \cdot f(CDC_{\text{ws}}(i), CC_{\max}) & \text{if } HU_{\text{sum}}(i) > HU_{\text{sen}}, \end{cases} \tag{2.5}$$

where $CC(i)$ $[m^2/m^2]$ is the canopy cover on day i, CC_{o} $[m^2/m^2]$ and $CC_{\max}$ $[m^2/m^2]$ are plant properties that describe the initial and maximum plant canopy cover, $CGC_{\text{ws}}(i)$ $[^\circ C^{-1}]$ and $CDC_{\text{ws}}(i)$ $[^\circ C^{-1}]$ are plant specific canopy growth and canopy decline parameters adjusted for water stress and HU_{sen} $[^\circ C]$ is a plant property that describes the amount of accumulated heat units required before canopy decline starts.

The effect of water stress on the canopy growth coefficient is calculated with

$$CGC_{\text{ws}}(i) = S_{\text{cgc}}(i) \cdot CGC, \tag{2.6}$$

in which CGC $[^\circ C^{-1}]$ is the plant parameter canopy growth coefficient and $S_{\text{cgc}}(i)$ $[-]$ is the water stress coefficient going from one (no water stress) to zero (maximum water stress). The water stress for the canopy growth coefficient depends on two things. Firstly, it depends on the moisture content in the soil, which is determined in the soil-water balance. Secondly, it depends on the sensitivity of the plant to water stress. Firstly the total amount of water the soil can hold is determined. This is a function of the water content at field capacity, the water content at wilting point and the rooting depth. A certain fraction of this states the soil moisture content where the plant will start to feel the stress (the point where the relative stress is zero). Another fraction, also a plant parameter, determines the content at which the stress is maximum (relative stress is one).

Water stress can also cause an early senescence of the plant. This is simulated in Aquacrop by an early canopy decline. Normally, the decline starts at the point where the accumulated heat units have reached the user specified amount of heat units at which senescence starts. Before this point, there is no canopy decline, i.e. the canopy decline coefficient is zero. To simulate early senescence due to water stress, Aquacrop uses the equation

$$CDC_{\text{ws}}(i) = (1 - {S_{\text{cdc}}}^8(i)) \cdot CDC, \tag{2.7}$$

where CDC $[^\circ C^{-1}]$ is the plant parameter canopy decline coefficient and S_{cdc} $[-]$ is the water stress coefficient for canopy decline. As can be seen in this equation, no water stress (stress coefficient is one) will result in no adjustment of the canopy decline coefficient. This means that no early decline occurs. Comparable with the water stress effects on the growth coefficient, the stress depends on the water availability and the sensitivity of the plant. The upper limit of the sensitivity is again specified by a plant specific parameter. The lower limit is equal to the wilting point.

Evapotranspiration

In Aquacrop, both evaporation and transpiration are governed by the reference evapotranspiration. Evaporation is determined by

$$E(i) = S_{\text{e}}(i) \cdot (1 - CC^*(i)) \cdot k_{\text{e,max}} \cdot ET_{\text{o}}(i), \tag{2.8}$$

where $E(i)$ $[mm]$ is the evaporation on day i, $S_{\mathrm{e}}(i)$ $[-]$ a stress coefficient for the evaporation, $CC^*(i)$ $[m^2/m^2]$ is the adjusted canopy cover, $ET_{\mathrm{o}}(i)$ $[mm]$ the reference evapotranspiration and $k_{e,max}$ $[-]$ is the plantfactor that describes the maximum evaporation rate. The adjusted canopy cover is a function of the normal canopy cover only, in which a higher canopy cover leads to a higher adjusted canopy cover. In other words, the higher the canopy cover, the lower the evaporation.

Evaporation normally takes place from the top 0.15 m of the soil. However, when the soil moisture content is too low, an evaporation reduction takes place. This causes the stress coefficient to become smaller than one. A dual process takes place. The soil water is slowly drained by the evaporation, until the point where it is air dry and the relative stress becomes one. At this point the stress coefficient S_{e} becomes zero. At the same time this process is limited by another process in the model. The model compensates for the loss of soil moisture by attracting water from deeper soils. This is simulated by the fact that the layer thickness of 0.15 meter expands, from which the maximum expansion is defined by the user.

The transpiration is calculated in a similar way as the evaporation. The equation that is used for the transpiration is

$$Tr(i) = S_{\mathrm{tr,aer}}(i) \cdot S_{\mathrm{tr,sto}}(i) \cdot CC^*(i) \cdot k_{\mathrm{tr}}(i) \cdot ET_{\mathrm{o}}(i), \tag{2.9}$$

where $Tr(i)$ $[mm]$ is the transpiration on day i, $S_{\mathrm{tr,aer}}(i)$ $[-]$ the stress coefficient from aeration stress on day i, $S_{\mathrm{tr,sto}}(i)$ $[-]$ the stomatal closure water stress coefficient and $k_{\mathrm{tr}}(i)$ $[-]$ the transpiration coefficient. As can be seen, also in this equation the adjusted canopy cover occurs; a higher canopy cover results in a higher transpiration.

The stress coefficient is composed of two different parts; a stress caused by aeration and a stress caused by a water shortage. The aeration stress is simulated as the stresses mentioned before, with the relative stress being zero at the anaerobiosis point, which is a plant parameter, and one at a soil moisture content equal to saturation. The stress caused by a water shortage is simulated to imitate the effect of stomatal closure. A plant parameter sets the upper threshold at which the soil moisture initiates this. Here the relative stress is one. The lower threshold is equal to the wilting point.

Besides the water stress, the transpiration is limited by two other processes. These are applied on the transpiration coefficient according to the equation

$$k_{\mathrm{tr}}(i) = f(K_{\mathrm{age}}(i), K_{\mathrm{sen}}(i), k_{\mathrm{tr,max}}), \tag{2.10}$$

in which $K_{\mathrm{age}}(i)$ $[-]$ is the ageing correction on day i, $K_{\mathrm{sen}}(i)$ $[-]$ is the senescence correction on day i and $k_{\mathrm{tr,max}}$ $[-]$ is the maximum transpiration coefficient. Both the ageing and the senescence correction simulate the process of an older leaf being less effective in transpiring. The ageing correction is applied on the transpiration coefficient when the canopy cover is at its maximum. It consists of a plant coefficient, the time it is on its maximum and the maximum canopy cover itself. When senescence occurs, the ageing correction is no longer applicable. To simulate a reduction of transpiration during senescence, a correction is applied that uses the relation of current canopy cover to maximum canopy cover.

From the transpiration equation described here, the model determines the transpiration demand of the plant. This demand is only met if the rooting depth of the plant is high enough. Otherwise, the plant cannot extract the full amount of water. Either way, the transpiration that occurs is divided over 4 layers in the soil. In each of the layers a certain fraction of the transpiration takes place.

Biomass

Being a water-driven model, the biomass in Aquacrop is a function of the transpiration. The equation for this is described by

$$B_{\mathrm{st}}(i) = S_{\mathrm{biomass}}(i) \cdot WP^*(i) \cdot \sum_{n=0}^{n=i} \frac{Tr(n)}{ET_{\mathrm{o}}(n)}, \tag{2.11}$$

where $B_{\mathrm{st}}(i)$ $[ton/ha]$ is the accumulated amount of aboveground biomass on day i, $S_{\mathrm{biomass}}(i)$ $[-]$ is a stress coefficient on the biomass and $WP^*(i)$ $[ton/ha]$ is the adjusted water productivity of the plant. This last one is the coefficient water productivity, adjusted for the carbon dioxide concentration in the atmosphere. This adjustment depends on the atmospheric carbon concentration on the simulation day, a plant parameter that determines the sensitivity of a plant to the carbon concentration and a number of program parameters that determine the relations with a reference concentration.

The stress coefficient for the biomass is a temperature stress. While a plant grows when the daily temperature is above the minimum temperature the plant requires, the plant has also an optimal temperature. The relative stress for the biomass is one when the temperature is exactly equal or lower than the minimum temperature. In this case the stress coefficient is zero and no biomass is accumulated. When the temperature has reached its optimum temperature, the relative stress is zero. At temperatures higher than the optimum, this relative stress stays zero.

Yield

Finally, from this biomass the yield can be derived. This is done by the equation

$$Y(i) = K_{\mathrm{hi}}(i) \cdot HI^*(i) \cdot B_{\mathrm{st}}(i), \tag{2.12}$$

in which $Y(i)$ $[ton/ha]$ is the yield on day i, $K_{\mathrm{hi}}(i)$ $[-]$ is an adjustment factor and $HI^*(i)$ $[-]$ the adjusted harvest index. As can be seen, a larger biomass leads to a larger yield. The harvest index is a plant specific parameter that, depending on the type of plant, grows according to a fixed growth curve to its maximum value. However, it is adjusted when early senescence occurs. If the canopy cover gets below a certain threshold, the program mimics the lack of photosynthesis by stopping the increase of harvest index. When this occurs too early in the season, the harvest index might stay at zero.

The adjustment factor for the harvest index is composed of multiple items. In the model this adjustment looks like

$$K_{\mathrm{hi}} = K_{\mathrm{ws,ante}}(i) \cdot K_{\mathrm{pol}}(i) \cdot K_{\mathrm{ws,post}}(i), \tag{2.13}$$

in which $K_{\mathrm{ws,ante}}(i)$ $[-]$ is the adjustment for water stress before the yield formation, $K_{\mathrm{pol}}(i)$ $[-]$ the adjustment for pollination failure and $K_{\mathrm{ws,post}}(i)$ $[-]$ the adjustment for water stress during yield formation. To start with the first one, the water stress before yield formation might cause an increase of harvest index because the plant has not yet spent its energy on the growing of the biomass. The size of this increase depends on the fraction of actual biomass at the start of flowering relative to the fraction of potential biomass. The range at which this fraction will cause a positive adjustment of the harvest index depends on the maximum harvest index increase the user allows for.

The second adjustment, the adjustment for failure of pollination, is applied when the conditions at the moment of flowering are such that the amount of flowers growing on the plant is not sufficient to grow the total amount of fruits. These severe conditions can be caused by water stress and temperature stress. For the water stress, a similar pattern as before is visible, with a plant parameter determining at which water content the stress occurs. The lower limit is set at wilting point. For the temperature stress, both a cold stress and a heat stress can cause the pollination to fail. Two plant parameters determine the minimum and maximum temperature for pollination. When the daily temperature is below this minimum or above this maximum, pollination starts to fail. The relative stress is zero at these temperatures, and increases to one when the temperature goes to five degrees below the minimum or five degrees above the maximum. At this point, no flowers grow.

Finally, water stress might occur during the yield formation. When this water stress limits the expansion of canopy, but does not limit the transpiration, this adjustment is positive. When the stress also limits the transpiration, the adjustment factor will become negative as the yield grows also less than optimal with such stress. In the equation of this adjustment, the stress coefficient limiting the canopy growth coefficient in the leaf development (S_{cgc}) is present for this first situation. For the second situation, when the transpiration is limited, the stress coefficient in the transpiration equation ($S_{\mathrm{tr,sto}}$) is present.

2.2.2 Apex

Being a watershed simulator, Apex has a more complex structure than Aquacrop as it contains more components. However, the processes themselves are not as physically based as Aquacrop, resulting in a simpler simulation of processes. This section will not discuss all simulation components; only the components relevant for the yield and evapotranspiration are explained. Also, as will become clear in chapter 3, Apex will be used on a field-level by making all the horizontal components in the soil water balance zero. From the stresses, the fertility stress and the aluminum stress are not considered. These parts are therefore also left out of the description in this section.

To simulate with Apex, the model needs maximum and minimum daily temperatures ($T_{\max}$ and $T_{\min}$), daily precipitation (P), mean daily solar radiation (R_{sol}) and yearly atmospheric carbon dioxide concentrations (CO_2). For the soil profile, the model requires much more parameters as Aquacrop did. The most important ones are the water content at field capacity (θ_{fc}), the water content at wilting point (θ_{wp}), the saturated hydraulic conductivity (K_{sat}) and the porosity (po). The rest of the soil parameters will be mentioned later.

The more simple simulation of processes in Apex is mainly visible in the simulation of stresses. Where Aquacrop has different stress coefficients for the different processes in the model, Apex is characterized by only two stress coefficients; one for the biomass of the roots and one for the remaining parts. This second one is composed of three components and looks like

$$S_{\min}(i) = \min(S_{\mathrm{ws}}(i), S_{\mathrm{as}}(i), S_{\mathrm{ts}}(i)), \tag{2.14}$$

in which $S_{\min}(i)$ $[-]$ is the minimal stress coefficient on day i, $S_{\mathrm{ws}}(i)$ $[-]$ the water stress coefficient, $S_{\mathrm{as}}(i)$ $[-]$ the aeration stress coefficient and $S_{\mathrm{ts}}(i)$ $[-]$ the temperature stress coefficient. As each of the three stress components can fluctuate between zero (full stress) and one (no stress), the minimal stress has the same range. The water stress coefficient is the actual transpiration divided by the potential one. The aeration stress coefficient is a function of the current water content, the field capacity and the porosity in the top soil layer and a plant parameter that states the sensitivity of the plant to aeration stress. Finally, the temperature stress is a function of the mean daily temperature and two plant parameters describing the minimum and optimal growing temperature. The other stress coefficient, the one for the roots, is described later.

In a similar way as Aquacrop, heat units are accumulated in Apex according to the function

$$HU(i) = \frac{T_{\max}(i) + T_{\min}(i)}{2} - T_{\mathrm{base}}; \quad 0 \leq HU(i). \tag{2.15}$$

As can be seen, this is the same equation as Aquacrop uses, except that the number of heat unit acquired on a certain day is not limited by a maximum. In Apex, the acquired heat units are used for the heat unit index according to the equation

$$HUI(i) = \frac{1}{PHU} \cdot \sum_{n=0}^{n=i} HU(n); \quad HUI(i) \leq 1, \tag{2.16}$$

wherein $HUI(i)$ $[°C/°C]$ is the heat unit index on day i and PHU $[°C]$ is a plant property that describes the heat units that are required before a plant is full-grown. The heat unit index is used for many different processes in the model. While the documentation states this simple equation for the heat unit index, corrections on the heat unit index occur, for example at harvest and when the heat unit index reaches one. These corrections are not mentioned in the model documentation.

Soil-water balance

The soil-water balance in Apex is to a certain extent comparable with the one of Aquacrop. This is caused by the fact that all horizontal components in the soil-water balance are set equal to zero. In a number of soil layers, the soil-water balance is responsible for the water stress component in the model as it can limit the amount of transpiration taking place. In figure 2.7 the soil-water balance is visualized.

The input of water into the system is firstly given by the precipitation, which is partly intercepted by the standing plant. The intercepted precipitation is calculated with the equation

$$P_{\mathrm{i}}(i) = f(P_{\mathrm{i,max}}(i), B_{\mathrm{st}}(i), LAI(i)), \tag{2.17}$$

in which $P_{\mathrm{i}}(i)$ $[mm]$ is the amount of intercepted precipitation on day i, $P_{\mathrm{i,max}}(i)$ $[mm]$ is the maximum amount of precipitation that can be intercepted on day i and $LAI(i)$ $[m^2/m^2]$ the leaf development on day i (more on the LAI below). The maximum amount of precipitation that can be intercepted is not further explained in the documentation, but is most likely a function of at least the precipitation on

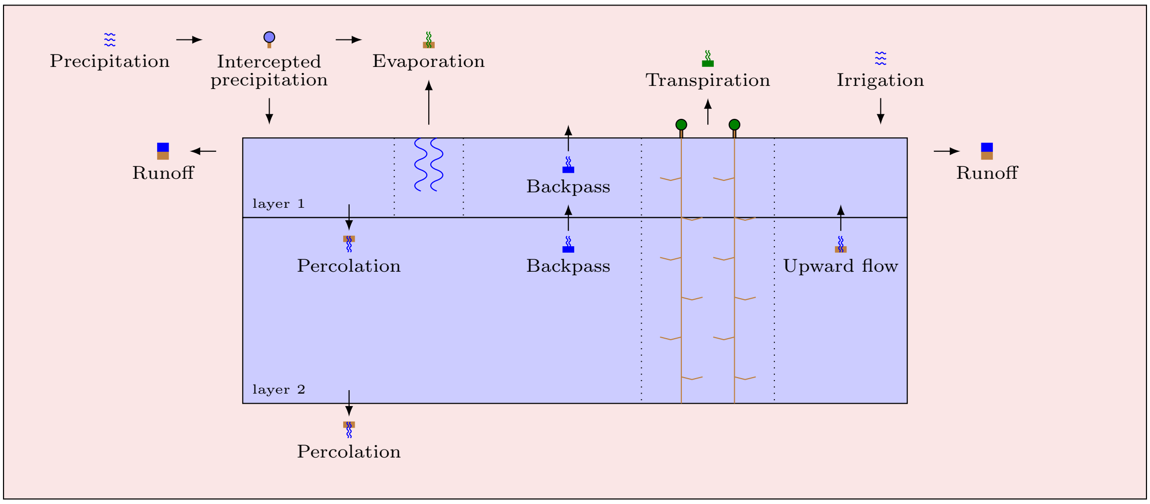


Figure 2.7: The components present in the soil water balance of Apex.

the day considered. The remaining precipitation, thus the precipitation minus the intercepted part, reaches the soil.

When reaching the soil, the precipitation partly becomes runoff. Just as with Aquacrop this is based on the curve number method. The equation for the runoff is

$$F_{\text{ro}}(i) = f(cn, P(i) - P_{\text{i}}(i)). \tag{2.18}$$

The curve number is not directly entered into the model, but is calculated indirectly by giving the land use number and the hydrologic soil group. The curve number is adjusted for the slope of the watershed. The remaining part of the precipitation, thus the original precipitation minus the intercepted part and the runoff part, adds to the soil-water balance. Besides this, also the irrigation water adds to the soil-water balance. A certain fraction of the irrigation can become runoff, but in this study this fraction is set to zero.

The water from the precipitation and irrigation will increase the water content in the layer. At some point, this water content will become larger than the field capacity, causing a flow from the layer. While the model allows for a horizontal component as well, this study only considers a vertical flow. This vertical flow, or percolation, is calculated according to the equation

$$F_{\text{perc}}(l, i) = f(K_{\text{sat}}(l), \theta_{\text{fc}}(l), po(l)), \tag{2.19}$$

in which po $[mm]$ is the soil porosity. Percolation occurs layer by layer, where the lowest layer contributes to the groundwater storage. The groundwater storage has no further interaction with the considered field; it only affects a possible downstream subarea.

Besides the vertical flow downwards, two upwards flows are present in the model. Firstly, there is a so-called backpass, which occurs in case of the physically impossible situation that the amount of water in a layer exceeds the porosity of that layer. This additional water is added to the above layer. In the highest layer, the water is transported out of the soil profile. Secondly, there is the upward flow, or capillary rise, which occurs when a lower layer exceeds field capacity. This is calculated according to

$$F_{\text{uf}}(l, i) = f(\theta_{\text{fc}}(l), \theta_{\text{wp}}(l), wt(i, l), wt(i, l-1)), \tag{2.20}$$

where $F_{\text{uf}}(l, i)$ $[mm]$ is the upward flow in layer l on day i and $wt(i, l)$ $[kPa]$ and $wt(i, l-1)$ $[kPa]$ are the water tensions in the layer considered and the layer above. The water tension of a certain layer is a function of the wilting point, the field capacity and the actual soil-moisture content. There is no upward flow into the lowest soil layer.

Besides these processes, also evaporation and transpiration influence the soil-water balance. More on these later.

Leaf development

In the soil-water balance, the leaf area index (LAI) was already mentioned. This is a widely applied leaf variable which is defined as the total area of leaves per area of soil. Both a leaf incline phase and a leaf decline phase are simulated, according to the equations

$$LAI(i) = \begin{cases} f(LAI(i-1), HUI(i), S_{\min}(i), LAI_{\max}, LGC_1, LGC_2) & \text{if } HUI(i) \leq HUI_{\text{sen}} \\ f(LAI(i-1), HUI(i), HUI_{\text{sen}}, LDC) & \text{if } HUI(i) > HUI_{\text{sen}}, \end{cases} \tag{2.21}$$

wherein $LAI_{\max}$ $[m^2/m^2]$ is the maximum leaf area index of a plant, LGC_1 $[-]$ and LGC_2 $[-]$ are two plant parameters that link the heat unit index with the leaf development, LDC $[-]$ is a leaf decline parameter and HUI_{sen} $[°C/°C]$ the heat unit index at which canopy decline is initiated.

Besides the decline phase of leaf area index, there is also a winter dormancy present in the model. However, the interaction between the decline and the dormancy is not expanded on in the documentation. The equation for the dormancy looks like

$$LAI(i) = LAI(i-1) \cdot (1 - \max(K_{\text{day}}(i), K_{\text{cold}}(i))), \tag{2.22}$$

in which $K_{\text{day}}(i)$ $[-]$ is a dormancy factor for the daylength and $K_{\text{cold}}(i)$ $[-]$ is a dormancy factor for the temperature. The first one is a function of the latitude and the day of the year. This factor is only considered when the daylength is within one hour of the shortest daylength. This factor is one when the daylength is equal to or larger than one hour above the shortest daylength. The dormancy factor for temperature only applies when the minimum daily temperature is below -1 $°C$. It is a function of this minimum daily temperature and two parameters that describe the sensitivity of a plant to this temperature.

Evapotranspiration

In Apex, some important parts of the evapotranspiration equations are documented unsatisfying. Therefore, the evapotranspiration process lets itself best be explained in words, with only a few clarifying equations. While here the evapotranspiration functions according to the documentation are presented, differences were observed between these documented processes and the output of the model.

The calculation of the potential evapotranspiration is rather straightforward, and is calculated according to one of the five evapotranspiration functions. In this study, the Hargreaves function is used, which is a function of the daily minimum and maximum temperature and the maximum possible solar radiation. This last one is a function of the latitude and the day of the year.

Evaporation is composed of a few parts; evaporation from soil, evaporation of snow and evaporation from litter storage. The potential evapotranspiration is split over the transpiration and the evaporation from soil. When the amount of intercepted rain is larger than the potential evapotranspiration, potential transpiration and potential evaporation from soil are zero on that day. When this is not the case, the potential transpiration depends on the leaf area index; a larger leaf area index results in a higher amount of transpiration. Furthermore, the potential transpiration can never be more than the potential evapotranspiration minus the intercepted precipitation. In equation this looks like

$$Tr_{\text{p}}(i) = \min(f(LAI(i)), ET_{\text{p}}(i) - P_{\text{i}}(i)), \tag{2.23}$$

in which $Tr_{\text{p}}(i)$ $[mm]$ it the potential transpiration and $ET_{\text{p}}(i)$ $[mm]$ is the potential evapotranspiration.

The actual transpiration is derived from this potential one. Depending on some soil properties, such as the soil water content of a soil layer, the field capacity and the wilting point, and some root properties such as the rooting depth and the root stress factor, the water for the transpiration is extracted from different soil layers. A soil layer with a high water content can compensate for a layer with little water. However, this can only continue for so long and at some point the potential transpiration will be hampered.

To calculate the actual transpiration, the root stress factor is required. The equation for this is

$$S_{\text{root}}(i) = \min(S_{\text{ts,root}}(i), S_{\text{strength}}(i)), \tag{2.24}$$

in which $S_{\mathrm{root}}(i)$ [−] is the root stress factor on day i, $S_{\mathrm{ts,root}}(i)$ [−] the temperature stress factor for the roots and $S_{\mathrm{strength}}(i)$ [−] the soil strength stress factor. The soil strength stress factor represents the resistance of a soil to root growth, and is a function of the bulk density and the sand content of the soil, both soil input parameters. The temperature stress factor for the roots is a soil layer specific variable and depends on the soil temperature of a certain layer and the optimal and minimum temperature of a plant. The soil temperature depends on the soil parameters depth of the layer, bulk density, albedo and water content, the plant biomass, the snow cover and the climatic variables daily minimum and maximum temperature and mean daily radiation.

When the potential evapotranspiration is larger than the intercepted amount of precipitation, besides transpiration also soil evaporation can take place. The amount of this potential evaporation depends on the amount of soil covered by the plants; a higher plant cover results in a lower potential soil evaporation. The plant cover is a function of the aboveground biomass and the leaf area index of the plant. The potential soil evaporation furthermore depends on the potential evapotranspiration and the part of this already distributed to potential transpiration.

The actual soil evaporation is derived from the potential soil evaporation depending on the water content, the field capacity and the wilting point of the first 0.5 meter of the soil. For the total evaporation, first the snow, if present, will evaporate, followed by the litter storage. After this, soil evaporation will take place. Snow will probably be a function of the precipitation and the temperature, but its equation is not mentioned in the documentation. The litter storage consists of the intercepted precipitation by the plant.

Biomass

In Apex, there are two different biomass components present; the root biomass and the aboveground biomass. As the yield is derived from the aboveground biomass, only this part is interesting here. However, the aboveground biomass is derived in three steps. First the total biomass, thus the aboveground biomass plus the root biomass is calculated. From this, the root biomass can be calculated. The aboveground biomass is then the total biomass minus the biomass of the roots.

As can be expected from a solar driven model, an important component in the biomass accumulation is the solar radiation. The equation for the total biomass is given by

$$B_{\mathrm{total}}(i) = \sum_{n=0}^{n=i} 0.001 \cdot \mathit{PAR}(n) \cdot (\mathit{RUE}(n) - f(T_{\min}(n), T_{\max}(n))) \cdot S_{\min}(n), \tag{2.25}$$

where $B_{\mathrm{total}}(i)$ $[ton/ha]$ is the total biomass on day i, $\mathit{PAR}(i)$ $[MJ/m^2]$ the intercepted photosynthetic radiation and $\mathit{RUE}(i)$ $[kg/ha \cdot (MJ/m^2)^{-1}]$ the radiation use efficiency. The radiation use efficiency is a function of the atmospheric carbon dioxide concentration and some plant parameters that represent the sensitivity of the plant to increasing carbon dioxide concentrations. The intercepted photosynthetic radiation is the radiation reaching the plant, which is a function of the mean daily solar radiation (R_{sol}), which is input, and the leaf area index.

The next step is to calculate the biomass of the roots. This is calculated with the equation

$$B_{\mathrm{root}}(i) = f(B_{\mathrm{total}}(i), \mathit{HUI}(i), rd_1, rd_2), \tag{2.26}$$

wherein $B_{\mathrm{root}}(i)$ $[ton/ha]$ is the root biomass on day i and rd_1 [−] and rd_2 [−] are two plant parameters that determine which fraction of total biomass goes towards the roots. The root biomass is distributed over different soil layers in the same fractions as the distribution of transpiration over the layers.

With the total biomass and the root biomass, the aboveground, or standing, biomass can easily be calculated according

$$B_{\mathrm{st}}(i) = B_{\mathrm{total}}(i) - B_{\mathrm{root}}(i). \tag{2.27}$$

The documentation also reports a dormancy influence on the standing biomass. This dormancy has the same construction as the dormancy on the leaf area index, with a dormancy factor for the daylength and a dormancy factor for the temperature.

Yield

Finally, the yield can be calculated with the standing biomass. The equation for the yield in Apex is

$$Y(i) = HI^*(i) \cdot K_{\text{pest}} \cdot K_{\text{machine}} \cdot B_{\text{st}}(i), \tag{2.28}$$

wherein $HI^*(i)$ [$-$] is the adjusted harvest index, K_{pest} [$-$] a factor that reduces the yield because of pests and K_{machine} [$-$] a reduction factor because of the harvest efficiency. The pest factor is a function of, among others, the sensitivity of the plant to pests. The adjusted harvest index is a function of the optimal and minimum harvest index, both plant properties, the heat unit index, which determines the growth from the minimum to the optimal harvest index, and the transpiration during the part of the season where the harvest index increases most, which is often the last half of the season.

Chapter 3

Method

In this chapter the method is described. An overview of this chapter is given in figure 3.1. To simulate and compare woody plants between models, the first step is to select the woody plants for this comparison, select the representative locations where the plants will be simulated and collect the necessary data for the simulations to take place. Parallel to this, the models are harmonized, such that they are forced in the same way to make a fair comparison possible. In addition, Aquacrop should be set-up such that it simulates the processes found in a woody plant as realistically as possible.

With these three preparations, the models can be simulated and the results can be compared. The analysis of the results is broken down into three steps, following the three research questions. First the method to analyse the average full-grown values of the yield and evapotranspiration is explained, followed by the method to analyse the influence of the environmental conditions. These are the climate conditions and the soil conditions. Finally, the method to determine the influence of the development phase and the method to calculate the water footprint is explained.

3.1 Plant selection & data collection

The plant selection, the location selection and finally the collection of data at the selected locations is explained in the coming three sections.

3.1.1 Plant selection

Aquacrop and Apex should be robust under a wide range of conditions to be used on a global scale, so the woody plants simulated in this study should be as diverse as possible. At the same time, the simulated plants should be significant in the sense that they are grown in large areas in the world. Rare plants can be interesting from a model perspective as well, but will have little meaning in global water studies like the Aqua21 modelling framework.

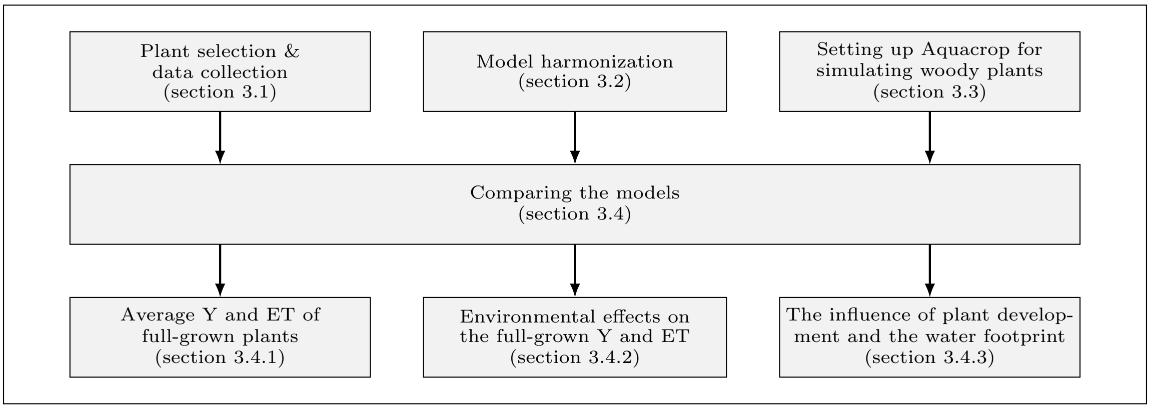


Figure 3.1: An overview of the chapter.

Table 3.1: The woody plants in the top 50 plants with the largest harvested areas. The second column shows the place in the top 50 (which includes both woody and herbaceous plants) of *Faostat* (2015).

Plant	Place in top 50	Harvested area [$\cdot 10^6 ha$]
Oil palm	17	17.6
Coconut palm	19	12.1
Olive tree	21	10.2
Coffee plant	22	10.0
Cacao plant	23	9.9
Rubber tree	24	9.9
Grapevine	28	7.0
Plantain plant	32	5.4
Cashew tree	34	5.3
Banana plant	37	5.0
Apple tree	40	4.8
Orange tree	46	3.8
Tea plant	49	2.3

From *Faostat* (2015) the harvested area of most plants can be retrieved. For this study, the woody plants in the top 50 plants with the largest harvested areas are considered. Whether a plant is woody or herbaceous is based on *Monfreda et al.* (2008). In table 3.1 the woody plants with the largest harvested areas are given.

To limit the number of plants to be simulated, the plants in table 3.1 are classified according to their phenological characteristics and their climatic range. For the first one, the groups deciduous broadleaved trees, evergreen broadleaved trees, deciduous shrubs and evergreen shrubs are distinguished. To cover the climatic influence, three different climate types are distinguished. These are tropical, temperate and boreal climates. The classification of the plants based on their phenological development and climatic range is displayed in figure 3.2.

In figure 3.2 it can be seen that some of the important woody plants are rather similar. Similarity is based on the fact that they (a) belong to the same plant type and (b) grow in the same climatic region. With this in mind, the apple tree, the oil palm, the olive tree and the grapevine are selected to be the plants of interest in this study. The apple tree is interesting because of the fact that it grows in a wide range of climates, more than other broadleaved deciduous trees. For the broadleaved evergreens, both the oil palm and the olive tree are chosen. The oil palm is interesting not because of its climatic range, but because its harvested area is expanding rapidly and this plant will thus become

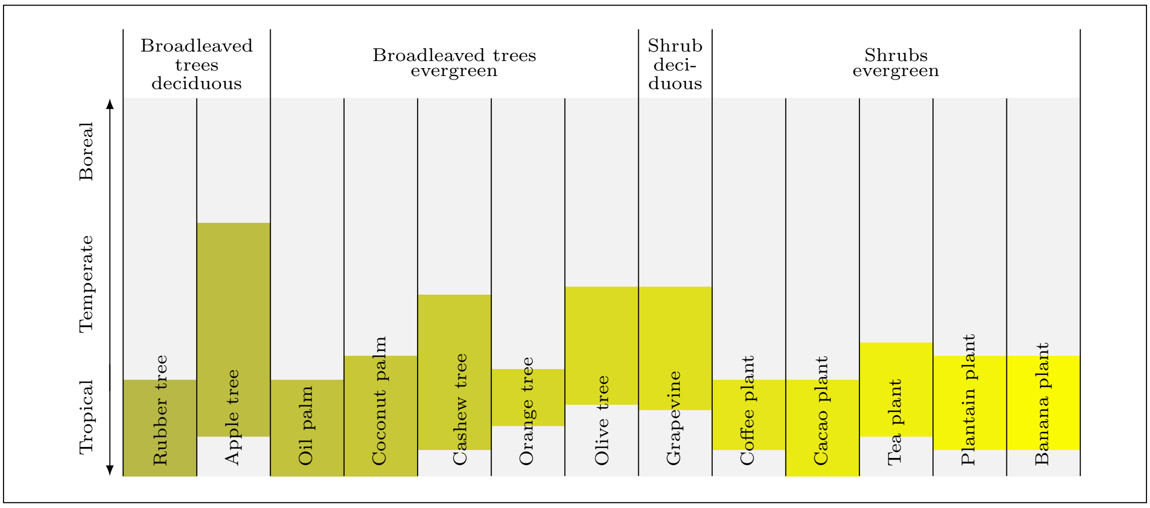


Figure 3.2: The classification of plants based on their periodic characteristics and their climatic range. The type of plant (tree/shrub) is based on *Monfreda et al.* (2008). The appropriate climatic region is based on a qualitative interpretation of the preferred temperature range of the plant.

even more important (*Faostat*, 2015). The olive tree is considered in this study as it can grow both as a shrub and as a tree. Finally, the grapevine is chosen as it is the only deciduous shrub in the top 50 plants with the largest harvested areas.

3.1.2 Location selection

Now that four plants for this study are selected, the next step is to find representative locations for these plants. Maps from *Monfreda et al.* (2008) are used to see where in the world the plants are grown. From the core production region, in the sense that it has the largest harvested area, a specific longitude and latitude are chosen based on the dominant climate and soil type in the region. For the apple tree, two additional locations are chosen such that the behaviour of the plant under different conditions can be evaluated. The maps, the considerations and the motivations for the location choices can be found in appendix C. The dominant climate in the region is based on the Köppen-Geiger classification, the soil characteristics on maps provided by *De Lannoy et al.* (2014). Figure 3.3 shows the selected locations on a global map, while table 3.2 lists the locations. Figure 3.4 shows the climate characteristics (temperature and rain) for each of the locations.

From the climate in figure 3.4 it can be seen that all locations except Johor show a clear northern hemisphere climate with warm summers and cool winters. Johor shows a typical tropical climate with a constant temperature and a relatively high amount of precipitation. The three locations for the apple tree, being Washington, Gagauzia and Shandong, have a slightly different temperature regime,

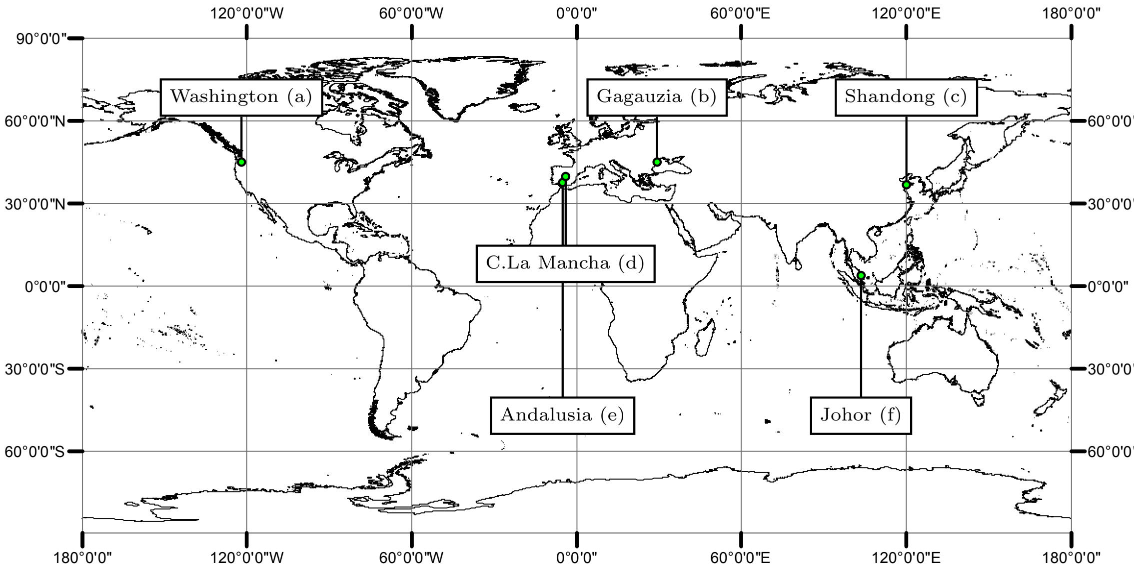
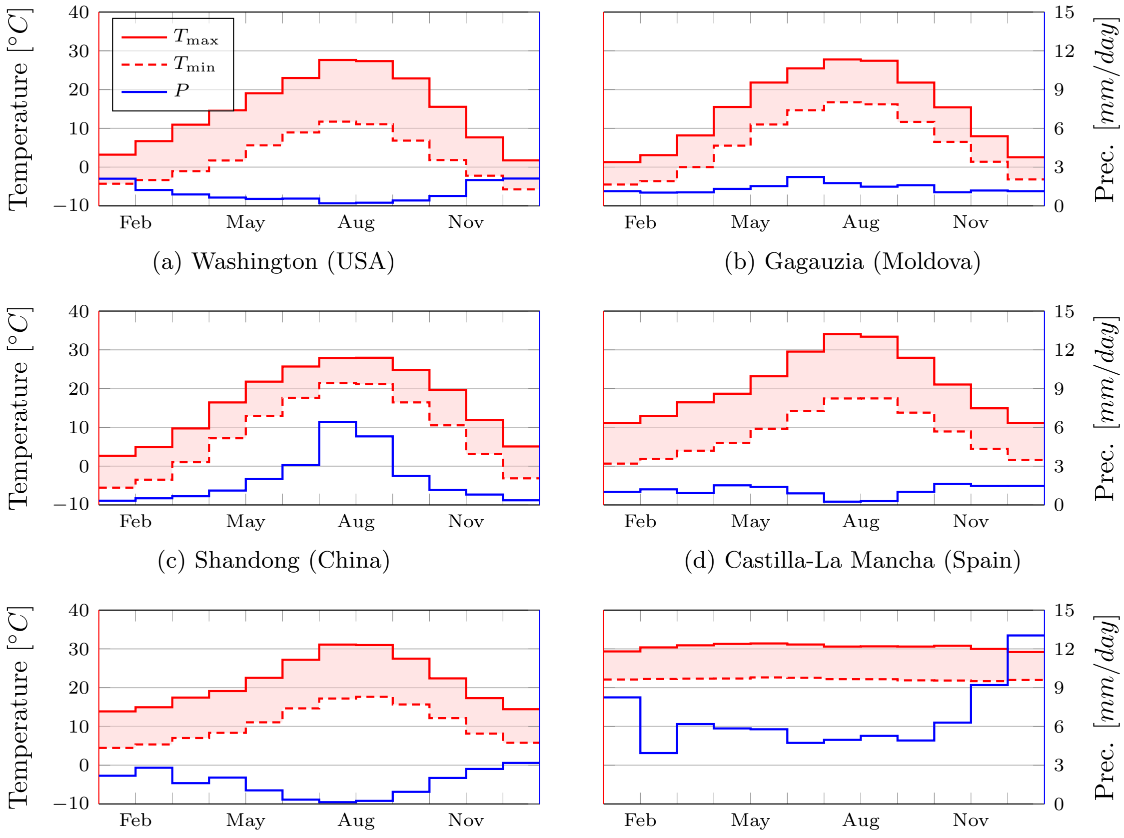


Figure 3.3: Overview of the simulation locations. All locations are provinces in the respective countries. Washington (USA), Gagauzia (Moldova) and Shandong (China) are the locations for the apple tree, Castilla-La Mancha (Spain), shortened as C.La Mancha, the location for grapevine, Andalusia (Spain) for olive tree and Johor (Malaysia) for oil palm. The letter behind the name (e.g. (a)) refers to the corresponding climate in figure 3.4.

Table 3.2: An overview of the locations for each of the plants. Note that for the apple tree, three locations are selected to make additional comparisons between the models possible.

Plant	Country	Province
Apple tree	China	Shandong
Apple tree	Moldova	Gagauzia
Apple tree	USA	Washington
Grapevine	Spain	Castilla-La Mancha
Olive tree	Spain	Andalusia
Oil palm	Malaysia	Johor



(a) Washington (USA)

(b) Gagauzia (Moldova)

(c) Shandong (China)

(d) Castilla-La Mancha (Spain)

(e) Andalusia (Spain)

(f) Johor (Malaysia)

Figure 3.4: An overview of the climate characteristics at the locations of the plant. The left axis shows the average temperature range (monthly average maximum temperature $T_{\max}$ and monthly average minimum temperature $T_{\min}$). The right axis shows the monthly average precipitation P. The averages are based on the period 1981 to 2010.

from a colder temperature in Washington to a warmer temperature in Shandong. The precipitation changes from a clear summer rainy season in Shandong to a relatively constant but low precipitation in Washington and Gagauzia. It is worth noticing that the core harvested area for the apple tree lies in Shandong rather than in Washington or Gagauzia.

3.1.3 Data collection

Aquacrop and Apex require both climate data and a soil profile as input. Of the first one, Aquacrop requires daily maximum and minimum temperatures, daily precipitation and daily reference evapotranspiration. Apex does not require reference evapotranspiration, but requires daily solar radiation instead. For the soil, both models require general soil characteristics and layer specific soil parameters.

The properties of the data underlying the simulations of this study are shown in table 3.3. Each of the datasets is available on a global scale and as the locations in this study are all point locations, only points from these global databases are picked. Note that not all data are available over the same period; the maximum simulation period is from 1981 to 2010 as this period is covered by all data. Furthermore, reference evapotranspiration is not retrieved from an external source, but is calculated with Apex. In Apex the user can choose between five evapotranspiration functions. These functions calculate potential evapotranspiration based on mainly the temperature and the solar radiation. This output variable of Apex is used as input in Aquacrop so that the two models use the same evapotranspiration function. In this study, the evapotranspiration function of Hargreaves is used. The choice for this function is motivated in appendix B.

For the soil data, *De Lannoy et al.* (2014) provide a global dataset of different soil parameters based on the sand, silt and clay content at a location. However, these soil parameters are only a part

Table 3.3: The global climate and soil databases used in this model, with their dimensions and source.

Type	Interval	Period	Resolution	Source
Maximum temperature	Daily	1958-2010	30 arcmin	*De Graaf et al.* (2014)
Minimum temperature	Daily	1958-2010	30 arcmin	*De Graaf et al.* (2014)
Precipitation	Daily	1958-2010	30 arcmin	*De Graaf et al.* (2014)
Solar radiation	Daily	1981-2010	30 arcmin	*Dee et al.* (2011)
Soil data	-	-	5 arcmin	*De Lannoy et al.* (2014)

of the parameters the models require. The rest of the parameters needed by the models are derived from these parameters as much as possible. Note that Aquacrop and Apex partly require different parameters. The exact derivation of the model specific parameters from the dataset of *De Lannoy et al.* (2014) is explained in appendix A.

3.2 Model harmonization

To compare the behaviour of the models it is important that differences in the simulated yields and evapotranspiration rates are caused by the underlying equations and not by inconsistent forcing or inconsistent simulation processes. Both of these components are explained below. A complete overview of the model set-up can be found in appendix A.

3.2.1 Input harmonization

In section 3.1.3 the climate and soil data is described. By using the same climate data for both models the climatic forcing is identical. This includes the evapotranspiration, which is calculated with Apex and then used as input for Aquacrop. In addition to the climate variables described before, Aquacrop also requires atmospheric carbon dioxide concentrations as input. The model provides its own database with yearly global CO_2 concentrations. Apex has a similar database embedded. As the default databases of the two models are not the same, the database of Aquacrop is given as input to Apex.

The parametrization of the soil is different between the models. Because of this the soil profiles cannot be harmonized completely. However, anomalies are avoided as much as possible by using the dataset of *De Lannoy et al.* (2014) as the basis for both models. Where this dataset is not sufficient, parameters are derived from this dataset. If applicable, the parameters for one model are obtained from the other model and the other way around.

3.2.2 Harmonization of model processes

The model structure of Apex is quite different from Aquacrop. From chapter 2 we know that Aquacrop is a field-level simulation model, capable of simulating only a single location. Apex is a watershed model with (a) interaction with other watersheds and (b) capabilities to simulate different watershed characteristics as reservoirs, rivers, and urban areas. To make a fair comparison between the models, Apex is also used on a field level in this study. This implies that there is no interaction with other watersheds in the model and that other watershed characteristics as rivers and urban development will have no effect on the plant growth. In practice, this is achieved by setting all the horizontal components in the soil-water balance to zero.

Aquacrop is capable of simulating water stress, aeration stress, temperature stress, fertility stress and salinity stress. The last two require calibration and since there is no information available on the these, they are turned off. Apex simulates water stress, aeration stress, temperature stress, fertility stress and toxicity stress caused by aluminium. To keep the stresses identical, also in Apex only water stress, aeration stress and temperature stress are simulated. However, in Apex the other stresses cannot be simply turned off. Fertility stress is avoided as much as possible by using the reactive automatic fertilizer in combination with a manual application of fertilizer every year. Toxicity stress is avoided by choosing a high soil pH value.

Simulations will be done in both rainfed as irrigated conditions. For irrigation, Aquacrop has the options sprinkler, surface and drip irrigation. The Apex user can choose between these irrigation methods and a few more. To harmonize the behaviour of the two models as much as possible, both models use the same irrigation method. For this study the sprinkler type irrigation is chosen as this is a widely applied method. In both models a reactive irrigation method is used, so that irrigation starts as soon as water depletion from the soil is detected.

3.3 Setting up Aquacrop for simulating woody plants

To make simulations of woody plants possible for Aquacrop, the model is used differently than the normal model set-up. In Aquacrop a simulated plant dies at harvest, as the plant has reached the end of its life cycle. As harvest takes place every year, the plant dies every year and the biomass is reduced to zero when this happens. This in contrast with a tree or shrub, in which the harvest of fruits will, of course, leave the standing biomass intact. In other words, woody plants are characterized by a lifelong accumulation of biomass, but Aquacrop does not allow for this.

To overcome this problem when simulating woodies in Aquacrop, an important assumption is made: Aquacrop simulates only the yearly foliage development for the biomass, while for the canopy cover the complete tree is simulated. See figure 3.5. The foliage development refers to the leaves, some small twigs and the fruits which will grow yearly upon the large body of stems. Since the tree loses this foliage in fall, they can be simulated similarly as a herbaceous plant. The heavy stems of a tree or shrub are assumed constant in Aquacrop. The consequence of this is that the plant is always considered full-grown in Aquacrop, as the assumption of a constant biomass of the stems only applies when a plant is full-grown. Related to this there will also be no root development for the plant, as the roots of a full-grown plant will already be fully developed.

To simulate a realistic yield with this modelling assumption, an adjustment has to be made in the set-up of the model. Not simulating the large biomass of the stems will reduce the yield significantly, as the yield is directly derived from the biomass. To overcome this, the harvest index, which is the fraction of biomass that becomes yield, should be adjusted accordingly. If the foliage is only a fourth of the weight of the total aboveground biomass, which includes the stems, the harvest index should be increased by a factor four to get the yield for the complete tree if only the foliage is simulated.

For the evapotranspiration a few adjustments should be made as well. The evapotranspiration in Aquacrop is directly related to the canopy cover. For a correct simulation of the evapotranspiration, the canopy cover therefore, in contrast with the biomass, should include the stems. Firstly, this results in a high initial and final canopy cover, as from the season start to the moment of harvest the stem will be present under the foliage. Secondly, the stem will be present all year round, also in winter when the foliage might not be present. This means that directly after harvest the plant of the following season grows, so that the canopy cover remains intact.

The exact set-up of Aquacrop, including the values for all parameters, can be found in appendix A. From the harmonization perspective mentioned in section 3.2, the parameters in Aquacrop are derived from Apex as much as possible. If this is not possible, external data had to be used to fill the missing plant parameters.

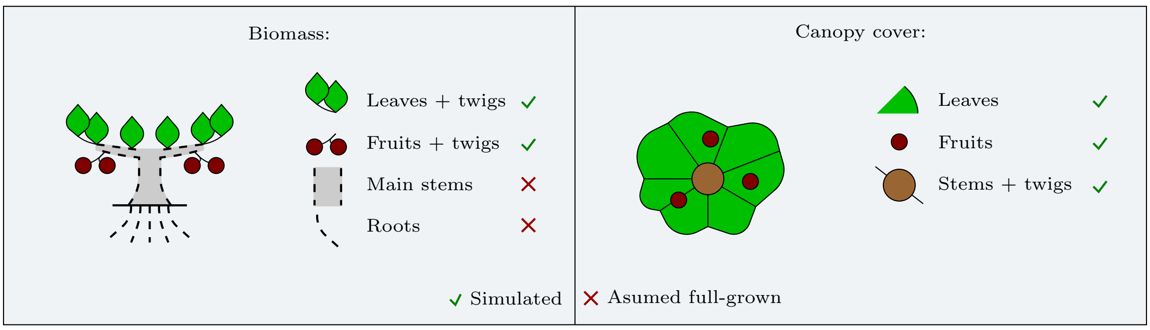


Figure 3.5: The main simulation principles in Aquacrop. For the biomass the main stems and roots are assumed full-grown. For the canopy cover all components are considered.

3.4 Comparing the models

With harmonization of the models and Aquacrop being set-up for woodies, the simulations can be done. This will result in 12 simulations per model; six for the simulations for apple trees at the three locations under both rainfed and irrigated conditions and six simulations for the remaining plants grapevine, olive tree and oil palm, also under rainfed and irrigated conditions. In this section, the methods to answer each of the three research questions are discussed.

3.4.1 Average yield and evapotranspiration of full-grown plants

The yield and evapotranspiration provided by the 12 simulations per model covers a period of 30 years; from 1981 to 2010. For Aquacrop the plant will be full-grown for the complete period of time, as this model is not capable of simulating plant development due to the set-up of the model (see section 3.3). For Apex, however, the first years are characterized by a steep incline of biomass and thus yield, because this model simulates the lifelong biomass accumulation present in a woody plant. At some point the biomass stabilizes and the tree can be considered full-grown.

In Apex we consider a plant full-grown when the yield is within 90 percent of the final yield. As the yield fluctuates over the years, it is possible that the very last year of the simulation is characterized by a very high or very low yield because it is for example a relatively warm or cold year. To avoid these yearly fluctuations, the yields of the final five years of the simulation period are taken as the final yield. In general this would mean that the average yield of the years 2006 to 2010 will represent the final yield. Only for the oil palm, this is the period 2005 to 2009, as the 2010 simulation cannot be completed within the year. The plant is thus considered full-grown when the yield is for the first time within 90 percent of this final yield. In table 3.4 the full-grown years are given for each of the plants. The full-grown years are derived from the simulations in irrigated conditions, as rainfed conditions might cause changes in the biomass resulting from the water stress rather than the development of the plant. The full-grown period under rainfed and irrigated conditions is identical.

For the years that the plants are considered full-grown, the average yields and evapotranspiration rates can be calculated. For Aquacrop the average yields and evapotranspiration rates are calculated for the same years, although the plant is full-grown for the complete simulation period. By comparing these yields and evapotranspiration rates to each other, differences and similarities between the models can be found.

To place the simulated yields and evapotranspiration rates in context, the values are compared to literature values that represent the actual yield and evapotranspiration found at the locations. Unfortunately, literature values are not available for exactly the locations and times of the simulations. However, the locations and times are approximated as much as possible.

Yearly fresh yield information is provided on a country level by *Faostat* (2015) for all plants considered in this study. For the locations where no more information is available, which are the apple tree in Gagauzia (Moldova) and the oil palm in Johor (Malaysia), these values are used as the literature values. The average yield is taken over the same period as the full-grown years in the simulation. For the apple tree in Washington, *USDA* (2016) provides state average yield data for the same period as the full-grown years. For the remaining locations, literature provides province scale data for only a number of years. These data are compared to the data of *Faostat* (2015) for the same years, and a ratio between the province and country yield can be derived. This ratio is then

Table 3.4: An overview of the years a plant is considered full-grown in this study, based on the development of plants in Apex in irrigated conditions. Note that the grapevine is considered full-grown for the complete simulation period. More on this in chapter 4.

Plant	Full-grown years	Full-grown period
Apple tree (Shandong)	1994-2010	17 years
Apple tree (Gagauzia)	1994-2010	17 years
Apple tree (Washington)	1995-2010	16 years
Grapevine	1981-2010	30 years
Olive tree	2001-2010	10 years
Oil palm	1998-2009	12 years

applied on the country average yield for the full-grown simulations years. As all literature provide their values as fresh weight while the models provide the yield in dry weight, the literature values are converted to dry weight using the rough approximation of *Raes et al.* (2012), which state that dry weight is approximately a quarter of fresh weight.

For the evapotranspiration, no actual, measured values are available; literature values are mostly a result of modelling studies. For all plants, the study of *Mekonnen and Hoekstra* (2010) provide the water footprint of the plants on a country level for the period 1996 to 2005. By comparing these with the country average yield values of *Faostat* (2015) for the same years, the evapotranspiration can be calculated. This evapotranspiration is used as the literature values for the apple trees in Shandong and Gagauzia, the grapevine and the olive tree. For the oil palm, *Yusop et al.* (2008) provide country average evapotranspiration rates. The average of them and *Mekonnen and Hoekstra* (2010) is used as the literature value. For Washington, state data are provided by *USBR* (2016) for the period 1988 to 1999. The average of these data is used. For more detailed information about the literature values of yield and evapotranspiration the reader is referred to appendix C.

3.4.2 Environmental effects on the full-grown yield and evapotranspiration

The environmental influence is in both models incorporated in two parts; climatic influence and soil influence. The climatic influence becomes visible as variability of the yield and evapotranspiration resulting from the climate variability. To analyse this, the same simulations as in section 3.4.1 can be used. Instead of averaging the yields and evapotranspiration rates over the complete full-grown period, the yearly average values can be calculated. For this we introduce the concept of plant year (or season), which starts at the green-up date and lasts until the harvest date. The green-up date is the day after harvest of the previous plant year. The yearly average values are calculated per plant year. For the yield there is only one value per plant year. These average plant year values can be compared to the average values of temperature, precipitation or any other variable that are found in the models.

To analyse the sensitivity of the models to different soils, the apple tree in Shandong is simulated with three additional soil profiles. These three soil profiles are manually selected from the same dataset as where the original soil profiles were retrieved from (*De Lannoy et al.*, 2014) and are topsoil/subsoil profiles 8/8, 234/234 and 82/172. Soil 8/8 is characterized with a relative high field capacity and wilting point, combined with an average saturated hydraulic conductivity and a rather small particle size. The second soil has a very high saturated hydraulic conductivity, has a coarse particle size and a low field capacity and wilting point. The last soil profile, soil 82/172, has a very low saturated hydraulic conductivity, has a small particle size and has an average field capacity and wilting point. All soil parameters required for the simulations in both models are derived from these soil profiles in the same way as was done for the original soil profiles. More information about the soil profiles is found in appendix C. By comparing the differences in yield and evapotranspiration and underlying variables, the influence of the soil in the models can be analysed.

3.4.3 The influence of plant development and the water footprint

To estimate the water footprint for the plants in this study, it is firstly important to determine the influence of the development phase on the lifelong average yield and evapotranspiration. As can be imagined, the first years of plant growth the yield and transpiration will be relatively low as compared to a full-grown tree, while the evaporation will be higher. As Apex simulates the plant development, this model can be used to analyse the influence of this development phase. This is done with the original simulations for only irrigated conditions to make sure that the development is not influenced by water stress. By calculating the average yield and evapotranspiration for the complete period of 30 years and comparing this to the full-grown yield and evapotranspiration, the importance of this development period will become clear. The importance can be expressed as a factor that relates the lifelong results with the full-grown results.

For Aquacrop, the lifelong average yields and evapotranspiration rates can be calculated with these factors. By taking the average yield and evapotranspiration over the whole simulation period, from 1981 to 2010, and correcting this with the derived factor, the lifelong average yields and evapotranspiration rates are derived. This lifelong average includes the influence of the development phase. From this the water footprint can be calculated. For Apex the approach is somewhat different; instead of using a factor, the yield and evapotranspiration over the whole simulation period is simply averaged as this already includes the development phase. As the yield is required to be fresh weight to calculate the water footprint, the factor four between the fresh and dry weight can again be applied.

To also put the calculated water footprints in context, the water footprint values are compared to literature. The study of *Mekonnen and Hoekstra* (2010) is used, as this provides a large dataset of water footprint values, often on a province scale. Only for the apple tree in Gagauzia (Moldova) the water footprint is given on a country level.

Chapter 4

Results

In section 4.1 the average yields and evapotranspiration rates of full-grown plants are examined. In section 4.2 the influence of the environmental conditions on these yields and evapotranspiration rates is discussed. Finalizing this chapter, section 4.3 is concerned with the calculation of the water footprint from the simulations in this study, taking into account the development of a woody plant.

4.1 Average yield and evapotranspiration of full-grown plants

In chapter 3, the moment that a plant is considered full-grown is defined. From this moment on, an average yield and evapotranspiration rate can be derived for the plant, deviating from this value only because of yearly fluctuations. These average values are discussed in this section, starting with the yield.

4.1.1 Average yields

In figure 4.1 the full-grown yields for the plants considered in this study are presented. The yields are simulated for both rainfed and irrigated conditions. Besides the simulated values of Aquacrop and Apex, also literature values are presented in the figure.

Figure 4.1 gives insight in the similarities and differences between the models when it comes to the yield of a full-grown plant. As can be seen, the general performance in irrigated conditions is very similar. This is caused by a similar parametrization, and then especially the parameters concerned with the harvest index and the biomass accumulation are important for these similarities. As can be seen, both models show the highest yield for the oil palm, followed by, roughly, the olive tree, the apple trees and finally the grapevine.

Aquacrop and Apex have a similar temperature response. Looking at the different apple trees in figure 4.1, both models show the highest yield in Shandong, followed by Gagauzia and finally Washington. Firstly, this has to do with the parametrization of the temperature preferences of the plants, which are identical for all apple trees in both models. Secondly, the similar temperature response has to do with the processes concerned with temperature stress; in both models this stress is lowest in Shandong and highest in Washington. The temperature in Shandong lies closest to the optimal temperature, followed by the temperature in Gagauzia.

The response to water stress is different between Aquacrop and Apex. The relative yield in rainfed conditions is, as a fraction of the yield when irrigated, always higher in Apex, except for the oil palm. In figure 4.1 this is especially visible for the apple trees, where the yield in rainfed conditions is higher for Apex than for Aquacrop. The reason for this difference is twofold. Firstly, the different biomass simulation processes between the models cause different yields. In Apex the biomass is accumulated over the complete life of the plant, where the biomass in one plant year builds upon the biomass of the previous plant year. In Aquacrop, on the other hand, the biomass accumulates per plant year. At the beginning of the year Apex thus already has a biomass standing and, when no plant growth occurs in the plant year, there will still be a yield. In Aquacrop, no plant growth in a plant year would mean no biomass at all, and thus no yield. Secondly, the water stress in Aquacrop is such that it can prevent a plant from growing, while in Apex the water stress in practice only limits the growth.

From figure 4.1 it can be seen that in irrigated conditions Aquacrop simulates a higher yield than Apex for the apple trees, while it is the other way around for the olive tree and the oil palm. This has partly to do with the parametrization of the plant, and more specifically the parametrization of the biomass. Parameters in Apex and Aquacrop that are not derived from each other in the harmonization procedure are responsible for this. These parameters cause a relative high biomass in Aquacrop and a low biomass in Apex for the apple trees, while for the olive tree and the oil palm this is the other way around. As a result, the yield shows the same pattern. Furthermore, the processes underlying the biomass accumulation are very different, as Aquacrop simulates biomass as a function of the transpiration while in Apex it is mainly the solar radiation that is responsible for the biomass accumulation.

Looking at the average yield of the grapevine in irrigated conditions, it can be seen that the absolute difference between the models is small. However, the relative difference between the predicted yields is largest of all plants, with Aquacrop yield being eight times higher than the one of Apex. The cause of this lies purely in Apex and is a combination of a different parametrization compared to the other plants and different processes resulting from this. In Apex, the grapevine is not simulated as a tree like the other plants, but as a shrub. While this seems reasonable, as the grapevine is indeed a shrub, the biomass accumulation for a shrub in Apex is on a yearly basis. This in contrast with a lifelong accumulation for trees. This causes a relative low biomass in Apex. Furthermore, the harvest index in Apex is much lower than the potential one, because of a different simulation of the heat unit index for a shrub as for a tree. The combination of the two cause a lower yield in Apex, but the first one also results in a deviating yield for Aquacrop; the factor that converts the harvest index of Apex to the harvest index of Aquacrop is based on trees only and presumes a lifelong biomass accumulation in Apex. The fact that the grapevine is simulated without this lifelong accumulation makes the harvest index in Aquacrop relatively high. Note that the yield of the grapevine in rainfed conditions is practically zero in both models, as the water stress is so severe that the plant hardly grows.

When we look at the yield values of the models in relation to the literature values, it can be seen that the literature values are in general lower than the simulated values. This has multiple causes. Firstly, the models simulate no fertility stress, diseases or plagues, which in reality do occur. Secondly, the models simulate dry yield while literature values are normally presented as fresh yield. To translate the fresh yield to dry yield the simple relation of *Raes et al.* (2012) is used, which states that the dry weight is approximately a quarter of fresh weight. In reality this depends on the water

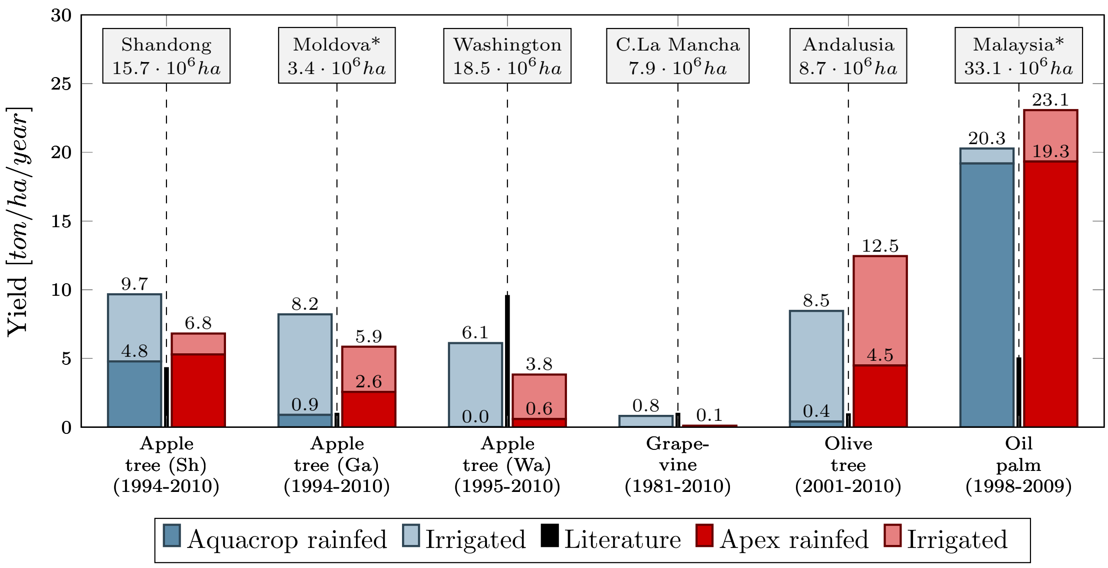


Figure 4.1: The average full-grown yields for the plants considered in this study. The x-axis shows the plant and the years in the simulation that the plant is considered full-grown. The literature values are as location specific as possible; the grey text boxes above the values show the region on which they are specified. Locations with an asterisk (*) are on a country level, the rest is on a province level.

content and the density of the fruit, causing a large uncertainty in the correctness of the literature values presented here. Furthermore, the values of the models are point locations while the literature values are regional averages, which can create deviations. Local climate and especially soil conditions might be different, causing different yield values. Also, the management in an orchard might be different than the simulated management. This applies to irrigation and fertilization, but also the density of the orchards and the cultivar that is grown.

For the apple tree in Washington, the literature yield is quite a lot higher than the simulated values. Besides the uncertainties already mentioned, also the development of the country might play a role here. In a developed country as the USA it is likely that the management is very close to optimal. There will be enough pesticides and fertilizers available to limit the stresses from these, and the water stresses will be limited due to advanced irrigation practices. Furthermore, densely planted cultivars might occur with a very high yield. Also for the grapevine it is visible that the literature yield is higher than the simulated yields, but here it is most likely the simulation rather than the literature that causes this deviation; the low harvest index in combination with the yearly accumulation of biomass results in a relatively low yield.

4.1.2 Average evapotranspiration rates

The average evapotranspiration rates for the full-grown plants are given in figure 4.2. A similar figure is given as with the yield, with the values for both rainfed and irrigated conditions in combination with literature values.

When we compare the evapotranspiration of the full-grown plant between the models, the similarity under rainfed conditions is directly visible. Because the water input into the model, which is only the precipitation, is exactly the same and because the potential evapotranspiration in Aquacrop is derived from Apex, the evapotranspiration values are closely related. Some minor differences between the models occur, partly caused by the parametrization of Aquacrop. This results in a potential evapotranspiration in Aquacrop that is slightly lower than the input evapotranspiration retrieved from Apex. Furthermore, the evapotranspiration processes differ greatly between the models, see chapter 2. This causes large differences in the underlying variables evaporation and transpiration and is therefore also visible in the evapotranspiration. Note that for the rainfed grapevine, the evapotranspiration is almost exclusively evaporation as the plant hardly grows due to high water stresses.

Under irrigated conditions, the evapotranspiration rates lie further from each other. For all except

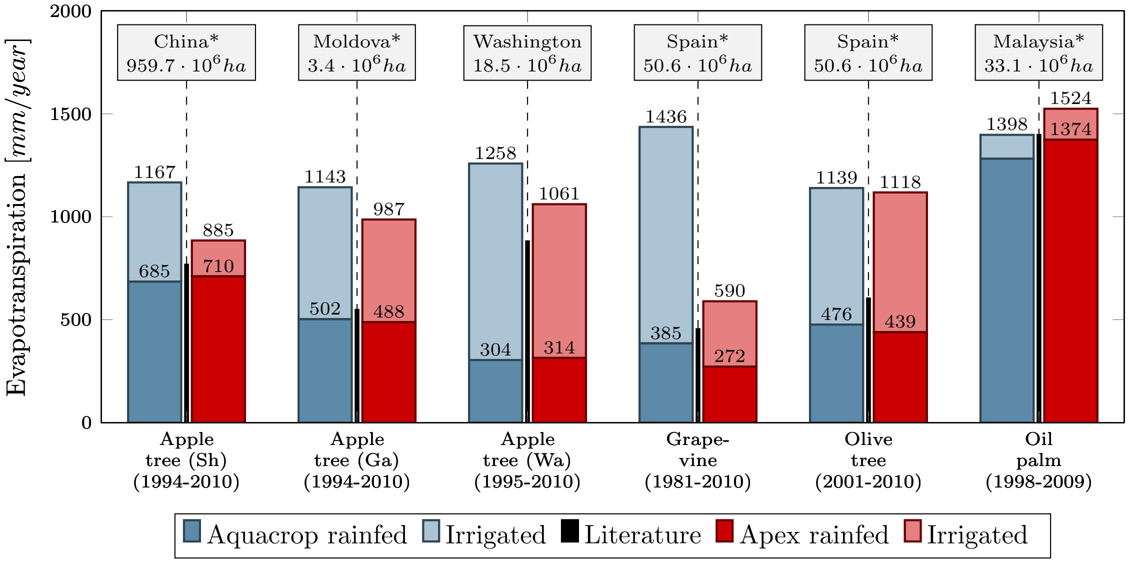


Figure 4.2: The average full-grown evapotranspiration rates for the plants. The x-axis shows the plant and the years in the simulation that the plant is considered full-grown. The literature values are as location specific as possible; the grey text boxes above the values show the region on which they are specified. Locations with an asterisk (*) are on a country level, the rest is on a province level.

the oil palm, the evapotranspiration is higher in Aquacrop. The differences between the models have to do with two processes. Firstly, the irrigation rigger differs between the models. In both models, irrigation water is applied to prevent water stresses in the plant. In Aquacrop, this irrigation is triggered at a certain depletion of the soil, which in practice results in an evapotranspiration that is about equal to the potential one. In Apex irrigation is triggered when water stress in the plant occurs, which results in a transpiration, thus not the whole evapotranspiration, that is about equal to the potential one. Secondly, the irrigation water in Aquacrop becomes available for both the evaporation and the transpiration. In Apex something else happens; when irrigation is applied, the evaporation is hardly affected. This is probably caused by the fact that evaporation in Apex consists of soil evaporation, litter evaporation (intercepted rainfall) and snow evaporation. While the model output gives only the total evaporation, it seems that the irrigation water only contributes to the soil evaporation, leaving the other two components untouched. Evaporation from litter and snow form a major part of the total evaporation, causing the total evaporation to be hardly affected by irrigation water. The irrigation thus almost exclusively contributes to transpiration alone.

Comparing the evapotranspiration rates from the models with literature vales, it becomes visible that there is a lot of resemblance. The literature values lie between irrigated and rainfed evapotranspiration. This makes sense, as a region will probably have both irrigated and rainfed orchards of a certain plant. The arguments for the literature values of the yield also apply here, and deviations from literature can thus occur because of different management practices and differences in location.

4.1.3 Concluding

In the previous two sections, the average yields and evapotranspiration rates of full-grown plants were presented, together with an explanation for the differences and similarities between the models. These explanations could all be traced back to either the parametrization of the plant, the underlying simulation processes in the models or the input into the models. Table 4.1 summarizes the similarities and differences, including their causes.

Table 4.1: An overview of the similarities and differences in the simulation of full-grown yields and evapotranspiration rates. The causes can be traced back to parametrization of the models, the processes in the models or the input.

Similarity or difference	Cause
The models show a very similar yield pattern between plants	Parametrization
Aquacrop and Apex show a similar response on temperature	Parametrization, processes
Aquacrop responds stronger on water stress than Apex	Processes
Sometimes highest yield for Aquacrop, other times for Apex	Parametrization, processes
Apex shows a very low yield for the grapevine	Parametrization, processes
Large differences occur with the literature yield	
Aquacrop and Apex show almost the same rainfed evapotr.	Input
Large differences can occur in irrigated evapotranspiration	Processes
Much similarity with the literature evapotranspiration	

4.2 Environmental effects on the full-grown yield and evapotranspiration

Because of climate fluctuations over the plant years, deviations occur from the average full-grown yields and evapotranspiration rates presented in section 4.1. In the first section, this variability of the yield and evapotranspiration is discussed. In the second section, the influence of the other environmental aspect, the soil profile, is discussed.

4.2.1 Climatic variability

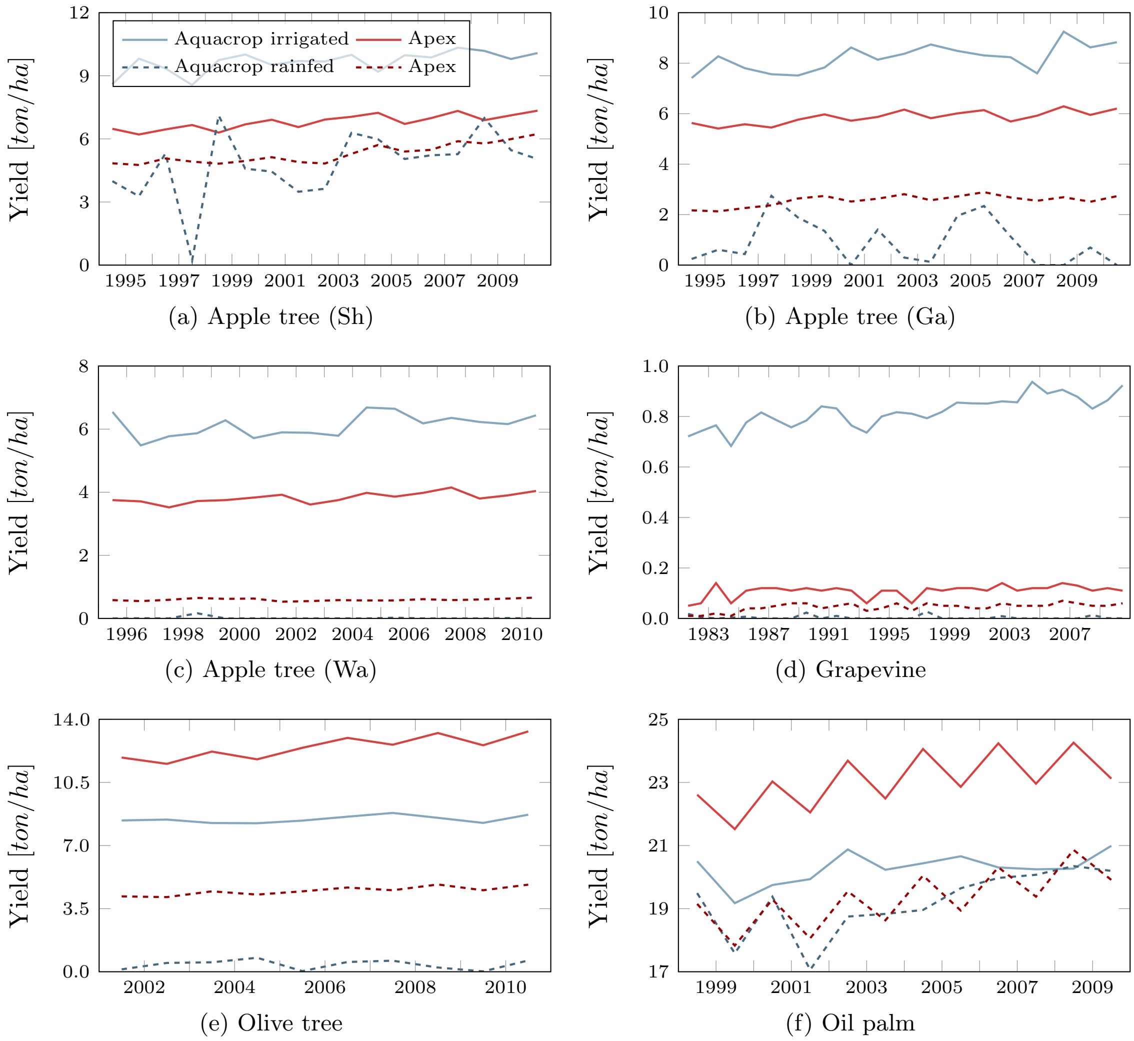
To analyse the climate variability, the yield and evapotranspiration are discussed separately. For this we will look at the average values per plant year, still for the full-grown years alone.

Yield variability

Figure 4.3 shows the variability of yield for the full-grown plants considered in this study. Again, both irrigated and rainfed conditions are shown.

At first sight there does not seem to be any resemblance in the yield variability between the models. This in contrast with the expectations, as for example a relatively warm plant year should influence the yield predictions in both models. However, if we take a closer look at the yield variability and some underlying variables, the influence of climate variability does become visible. To start with, the effect of the atmospheric carbon dioxide concentration is visible in the yield values. Biomass is accumulated easier with higher carbon dioxide concentrations, and higher concentrations will thus result in higher yields. Over the years the carbon dioxide concentrations rise, and the effect of this is clearly visible in Aquacrop. The yields in this model also rise over the years, see for example the apple tree in Gagauzia (figure 4.3b). In Apex also a rising yield is visible, but besides the concentration this is also a result of the lifelong accumulation of biomass. Only for the grapevine this biomass accumulation is not applicable, but there is no real rising trend visible here.

The effect of the temperature is important in the models. First of all, a higher temperature reduces the temperature stress in both models. From this, one would expect some correlation between the yield predictions of the models in figure 4.3. The reason that this is not visible has to do with the fact that this effect is, especially in Apex, overwhelmed by other fluctuations. In Apex, the temperature



(a) Apple tree (Sh) (b) Apple tree (Ga) (c) Apple tree (Wa) (d) Grapevine (e) Olive tree (f) Oil palm

Figure 4.3: The yield variability of the full-grown plants considered in this study. Note the different time-scales between the plants, caused by the fact that the time it takes to become full-grown differs between the plants.

affects the accumulation of heat units, and for reasons not mentioned in the documentation, the heat unit index declines when reaching a certain value or at certain events (harvest). As a result, the heat unit index at harvest can fluctuate over the years, and with this the harvest index and thus the yield. It is especially this undocumented process that is visible in the yield variability of Apex, which is best noticeable for the oil palm in figure 4.3f. The heat unit index at harvest shows a stepwise pattern, and the exact same thing is visible in the yield, both for the irrigated case and the rainfed case.

In Aquacrop the temperature affects the yield in another way. As harvest occurs at a certain amount of accumulated heat units after green-up, a warmer year would result in an early harvest. As a result of this, the next plant year starts earlier, as this starts right after harvest to keep the canopy cover intact through the winters (see chapter 3). This causes the next plant year to be longer and because of this, this plant year will have a higher biomass and thus a higher yield in Aquacrop.

The effect of a fluctuating precipitation pattern is visible for Aquacrop. In rainfed conditions, lower precipitation in a plant year will not directly result in a lower yield, but a lack of precipitation at the right time will. It is thus not the amount of precipitation that is important, but rather the timing and distribution over the year. This will influence the soil-moisture content in the soil-water balance and can create water stress at moments that a plant cannot have much. This is for example visible for the apple tree in Gagauzia (figure 4.3b), where many years are characterized by zero biomass and thus zero yield. This is caused by a too low soil-moisture content at the very beginning of the plant year, from which the plant dies right away. If the green-up date would have been later in the year, the plant might still have grown. Furthermore, also the soil-water content during the plant year is relevant, which is for example visible for the apple tree in Shandong (figure 4.3a). The year 2006 is one of the driest years for the full-grown tree. However, as the lack of precipitation occurs mainly in the winter, the soil-moisture content is high enough in the summer to limit the amount of water stress. This in contrast with 1997, which is also a dry year but is characterized by a low summer precipitation and soil-moisture content. As a result, there is hardly any plant growth taking place and a near zero yield marks this year. The precipitation of course also affected the water stress in Apex. However, the lifelong biomass accumulation limits the influence within a plant year. Also the dominant effect of the heat unit index on the yield causes the yearly effect of precipitation to remain unseen.

In Apex, there is also the effect of a fluctuating solar radiation. However, for the same reasons as with the carbon dioxide concentration and the precipitation, the effect of this is invisible. A slight correlation between the solar radiation and the biomass accumulation is only visible for the grapevine.

Evapotranspiration variability

In figure 4.4 the variability of the evapotranspiration is visible. In contrast with the yield variability, both models show a very similar trend in the evapotranspiration rates over the years. In rainfed conditions the evapotranspiration rates lie closer together as in irrigated conditions, because of the fact that the irrigation trigger and the irrigation amounts differ.

When we look at the effect of the climate variables on the evapotranspiration variability, there are two variables that cause the resemblance in evapotranspiration variability visible in figure 4.4. Firstly, the temperature has a major effect on the evapotranspiration. In the models, this effect has two sides. The direct effect is that a warm plant year will have a high evapotranspiration rate, because of the positive relation between temperature and evapotranspiration. The indirect effect is that a high temperature will shorten the plant year, because of the use of heat units. This causes a relative large fraction of the plant year to fall in the summer months, where the evapotranspiration is highest. This increases the average evapotranspiration. In irrigated conditions, it is the temperature that causes the variability we see at the plants.

The second variable that influences the evapotranspiration is the precipitation. For the irrigated plants, the precipitation is only important for the distribution of evaporation and transpiration in Apex, as intercepted rain by the leaves causes the evaporation to go up and the transpiration to go down. For the rainfed case it is much more important, as the evapotranspiration that can take place depends on the water availability. More available water will result in a higher evapotranspiration. However, a change of precipitation will not directly cause a similar change in evapotranspiration. Just as with the yield, also the timing and distribution of the rainfall is important. Precipitation in winter will only have a limited effect on the evapotranspiration, as the potential evapotranspiration is limited because of the temperature. At the same time, intense rainfall events cause overland runoff,

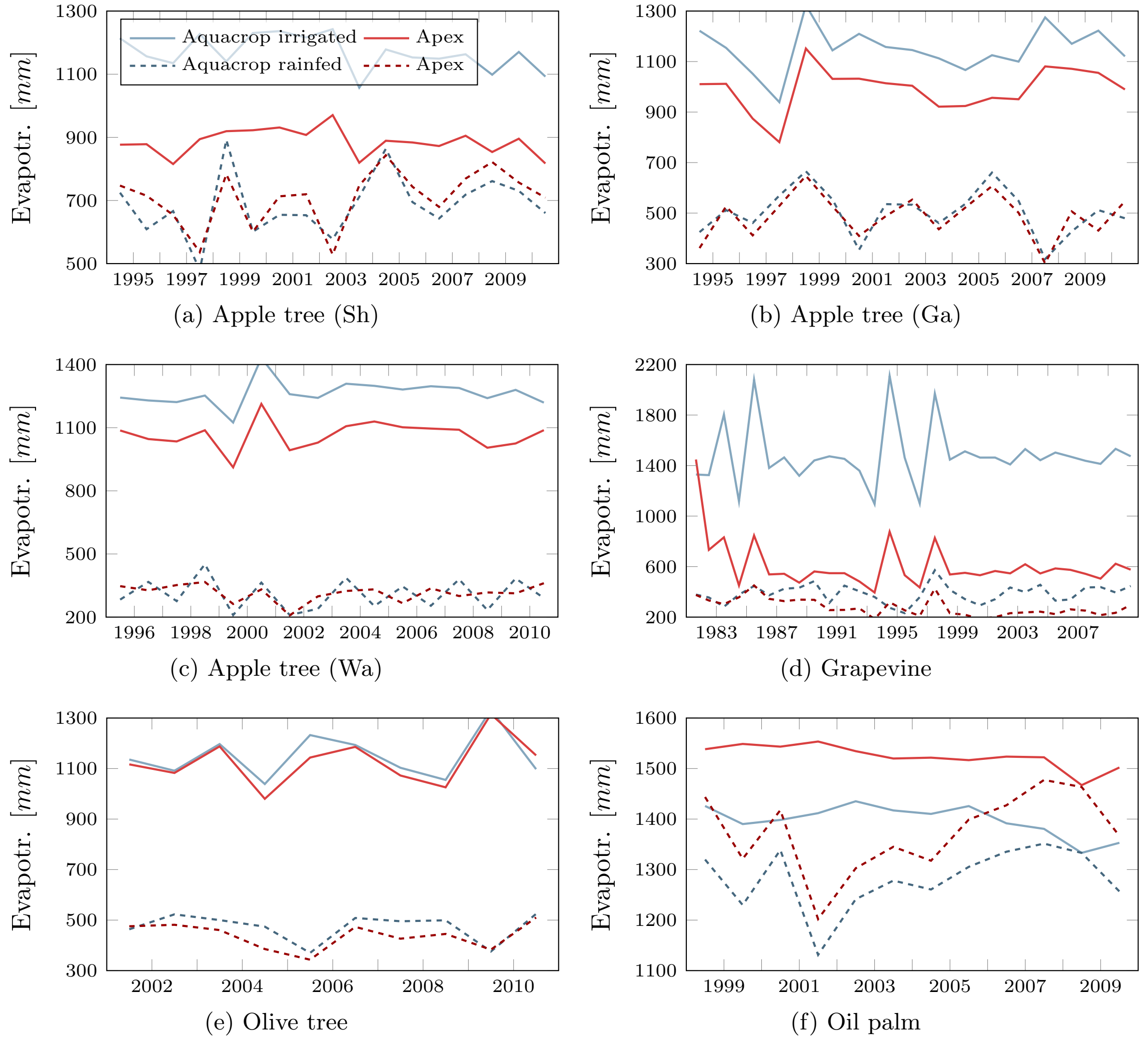


Figure 4.4: The variability of the evapotranspiration rate for the full-grown plants considered in this study. Just as with the yield variability, also here the time-scales differ between the subfigures.

without affecting the evapotranspiration much. In the rainfed cases in figure 4.4, it is the combined influence of the temperature and the precipitation that influences the evapotranspiration rates.

Although solar radiation also influences the potential evapotranspiration rate in Apex and thus the reference evapotranspiration in Aquacrop, the evapotranspiration function used in this study, the Hargreaves function, uses the clear day radiation, without considering the cloud cover. As this is only a function of the day of the year and the latitude, this will not change over the years and is thus irrelevant for the evapotranspiration variability.

4.2.2 Influence of soils

The influence of the soil profile on the simulated yields and evapotranspiration rates is relevant for rainfed conditions only, although minor differences can occur in irrigated conditions as well. The influences of different soil profiles as a percentage of the original yield and evapotranspiration is given in table 4.2.

Looking at the table, the first thing that can be noticed is that Aquacrop responds more strongly to a changing soil profile than Apex, especially for the yield. This is caused by the water stress in a similar way as the climatic variability affected the yield. In Aquacrop a small change in soil-water content can have large consequences for the yield. The water stress consists of many components, and in each of these components the change can cause the water content to be just above or below the minimum threshold required for yield forming. In Apex the influence of the soil profile on the yield is

Table 4.2: The influence of the different soils on the yield and evapotranspiration in Shandong under rainfed conditions for the full-grown plants only. The percentage of yield and evapotranspiration with regard to the original soil is shown. The soil number refers to the topsoil/subsoil combination as given by *De Lannoy et al.* (2014).

	Yield		Evapotranspiration	
Soil layer	Aquacrop	Apex	Aquacrop	Apex
224/55 (original)	100.0	100.0	100.0	100.0
8/8	86.2	100.9	101.3	100.5
234/234	88.3	89.9	88.3	91.2
82/172	84.4	98.9	97.8	99.0

limited, because (a) the water stress reduces gradually and is not characterized by these thresholds, because (b) Apex uses a minimum stress factor composed of also temperature stress and aeration stress and water stress is the limiting factor only in less than half of the simulation days, and because (c) the stress only limits the growth of a plant and does not stop it. With a changing plant also the transpiration is affected, but because this is compensated by a change of evaporation, the change of evapotranspiration is limited.

The second thing that can be noticed is that soil type 8/8 shows an increase of yield and evapotranspiration compared to the original soil for Apex. In Aquacrop, however, the evapotranspiration increases while the yield decreases. Looking at this soil profile we see an increase of both field capacity and wilting point in relation to the original profile, but the field capacity rises more than the wilting point. As a result, the distance between field capacity and wilting point increases. To keep the water content at the same point between field capacity and wilting point, more water is required. This water requirement for the evapotranspiration and thus the yield is determined by the infiltration (input) and the drainage (output). In Aquacrop this amount of water cannot be provided as the infiltration is low. In this model, infiltration is determined by both the curve number and the saturated hydraulic conductivity of this soil profile. In Apex the infiltration is only determined by the curve number and is therefore relatively high. For this reason the relative water content in Aquacrop decreases while the relative water content in Apex increases. As a result, a similar pattern is visible in the yield. The evapotranspiration in Aquacrop rises because the decrease in transpiration is compensated by a larger increase of evaporation.

4.2.3 Concluding

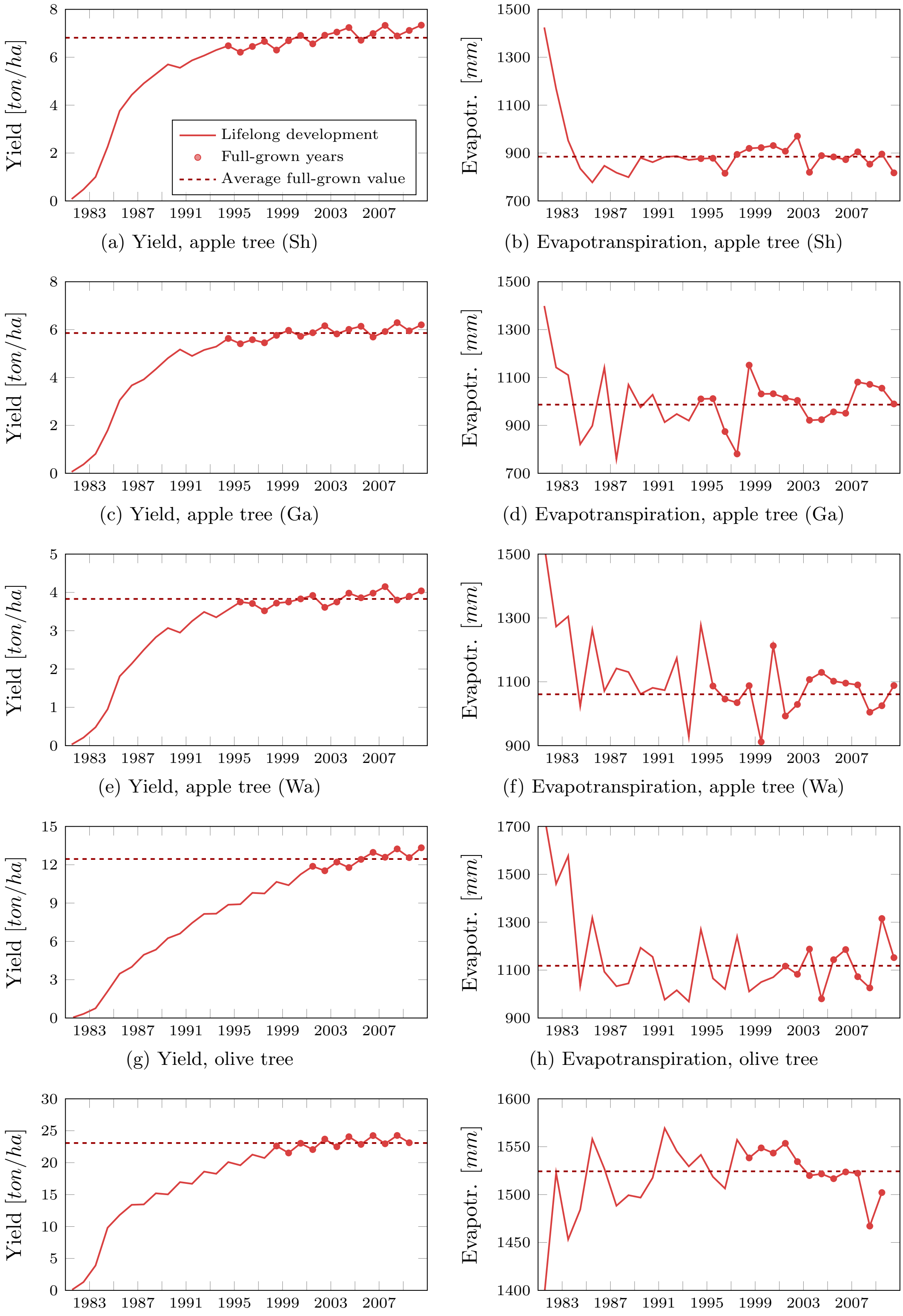
In section 4.2 the variability of the yields and evapotranspiration rates as a result of the fluctuating climate has been discussed. Also the effect the soil conditions have on the models is explained. In table 4.3 the effects of the climate and soil conditions are summarized.

Table 4.3: An overview of the effect of the climate conditions and soil conditions on the yields and evapotranspiration rates in Aquacrop and Apex.

Environmental condition	Effect on models
Carbon dioxide conc.	Affects yield, but in Apex overwhelmed by heat unit index
Precipitation	Can affect yield and evapotranspiration when rainfed
Temperature	Affects yield and evapotranspiration
Solar radiation	Affects yield in Apex, but overwhelmed by heat unit index
Soil profile	Affects Aquacrop more than Apex when rainfed

4.3 The influence of plant development and the water footprint

Before a plant reaches its full-grown yield and evapotranspiration rate, it experiences a period in which the yield and evapotranspiration develops. This development, and more specifically, the importance of this development in the calculation of the water footprint, is examined here.



(a) Yield, apple tree (Sh)
(b) Evapotranspiration, apple tree (Sh)
(c) Yield, apple tree (Ga)
(d) Evapotranspiration, apple tree (Ga)
(e) Yield, apple tree (Wa)
(f) Evapotranspiration, apple tree (Wa)
(g) Yield, olive tree
(h) Evapotranspiration, olive tree
(i) Yield, oil palm
(j) Evapotranspiration, oil palm

Figure 4.5: The Apex simulation of yield and evapotranspiration growth towards the full-grown years. Grapevine is left out of this figure, as this plant is simulated as full-grown the whole period (see figure 4.3d). The simulations are all irrigated.

In figure 4.5 an overview is given of the development curve found in Apex. During the 30 years of simulation in this study, the yield grows towards a certain equilibrium as a result of biomass growth that follows a similar pattern. However, the time it takes for a plant to become full-grown differs. The apple trees reach their full-grown phase quite fast, while the olive tree is still developing at the end of the simulation period. The oil palm lies in between these. The different lengths of the development phases are probably caused by a different parametrization, although this cannot be traced back to the documentation of Apex. Because of the development phase, the lifelong average yield, which includes the yield in this development phase, is lower than the yield of a full-grown plant. It is worth noticing that in reality, in contrast with what Apex shows here, the yield does not continue to increase over a plants life. At some point the productivity of a tree reaches an optimum, where after the yield slowly decreases (see for example *Flore et al.* (1984)).

The evapotranspiration also shows development over a plants life. As can be seen in figure 4.5, the first few years show a different evapotranspiration rate. In these years, where the leaves still develop, the distribution of evapotranspiration over evaporation and transpiration changes. With the leaf area growing, the amount of evaporation decreases while the amount of transpiration increases. As the evaporation declines more than the transpiration inclines, the initial years are characterized by a higher evapotranspiration. For the oil palm it is the other way around, as the transpiration increases more than the evaporation decreases. Because this initial anomaly is short in time and because the evapotranspiration is much more variable in general, the lifelong average evapotranspiration rate deviates only little from the average evapotranspiration rate of the full-grown tree.

Figure 4.6 shows the ratios between the lifelong results and the full-grown results. These factors show the importance of the development phase and can be used to adjust the results of a simulation for the full-grown period only to the lifelong results. As can be seen, the yield has a factor that is well below one, meaning that the lifelong yield is indeed lower than the full-grown yield. The evapotranspiration factors for the plants considered in this study only slightly deviate from one. When simulating yields of full-grown plants, the figure shows the relevance of correcting these to the lifelong average results. For the evapotranspiration this is not necessary, as the lifelong results are practically equal to the full-grown evapotranspiration rates.

Knowing the importance of the development phase on the yield and evapotranspiration, the water footprint can be calculated by using this factor to correct the yield of Aquacrop to include the development phase as well. For the water footprint calculated for Apex no factor is applied, as the lifelong average evapotranspiration and the lifelong average yield can be directly used from the model. In figure 4.7 the water footprints are calculated for all plants considered in this study. Note that the water footprint calculation requires fresh weight; to convert the dry weight from the models to fresh

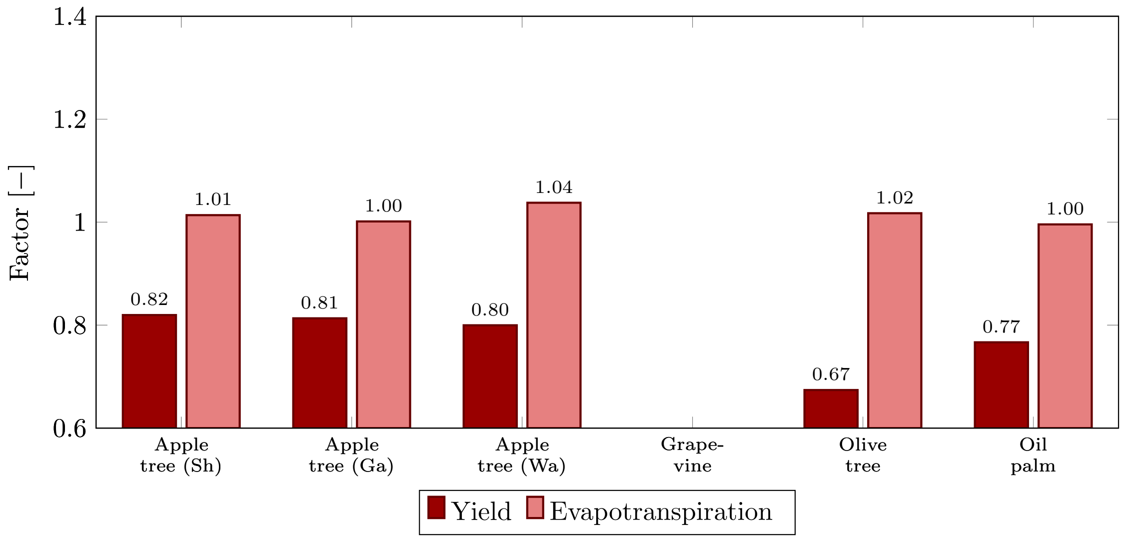


Figure 4.6: The factors that relate lifelong results with the average values for yield and evapotranspiration. Note that grapevine is not considered as this plant is simulated in Apex as full-grown the whole period. The factors are derived for irrigated conditions.

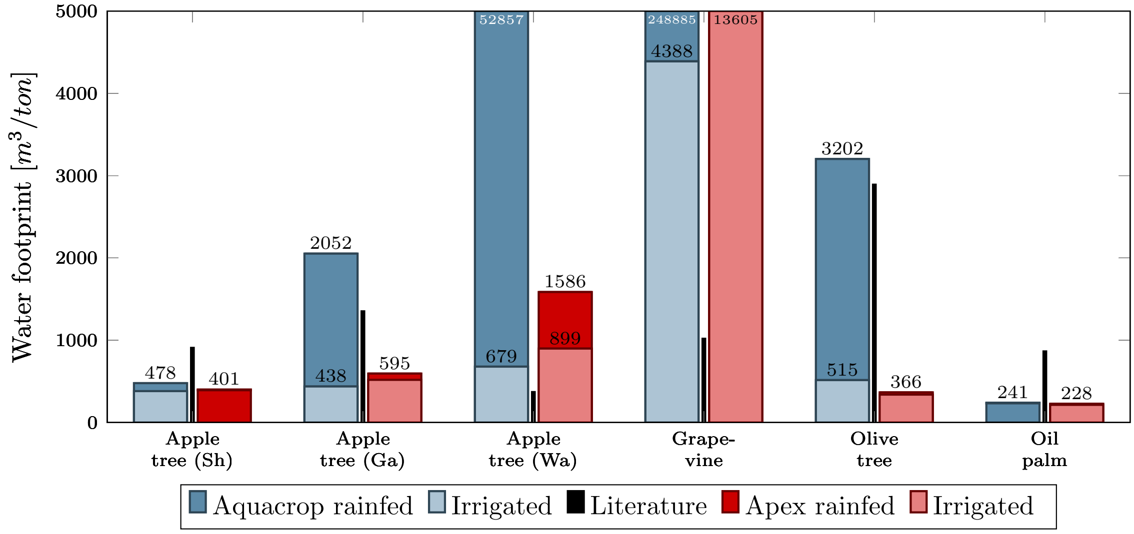


Figure 4.7: The water footprints of the plants considered in this study, both in rainfed and irrigated conditions. For Aquacrop, the factor from figure 4.6 is used to get lifelong yield, the grapevine has a factor 1. For Apex, no factor is applied. The literature values are on a province level, except for the apple tree in Moldova. The literature values are retrieved from *Mekonnen and Hoekstra* (2010).

weight, all yields are multiplied by a factor four (*Raes et al.*, 2012).

As can be seen in the figure, the rainfed water footprint is almost always higher than the irrigated water footprint. This might seem unnatural, but as the yield can be much lower in rainfed conditions than in irrigated conditions, the water footprint can be much higher. One might wonder the usefulness of the rainfed water footprint in this case, as the high water stress can result in very low yields. The resulting water footprint can be very large or even infinite. For the grapevine, it can be seen that the water footprint is also very large in irrigated conditions, caused by the low yield of the plant. This raises questions about the correct implementation of the grapevine in the models.

In general, the performance of the models is quite alike for irrigated conditions, but can differ tremendously in rainfed conditions because of the differences in yields between the models. The difference with literature can be large, caused by the deviation between the simulated yield and the literature yield that lies at the foundations of the water footprint calculations.

Chapter 5

Discussion

The methods and the models are discussed in the coming sections. First, the performance of woodies in Aquacrop and Apex is discussed, where after the difference between this study and literature is discussed when simulating a woody plant in Aquacrop. Finally, the applicability of this study for other studies is described.

5.1 The performance of woodies in Aquacrop and Apex

The results of Aquacrop and Apex can differ quite a lot. When rainfed, the evapotranspiration is quite alike but the yield can differ tremendously because of the difference between the models in simulating water stress. When irrigated, the evapotranspiration rates lie often far from each other because of a different simulation of irrigation water.

These different results are striking, but unfortunately there is no such thing as a reference that state the correct value and help us decide which model is 'good' and which model is 'bad'. The difference does not have to be a flaw of the implementation of woodies in Aquacrop and can be just as easy be a problem in Apex. It is exactly this uncertainty that makes it hard to draw solid conclusions from the results. What does help is the further analysis that identifies some ordinary behaviour in especially Apex. The yield in this model is mainly driven by the variable heat unit index, which can show for a full-grown tree very conspicuous behaviour. Also the distribution of irrigation water to almost exclusively the transpiration is something that is questionable for Apex. On the other hand, the sensitivity of Aquacrop for the soil water content, where a small difference can lead to large changes in the biomass and the yield, might be realistic for herbaceous plants. For woody plants the stress effects are however more limited (*Steduto et al.*, 2012).

Thus both models seem to have limitations, but on top of that there is also uncertainty in the parametrization in both models. In Aquacrop, one of the main consequences of only simulating the foliage is the adjustment of the harvest index. However, in this study this is taken very roughly as a factor four of the normal harvest index, as the weight of the total biomass is approximately a factor four of the foliage. But of course this can differ tremendously between plants. Furthermore, the canopy cover in Aquacrop is derived from the leaf area index of Apex in order to harmonize the models, but the relation used is based on herbaceous plants and its applicability on woodies is rather uncertain. If the parameter assumptions prove to be incorrect, a very different yield and evapotranspiration might be the result. At the same time also Apex has problems in the parametrization, which become visible for especially the grapevine. This plant is simulated as a shrub rather than a tree, resulting in a yearly, instead of lifelong, accumulation of biomass as if it is a herbaceous plant, which seems very unrealistic. Also the parametrization of trees is doubtful, as plants as the oil palm or the olive tree, which are evergreen plants according to literature, are parametrised as deciduous plants in Apex.

In short, there are large uncertainties in both models. The method to simulate woodies in Aquacrop does not seem to be inferior to the simulations of woodies in Apex.

5.2 Comparison of Aquacrop simulation with literature

The implementation of woody plants in Aquacrop is rather different as the studies so far, although the number of studies that simulate woody plants with Aquacrop is limited. *Hunink and Droogers* (2010) and *Hunink and Droogers* (2011) estimated the parameters regarding the planting date, the harvest date, the harvest index, the canopy cover and the management based on reasoning and literature. *Zhuo et al.* (2016) set the properties planting date, harvest index, rooting depth and the length of different growth stages based on literature. All of these studies do not discriminate between herbaceous plants and woody plants; only the parameter values differ between the plants.

This study proposes an alternative method to simulate woodies. Of course, a number of parameters should be selected for the different plants, in this study mainly based on the parameters of Apex for harmonization between the models. However, by keeping the canopy cover intact through the winter, by increasing the harvest index to account for the foliage weight only and by choosing a constant rooting depth corresponding to that of a full-grown woody, a few fundamental differences in parameter settings and model use occur between the studies so far and the simulation of woodies in this study.

The relevant question is, of course, if this different approach leads to truly different yield, evapotranspiration and resulting water footprint values. Fortunately *Zhuo et al.* (2016) made their Aquacrop plant file for the apple tree available for this study. They used the method described by *Hoekstra et al.* (2011) to calculate the water footprint, which would mean that for perennial plants, as the apple tree is, the yield and evapotranspiration is averaged over the complete life of the plant for the calculation of the water footprint. So this is the evapotranspiration rate from the first planting date up to the last harvest date, although during the time between harvest in one season and planting in the following season no plant grows. For the yields these are just the average yields at harvest.

When using the original plant file of *Zhuo et al.* (2016), which was used for the Yellow River Basin in China, for the Shandong point simulation of in this study under irrigated conditions, an average lifelong yield for the period 1981 to 2010 of 3.4 ton/ha is retrieved, against 9.3 ton/ha in this study. The evapotranspiration for *Zhuo et al.* (2016) is 1017 $mm/year$, against 1165 $mm/year$ in this study. Especially the difference in yield is very large, which would have a great effect on the water footprint.So the method proposed here leads to very different results than the method used by *Zhuo et al.* (2016). Note that the original file of *Zhuo et al.* (2016) is used here, without any changes. This results in, among others, a different growing method (in days instead of heat units), a different rooting depth, a different harvest index, a different canopy development and different temperature preferences. This explains the large difference in yield and evapotranspiration.

Because of the differences in parametrization, large deviations in the resulting yield and evapotranspiration are not surprising. To analyse only the effect of the rooting depth and winter canopy on woodies, another simulation of Aquacrop is done. The plant file used in this study is simulated again, but now without the constant rooting depth and without the winter canopy. This again under irrigated conditions. With this, a yield is found of 8.5 ton/ha instead of the 9.3 ton/ha in the original simulation. The evapotranspiration is now 981 $mm/year$. As can be seen, the difference in yield is smaller, but the difference in evapotranspiration increases. The woody set-up, without changing the rest of the parameters, thus leads to different yields and evapotranspiration values.

5.3 Applicability of methods and results

In this study only four plants are tested on a field level. To draw solid conclusions of the performance of Aquacrop and Apex, a wider analysis is required. Ideally, a comparison to measured yields and evapotranspiration rates is made for an orchard from which the management and plant conditions are known. The local plant density, the canopy cover and leaf area index, but also the weight of the foliage in comparison to the whole aboveground biomass are properties that are assumed in this study without much certainty. When these properties can be measured, a better estimate of the parameters for the trees and shrubs can be made. With this, a very good comparison between simulated yield and evapotranspiration and measured yield and evapotranspiration can be made. It would then also be unnecessary to derive parameters from Aquacrop from Apex and the other way around. Instead of setting up the models such that Aquacrop and Apex are as much alike as possible, the models will both be set-up to simulate the considered orchard as good as possible.

More plants should be simulated in combination with a grid-based study to make a more comprehensive comparison between the models. More climate and soil conditions can be simulated, and the performance of the models for a wider range of plants can be analysed. Also a better comparison with literature is then possible, as these values are mostly available on a country or province scale.

With an expansion of this study to make a more comprehensive comparison with literature and to draw more solid conclusions on the simulated yields and evapotranspiration rates, more confidence of the performance of the two models is gained. This study forms the basis for such a more comprehensive study. Future studies benefit from this as they can make a more reliable simulation of woodies.

Chapter 6

Conclusions & recommendations

By selecting four important woody plants, the apple tree, the grapevine, the olive tree and the oil palm, and simulating them on the locations in the world where they are cultivated most, Aquacrop and Apex are compared in their simulated yields and evapotranspiration rates under different climatic and soil conditions. To simulate woodies with Aquacrop, for which the model is not designed, Aquacrop has been set-up to simulate only the annual foliage development of a full-grown tree. The model set-up and parametrization of Aquacrop and Apex are harmonized in order to make a fair comparison possible.

6.1 Conclusions

For full-grown woody plants, Aquacrop and Apex show roughly the same yield and evapotranspiration patterns over the different plants. Both Aquacrop and Apex show in irrigated conditions the highest yield for the oil palm and the lowest yield for the grapevine. In rainfed conditions, the evapotranspiration rates between the models are closely related. When we look at specific plants, however, large differences can be observed between the models, caused by differences in the input, the parametrization and the simulation of processes. The response of the models to different temperature regimes is comparable, but the influence of water stress in the models is very different. In Aquacrop the simulated yield can be reduced a lot from only a small increase of water stress, while Apex is still able to produce a rather high yield even under severe water stress. When we look at the evapotranspiration, it is observed that the irrigation water contributes to both evaporation and transpiration in Aquacrop, which is realistic for the sprinkler type irrigation used in this study. In Apex, however, irrigation almost exclusively contributes to transpiration alone. When we compare the evapotranspiration rates with literature values, the literature always lies between the rainfed and the irrigated evapotranspiration, which makes sense as a country would have both rainfed and irrigated orchards. Compared to literature, the models however overestimate the yields for most plants.

The climatic influence in the models on the evapotranspiration is very similar. An increase in temperature or available water leads in both models to an increase of evapotranspiration, which is logic behaviour if we look at the evapotranspiration function. Looking at the yield, Aquacrop shows fluctuations that correspond to the climatic variability, although the effect of the woody set-up applied in this study becomes visible. The yield fluctuations in Apex are driven completely by a model variable that shows very erratic behaviour, not corresponding to any of the climatic variables. In underlying variables in Apex there is correspondence with climatic variables. The influence of the soil profile on the simulated yields and evapotranspiration rates are quite different, caused by the rather strong response of Aquacrop to a changing water stress.

To calculate the water footprint, the lifelong average yields and evapotranspiration rates should be known. This includes the full-grown years, but also the years in the beginning of a plants life where the plant is still developing. The effect of this development phase can be analysed with Apex. For the evapotranspiration this development is negligible. When we look at the yield, however, the development phase causes a decrease of about 20 percent in the lifelong average yield compared to the full-grown yield. Knowing this, the water footprints can be calculated for the plants in both models. These water footprints are quite similar between the models in irrigated conditions, but the differences in rainfed conditions can be large. Also the difference with literature values can be large, caused by the yields underlying the water footprint values.

At first sight the performance of the models is rather similar. However, when taking a closer look large differences can be observed. The causes of these differences lie in both Aquacrop and Apex. Comparing the results of Aquacrop, Apex and literature, it cannot be stated that one model is better than another. But from this study, Aquacrop does not seem to be inferior to Apex when simulating woodies, despite the fact that it is not designed for this.

6.2 Recommendations

This study forms the basis for a more comprehensive comparison between Aquacrop and Apex. Further study should focus on expanding the scope, firstly by including more plants. In this study three broadleaved trees and a broadleaved shrub were simulated.In addition more trees and especially more shrubs, both broadleaved and needle-leaved, should be simulated. Secondly, a grid-based simulation of plants should be done in order to make a better comparison to literature. The differences between literature and the simulated values of especially the yield and water footprint are large, but as these values are often available on a province or even a country level, it is difficult to say whether the differences are caused by the simulation processes or by the scale differences. A more comprehensive grid-based study will avoid these scale differences.

Besides the expansion of the scope, a case study is recommended to analyse the performance of the models. This will not only allow for a better comparison with external data, but this study can also be used to find better values for the parameters in the models. Parameters as the harvest index, the canopy cover and the leaf area index are important for the resulting yield and evapotranspiration, but their values are uncertain. The harmonization in this study caused the models to be comparable to each other, but did not result in an optimal setting with respect to literature. With a case study the important parameters can be estimated independently for Aquacrop and Apex and a better comparison between the models and with external data is possible.

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Appendix A

Technical information

This appendix provides detailed information about the set-up for both Aquacrop and Apex. The aim of this appendix is that it should provide all the necessary information to reproduce the simulations of this study. This is important not only for checking the results, but also to allow future users of Aquacrop or Apex in this field of study to use the methods proposed here. This appendix does not provide a full explanation of the two models; it is meant as a study specific addition to the model documentation provided by *Raes et al.* (2012) for Aquacrop and *Williams et al.* (2012) and *Steglich and Williams* (2013) for Apex.

There is no space to explain all the decisions that where taken when setting up the models. This namely involves the allocation of hundreds of parameters, many different paths that are taken which proven to be a dead end and considerations about fundamental different approaches. Nevertheless, an attempt is made to explain the most important decisions as much as possible.

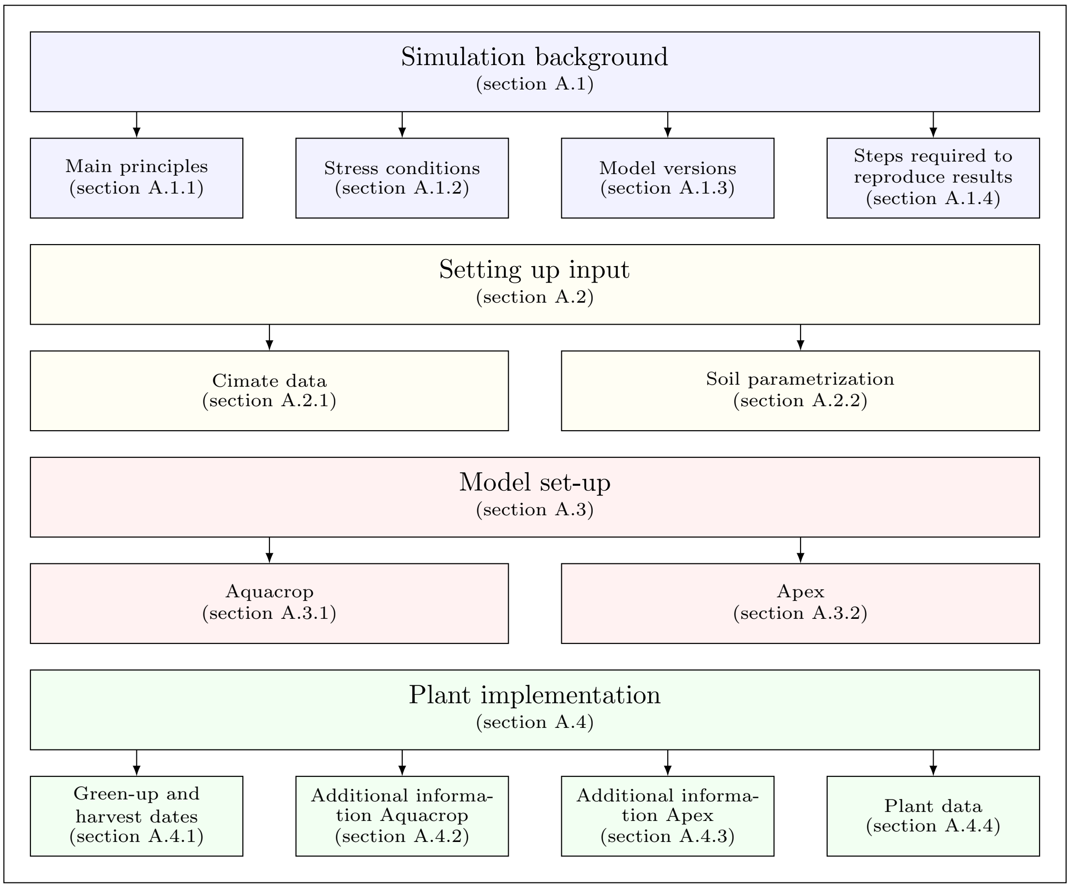


Figure A.1: An overview of the appendix.

To guide the reader through the information, an overview of this appendix is given in figure A.1. The appendix starts with some important background information that is required to understand the decisions made for the set-up chosen here. This includes the main assumptions and the stresses that are being considered. Furthermore, information is provided about the model versions used in this study and the steps that are ought to be taken to come to the result. Following this, the properties of the input are explained, both for the climate data and the soil parametrization. Hereafter, the general set-up of the models is explained. This section is concerned with the set-up that stays the same throughout all the simulations, independent of plant type, location or time. Finally, the set-up which is plant, location or time dependent is explained.

In this appendix, the symbology for parameters is as much as possible equal to the original ones used in the models. This in contrast with the rest of this document, where alternate symbols were used due to the fact that both models use different symbols for the exact same parameter.

A.1 Simulation background

To start the technical explanation, some simulation keynotes are given. These are crucial for understanding the decisions made when setting up the model and to reproduce the results of this study.

A.1.1 Main principles

There are two main principles underlying the simulations. These are:

1. Both models simulate on a field-level
2. For the biomass, Aquacrop simulates only the foliage

These two principles have a few consequences.

Simulating on a field-level is standard for Aquacrop. Apex on the other hand is designed for the simulation of complete watersheds with different processes influencing each other. To harmonize the two, Apex is used on a field-level as well. To do so, all the horizontal components in the model are set to zero. By simulating only a single watershed (so that there is no upstream watershed that provides water to the model) with no slope (so that the horizontal outflow is zero) and no horizontal pipe flow (by setting the horizontal pipe flow parameter to zero), this is achieved. Note that, even with the slope at zero, very small horizontal flows where still observed in some simulations. However, these are negligible and also unavoidable.

The second principle has no consequences for Apex. In this model, the plants are simulated as they are found in the model in combination with the model set-up as described later. In Aquacrop, the set-up is also described in the coming sections, but underlying this set-up it is important to realize the consequences of this second principle. Aquacrop is designed to simulate herbaceous plants, which are often annual, and not woody plants, which are always perennial (the difference between annual-perennial and herbaceous-woody is explained in figure A.2). An attempt to simulate the woody plants anyway is done by simulating only the foliage of the plants. This is considered here as the annual part

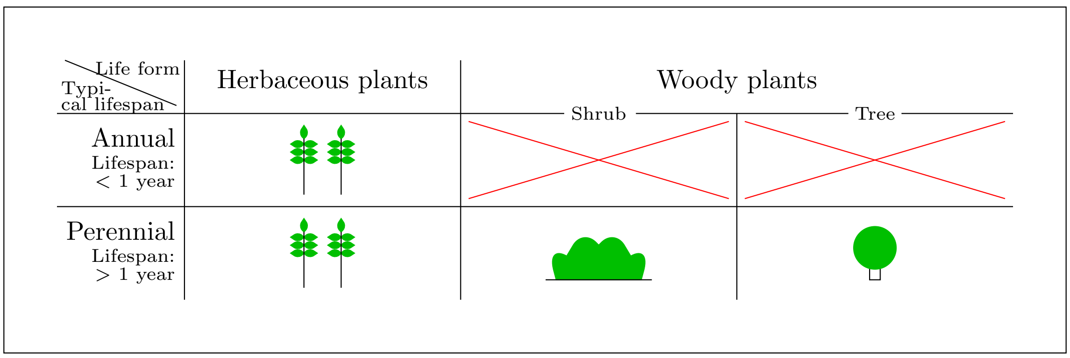


Figure A.2: The relation between the life form and the lifespan of plants. In the life form there are herbaceous plants (no woody content) and shrubs and trees (woody content). Herbaceous plants can be both annual and perennial, whereas woody plants can only be perennial.

Table A.1: All stresses in the models. The crossed stresses are not considered in this study.

Aquacrop	Apex
Water stress	Water stress
Aeration stress	Aeration stress
Temperature stress	Temperature stress
~~Fertility stress~~ → requires calibration	~~Fertility stress~~ → not usable in Aquacrop
~~Salinity stress~~ → requires calibration	~~Salinity stress~~ → not enabled in Apex version
	~~Toxicity stress~~ → not in Aquacrop

of the woody plants. The rest of the biomass, the stem and the major branches, does not develop significant once a tree is mature and in this study this part is assumed constant. As the yield is a direct function of (a) the biomass and (b) the harvest index, the harvest index should be adjusted to be applicable to the biomass of the foliage only instead of on the whole biomass. The other variable that is important in this study, the evapotranspiration, is a function of the canopy cover in Aquacrop. To make a realistic estimate of the evapotranspiration, the whole tree, so the foliage and the standing tree, is included in the canopy cover. In the model set-up the consequences of this will become clear. As only the annual fluctuations of a full-grown tree are simulated, there is no tree growth and thus, if the environmental conditions would be identical every year, the yield and evapotranspiration will also be identical. This in contrast with Apex, where there is tree development and therefore also the yield and evapotranspiration will change during the life of the plant.

Besides these two principles, one more thing can be said about the simulations. The simulations are done with two types of irrigation scheduling, namely with full irrigation (so water stress does not occur) and with no irrigation (so that water stress does occur).

A.1.2 Stress conditions

In table A.1 an overview is given of the stresses the models contain. Aquacrop can simulate water stress, aeration stress, temperature stress, fertility stress and salinity stress. Apex is capable of simulating water stress, aeration stress, temperature stress, fertility stress and toxicity stress from aluminium. The salinity stress component in Apex is not enabled in the version used. Fertility stress and salinity stress in Aquacrop require calibration and are therefore turned off. To harmonize the models, the fertility stress and toxicity stress in Apex should also be disregarded. In Apex, however, a stress cannot be turned off and is simulated by simply avoiding it as much as possible. The exact implications of this are explained later. The stresses applicable on the simulations of this study are thus water stress, aeration stress and temperature stress.

A.1.3 Model versions

Aquacrop can be downloaded from the website of the Food and Agriculture Organization (FAO) of the United Nations (`http://www.fao.org/nr/water/aquacrop.html`). For this study, version 4 of Aquacrop is used. While version 5 came available during this study, it was not used because it contained a new function (hot start) which caused problems with the simulations for this study. Also, the early version 5 gave errors in the user interface when simulation plants using heat units (growing degree days).

For Apex, the simulations were done in version 1501 revision 1604, the latest version available during this study. It can be downloaded from the model website (`http://epicapex.tamu.edu/`). The Apex simulations in this study are all done with the executable version (so not with iAPEX or WinAPEX). One might wonder why Apex is used, and not Epic, its sister model. The choice for Apex has two reasons. First of all, the Epic software (in the form of iEPIC and WinEPIC) gave many errors at the time the model choice was made. In fact, at that time it was not possible to simulate at all with Epic. The download link for the executable version was unavailable at that time. The second reason to choose Apex over Epic is that on the department of the University of Twente, there is more experience with Apex.

A.1.4 Steps required to reproduce results

To recreate the results of this study it is recommended to follow the lines of this appendix. This implies that one should start by creating the required climate data and setting it up for each of the models. To acquire the reference evapotranspiration, which is derived from Apex, it is necessary to apply the general set-up first. After this, the general model parameters can be set and following this the location and plant specific parameters can be chosen for the required simulation. When one is not familiar with Aquacrop, it is recommended to start with the tutorials available on the download website. For Apex such tutorials are not available, but to get a feeling for this model one can use the user guide to go through the different model components.

A.2 Setting up input

The forcing of the models is given by the climatic input and the parametrization of the soil. For the first one, a general description of the data with some small in depth clarifications for each of the models is sufficient to recreate the data. For the soil data, both models are described separately.

A.2.1 Climate data

The climate files required for Aquacrop consist of five files; one main file (extension .CLI) and four subfiles (.TMP, .PLU, .ETo and .CO2) from which the names are saved in the main file. Each of these subfiles contain climate variables on a daily basis. In Apex, there are two files; one file that contains all the daily climate variables (.DLY) and one that contains monthly values (.WP1).

The following climate variables are used in this study:

- Maximum temperature (daily)
- Minimum temperature (daily)
- Precipitation (daily)
- Solar radiation (daily)
- Reference evapotranspiration (daily)
- Atmospheric carbon dioxide concentration (yearly)

The first three climate variables are available from 1958 to 2010. Solar radiation and reference evapotranspiration rates are available from 1981 to 2010. The carbon dioxide concentrations are available on a yearly basis from 1958 to 2014. Knowing this, the maximum simulation period is from 1981 to 2010. The monthly average temperatures, precipitation and reference evapotranspiration for each of the locations during the period 1981 to 2010 are visible in table A.2. Each of the climate variables is explained below.

Maximum & minimum temperature and precipitation

The maximum temperature, the minimum temperature and the precipitation are all retrieved from *De Graaf et al.* (2014). From this global database, data is picked based on the longitude and latitude of the location. The data is available from 1958 to 2010, although only the years 1981 to 2010 are used. Both models require daily values of these three variables. In addition, Apex requires also monthly values of them. More on the derivation of monthly data is explained at the end of this section.

Solar radiation

Apex requires daily solar radiation data for the calculation of biomass. The model can also require net solar radiation for the evapotranspiration calculation, but the Hargreaves function that is used in this study does not require this data (see appendix B).

Table A.2: An overview of the mean monthly values of the maximum daily temperature ($T_{\max}$) in $^{\circ}C$, the minimum daily temperature ($T_{\min}$) in $^{\circ}C$, the precipitation (P) in mm/day and the reference evapotranspiration (ET_{o}) in mm/day per location.

(a) Shandong (China)

Var.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\max}$	2.7	4.9	9.7	16.4	21.8	25.7	27.9	28.0	24.8	19.7	11.9	5.1
$T_{\min}$	-5.5	-3.5	1.0	7.2	12.9	17.6	21.4	21.2	16.4	10.5	3.1	-3.1
P	0.3	0.5	0.7	1.1	2.0	3.1	6.4	5.3	2.2	1.2	0.8	0.4
ET_{o}	1.1	1.6	2.6	4.2	5.4	6.0	5.5	5.2	4.5	3.2	1.8	1.1

(b) Gagauzia (Moldova)

Var.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\max}$	1.3	3.1	8.2	15.5	21.8	25.5	27.8	27.4	21.8	15.4	8.0	2.5
$T_{\min}$	-4.5	-3.6	0.0	5.5	11.0	14.7	16.7	16.2	11.7	6.5	1.4	-3.2
P	1.1	1.0	1.0	1.3	1.5	2.2	1.8	1.5	1.6	1.1	1.2	1.1
ET_{o}	0.5	0.9	2.0	3.9	5.8	6.9	7.1	6.1	3.9	2.1	0.9	0.5

(c) Washington (USA)

Var.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\max}$	3.2	6.7	10.9	14.7	19.1	23.0	27.6	27.3	22.9	15.6	7.7	1.7
$T_{\min}$	-4.3	-3.3	-1.0	1.7	5.6	8.9	11.7	11.1	6.8	1.8	-2.2	-5.7
P	2.1	1.2	0.9	0.6	0.5	0.6	0.2	0.2	0.4	0.8	2.0	2.1
ET_{o}	0.7	1.3	2.5	4.1	5.8	7.1	8.2	7.1	4.8	2.4	1.0	0.5

(d) Castilla-La Mancha (Spain)

Var.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\max}$	11.1	12.9	16.5	18.7	23.2	29.5	34.1	33.4	28.0	21.1	14.9	11.2
$T_{\min}$	0.7	1.9	4.0	6.0	9.7	14.2	17.5	17.5	13.8	8.9	4.5	1.6
P	1.0	1.2	0.9	1.5	1.4	0.9	0.3	0.3	1.0	1.6	1.5	1.5
ET_{o}	1.6	2.3	3.7	5.0	6.8	8.9	10.0	8.6	5.9	3.4	1.9	1.4

(e) Andalusia (Spain)

Var.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\max}$	13.9	14.9	17.4	19.1	22.5	27.2	31.1	31.0	27.5	22.4	17.3	14.4
$T_{\min}$	4.5	5.4	7.0	8.3	11.1	14.7	17.2	17.6	15.7	12.1	8.1	5.8
P	2.2	2.8	1.6	2.0	1.1	0.3	0.1	0.2	0.9	2.0	2.7	3.2
ET_{o}	1.8	2.5	3.7	4.8	6.2	7.6	8.6	7.7	5.6	3.5	2.1	1.6

(f) Johor (Malaysia)

Var.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{\max}$	29.3	30.4	30.9	31.3	31.4	31.1	30.6	30.6	30.6	30.8	30.0	29.2
$T_{\min}$	22.1	22.2	22.3	22.4	22.6	22.5	22.2	22.2	21.9	21.8	21.7	22.0
P	8.2	3.9	6.2	5.8	5.8	4.7	5.0	5.3	4.9	6.3	9.2	13.0
ET_{o}	5.3	6.0	6.4	6.4	6.1	5.8	5.8	6.0	6.3	6.3	5.8	5.1

According to *Allen et al.* (1998), the extraterrestrial daily solar radiation can be calculated according to the latitude and the day of the year. Following the symbols used by *Allen et al.* (1998), this looks like the equation

$$R_a = f(J, \varphi), \tag{A.1}$$

wherein R_a $[MJ/m^2/day]$ is the extraterrestrial solar radiation, J $[-]$ the day in the year and φ $[°]$ the latitude in decimal degrees. In reality, not all of this radiation will reach the earth. This because of clouds, dust, humidity etcetera. For Apex, the net solar radiation is required, which is the radiation corrected for all these factors. The equation for this radiation looks like

$$R_s = \left(a_s + b_s \cdot \frac{n}{N}\right) \cdot R_a, \tag{A.2}$$

in which R_s $[MJ/m^2/day]$ is the solar radiation and a_s $[-]$ the fraction of the radiation that would reach the earth if the sky is covered the whole day with clouds. b_s $[-]$ is the fraction of radiation that reaches the earth surface if there is a clear sky during a certain period of the day. This period depends on n $[hours]$, the amount of sunshine hours on a day and N $[hours]$, the maximum amount of sunshine hours on a day. This last one is also a function of the day of the year and the latitude. The amount of sunshine hours n is obtained from Era Interim and is available from 1981 to 2010 (*Dee et al.*, 2011).

Reference evapotranspiration

The reference evapotranspiration, required by Aquacrop, is calculated with Apex. At each of the locations, the temperature, precipitation and solar radiation is set-up. The resulting potential evapotranspiration is considered as the reference evapotranspiration for Aquacrop. More on this in appendix B. The set-up of the model during these simulations is as the general set-up (see section A.3). A few changes are made. The albedo of the soil is chosen as 0.23 (*Allen et al.*, 2006). The plant simulated is summer pasture, in combination with a land use number of 22, although this does not change the results of the potential evapotranspiration. The sowing date is the first day of January in the first year, which is 1981. The simulation runs from 1981 to 2010.

Atmospheric carbon dioxide concentration

There are also yearly atmospheric carbon dioxide (CO_2) concentrations required by the models. Both models have an embedded database of global atmospheric concentrations, but these databases are not the same. As the CO_2 concentrations of Aquacrop are better accessible, these concentrations are used in both models. The CO_2 concentrations in Aquacrop are the atmospheric concentrations at Mauna Loa (Hawaii).

To put the carbon dioxide concentration of Aquacrop in Apex, there are a few complications. The way Apex reads the CO_2 concentration is namely not straightforward. When the model finds a CO_2 concentration on a specific date, it only starts using it the year following this date. So the

Table A.3: The global atmospheric carbon dioxide concentrations (in parts per million) for each of the years.

Year	concentration	Year	concentration	Year	concentration
1981	340.11	1991	355.48	2001	371.13
1982	341.22	1992	356.27	2002	373.22
1983	342.84	1993	356.95	2003	375.77
1984	344.40	1994	358.63	2004	377.49
1985	345.87	1995	360.62	2005	379.80
1986	347.19	1996	362.37	2006	381.90
1987	348.98	1997	363.47	2007	383.77
1988	351.45	1998	366.50	2008	385.59
1989	352.89	1999	368.14	2009	387.37
1990	354.16	2000	369.41	2010	389.85

concentration entered on the first of January 1990 will be used as the CO_2 concentration in 1991. Knowing this, the CO_2 concentration for a specific year should be entered in the year before. For the first year, the model uses the CO_2 parameter (called CO2) in the control file of Apex. The value for 1981 is entered at this location. An overview of the concentrations for each of the years can be found in table A.3.

Deriving monthly data

Both models require daily climate files. In addition, Apex also requires a monthly climate file. The average monthly values for the maximum temperature, minimum temperature and solar radiation can be derived by summing up the values per month and taking the average of this. This will result in the values that are also present in table A.2. The standard deviation can be calculated easily from this list of all values per month.

The average monthly precipitation can be calculated similarly. The number of rainy days per month can be calculated from the list by taking the total number of rainy days for the whole period 1981 to 2010 and divide this by the length of the period (30 years). The rest of the variables in the monthly weather file are left at zero, because the model documentation of Apex states that this can be left zero. An example of a monthly weather file of Apex is given in figure A.3.

A.2.2 Soil parametrization

While the climatic input is identical in the models, the soil parametrization is to a certain extent different. What the models do have in common is that the soil parametrization is in both cases derived from *De Lannoy et al.* (2014). They provide a global map with 253 different soil types, each of them representing a soil structure that consists of two layers with a thickness of 0.30 and 0.70 meter, with different values for soil parameters per layer. The soil types per location are acquired on a similar method as the climate data; based on the longitude and latitude the soil type is picked from the global database. For each of the models, the soil structure is further explained below. The soil types from *De Lannoy et al.* (2014) that are used in this study are given in table A.4.

Aquacrop soil

The parametrization of Aquacrop consists of the soil file itself (.SOL), a file containing the initial soil water content (.SW0) and a file with the groundwater characteristics (.GWT). In the first one there are four general soil parameters that need to be set: the curve number, the readily evaporable water

```
Shandong
119.16   35.56
  2.69  4.89  9.73 16.44 21.80 25.70 27.91 27.96 24.84 19.67 11.86  5.08
 -5.54 -3.48  1.02  7.20 12.90 17.63 21.43 21.17 16.45 10.53  3.12 -3.14
  3.14  3.56  3.60  3.56  3.22  2.60  2.20  2.02  2.53  3.38  4.20  3.67
  3.02  3.42  3.47  3.48  3.07  2.48  2.12  2.06  2.48  3.40  4.12  3.55
  9.86 15.02 20.20 33.40 59.99 92.44192.94159.10 67.38 34.77 24.11 10.75
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
  2.73  3.67  4.00  4.87  6.60  8.73 16.87 16.27  7.13  5.03  3.90  2.77
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
 13.60 16.00 18.41 19.95 19.80 19.78 19.73 19.69 18.41 15.98 13.59 12.61
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
```

Figure A.3: An example of a monthly weather file of Apex. Here the climate file of Shandong is shown. The first two lines contain comments and are not used by the model.

Table A.4: The soil types for each of the locations, including their sand, clay and silt content. The soil code refers to the one of *De Lannoy et al.* (2014).

Plant	Topsoil (Sa% / Cl% / Si%)	Subsoil (Sa% / Cl% / Si%)
Apple tree (Sh)	224 (46.67 / 16.67 / 36.67)	55 (53.33 / 13.33 / 33.33)
Apple tree (Ga)	186 (13.33 / 43.33 / 43.33)	186 (13.33 / 43.33 / 43.33)
Apple tree (Wa)	224 (46.67 / 16.67 / 36.67)	40 (43.33 / 23.33 / 33.33)
Grapevine	210 (33.33 / 23.33 / 43.33)	126 (33.33 / 23.33 / 43.33)
Olive tree	185 (16.67 / 46.67 / 36.67)	16 (23.33 / 43.33 / 33.33)
Oil palm	207 (46.67 / 26.67 / 26.67)	110 (36.67 / 36.67 / 26.67)

Table A.5: An overview of some important soil parameter values for the .SOL file of Aquacrop.

Plant	cn $[-]$	REW $[mm]$	Soil class	CR_{a} $[-]$	CR_{b} $[-]$
Apple tree (Sh)	34	8	I Sandy	-0.3143	-0.1072
Apple tree (Ga)	77	11	IV Silty clayey	-0.4967	1.7307
Apple tree (Wa)	58	8	II Loamy	-0.4772	0.4829
Grapevine	58	9	II Loamy	-0.4751	0.5273
Olive tree	71	11	III Sandy clayey	-0.5738	-0.7387
Oil palm	71	8	III Sandy clayey	-0.5749	-0.6456

from the top layer, the number of soil horizons and the depth of the restrictive layer. First of all, the curve number is set equal to the curve number Apex calculates. The values of these curve numbers can be found in table A.5 and are retrieved in the same run as the potential heat units (more on these runs in section A.4.1). The readily evaporable water, or REW, is calculated by the equation given in the manual of the model. This equation is

$$REW = 0.4(\theta_{\mathrm{FC}} - 0.5 \cdot \theta_{\mathrm{WP}}), \tag{A.3}$$

in which REW $[mm]$ is the readily evaporable water, θ_{FC} $[mm]$ the field capacity and θ_{WP} $[mm]$ the wilting point. This equation is applied on the topsoil layer only, resulting in a certain amount of REW. This REW is entered as an integer in the soil file. The values for the readily available water are shown in table A.5. There are two soil horizons, as described by *De Lannoy et al.* (2014). There is no restrictive soil layer, resulting in a value for this parameter of -9.

Besides the general soil parameters there are also layer specific parameters in the soil file of Aquacrop. The thickness of the layer (in the file called Thickness), the soil moisture content at saturation (Sat), the field capacity (FC), the wilting point (WP) and the saturated hydraulic conductivity (Ksat) are all given by *De Lannoy et al.* (2014). This means that there are two parameters left, namely the capillary rise parameters a (CR_{a}) and b (CR_{b}). As this study does not considers a groundwater table, the values for these parameters do not influence the results. The capillary rise parameters used in this study are given in table A.5. The soil classes, which were important for the calculation of capillary rise, are still important for Apex. The class is determined using the method in the documentation of Aquacrop. This means that based on the soil moisture content at saturation, the field capacity and the wilting point, all of the bottom layer only, the soil class is determined. If multiple classes can occur given these three parameters, the highest class is chosen.

Next to the soil file, Aquacrop also requires a file that contains the initial conditions of the soil (.SW0). This file also consists of general soil parameters and layer specific parameters. In the general soil file, only the number of soil layers is filled in (2), while the water stored between soil bunds, the electrical conductivity and the soil water content for specific layers are all put to zero. In the layer parameters, the thickness of each of the layers and the initial water content need to be set. The thickness of the first layer is 0.30 m and the thickness of the second layer is 0.70 m. The initial water contents are equal to the field capacities of the layers. The electrical conductivity (EC_{e}) is set to zero.

In Aquacrop, a groundwater table can be set with the groundwater file. As said, no groundwater is simulated in this study. In the project file (.PRM), explained in section A.3, the name for the groundwater file is set to '(None)'.

Apex soil

In Apex, the soil parameters are all stored in the same file (.SOL). Just like with Aquacrop, this file also consists of general soil parameters and layer specific parameters. The largest difference between the two is that Apex requires much more parameters than Aquacrop. Table A.6 provides an overview of the values that are allocated to each of the parameters.

For the general soil parameters the soil albedo, the hydraulic soil group and the initial soil water content are firstly defined. The soil albedo (SALB) is not given by *De Lannoy et al.* (2014) and therefore a different source had to be found. As there is no general relation with certain soil properties, a general value for the soil albedo based on *Post et al.* (2000) is used. This is a value for the albedo of 0.19. The hydraulic soil group (HSG), the second soil parameter, is chosen identical to the soil class in Aquacrop and thus differs per location. For the initial soil water content (FFC), the value of 1.00 is used for all locations as the initial soil water content is equal to field capacity, just as in Aquacrop.

Following these three parameters there are some groundwater parameters in the model. All of these parameters (WTMN, WTMX, WTBL, GWST, GWMX and RFTT) are set to zero. The return flow parameter RFPK is left blank. These are all default values.

Furthermore, there are some model based soil parameters. The maximum number of soil layers after the soil layers are splitted (TSLA) is left at its default value of 10, the soil weathering code (XIDS) is set to zero, as this seem to cover the widest range of soils. The number of years of cultivation at the start (RTN1) is set to zero. The soil grouping (XIDK) is set to 2 as this seem to contain the widest range of soils. The minimum layer thickness parameters (ZQT, ZF and ZTK) are all set to 0.10, as this is default and no better estimation can be given for these parameters. The next two parameters (FBM and FHP) are left at their default blank. The last general soil parameter, XCC, should be left blank as stated in the user manual.

The list of parameters that are layer specific is even longer. The depth of the soil surface to the bottom of the layer (Z), the bulk density (BD), the wilting point (UW), the field capacity (FC), the sand (SAN) and silt (SIL) content, the organic carbon content (WOC) and the saturated hydraulic

Table A.6: The values for the soil parameters in Apex. When there is a asterisk (*) at the name of the parameter, the parameter value is different per location. At these parameters, the table gives the value belonging to soil type 224/55 (Shandong).

General soil parameters					
SALB	=	0.19	*HSG	=	1
*FFC	=	0.23	WTMN-RFTT (6x)	=	0
RFPK	=	blank	TSLA	=	10
XIDS	=	0	RTN1	=	0
XIDK	=	2	ZGT-ZTK (3x)	=	0.10
FBM-FHP (2x)	=	blank	XCC	=	blank
Layer specific parameters					
Upper layer			Lower layer		
Z	=	0.30	Z	=	1.00
*BD	=	1.37	*BD	=	1.52
*UW	=	0.10	*UW	=	0.08
*FC	=	0.25	*FC	=	0.21
*SAN	=	46.67	*SAN	=	53.33
*SIL	=	36.67	*SIL	=	33.33
WN	=	0.00	WN	=	0.00
PH	=	6.00	PH	=	6.00
SMB	=	6.00	SMB	=	6.00
*WOC	=	1.12	*WOC	=	0.26
CAC-PSP (8x)	=	0.00	CAC-PSP (8x)	=	0.00
*SATC	=	17.78	*SATC	=	12.94
HCL-STFR (5x)	=	0.00	HCL-STFR (5x)	=	0.00
ST	=	1.00	ST	=	1.00
SPRV-WHPN (17x)	=	0.00	SPRV-WHPN (17x)	=	0.00

conductivity (SATC) are all found in *De Lannoy et al.* (2014). The initial soil water storage (ST) is set equal to the field capacity, which results in a parameter value of one (as this is the fraction of field capacity). The parameters that describe the pH of the soil (PH and SMB) are both set to 6. The pH is important for the aluminium stress and to avoid this stress it is necessary that these values are higher than 5.6. The rest of the parameters, all 31, are left at zero because (a) no values are available for these parameters and the documentation states that they can be left at zero or (b) the values for these parameters do not change the results.

A.3 Model set-up

The general set-up of the models is explained in this section. The general set-up refers to the parametrization of the models that does not change over the years, the plants, the locations or the type of simulation (irrigated or rainfed). For each of the models this set-up is explained below. To value the parameters there is no general source available as it was for the soil parametrization. Therefore, a best guess is made for each of the parameters. When this is not possible, the default value is assumed to be representative.

A.3.1 Aquacrop

The simulations in Aquacrop are run through multiple run project files (.PRM files). Such a file can be seen as the main file that contains the program parameters and contains links to all subfiles. Each of these subfiles also contains parameters for a component of the model. These subfiles are the climate files (with the extensions .CLI, .TMP, .ETo, .PLU and .CO2), the soil files (.SOL, .SW0 and .GWT), the plant file (.CRO) and some management files (.IRR, .MAN and .OFF). The climate files and the soil files are already discussed in section A.2. The rest of the files are discussed here. An overview of all the parameters is given in table A.7.

Plant file (.CRO)

The plant file contains all the plant specific parameters. It is not surprising that a lot of these parameters can not be considered as general parameters, but depend on the plant being simulated. These plant specific parameters are given in table A.7a. These contain all the parameters that describe the plant growth as a function of heat units (or growing degree days), the minimum temperature the plant needs for growing, the crop coefficient, the depth of the roots, the maximum canopy cover, the minimum canopy cover (function of the planting density) and the harvest index. The values for these parameters are explained in section A.4.

In the plant file there are also parameters that can be set for all simulations. First of all, the plant is sown, although this will not lead to different results in respect to a transplanted plant. The plant development is set in heat units (GDD), corresponding to Apex which also has heat units underlying the simulation. The upper temperature is set to 40 $°C$. The reason that this is a general parameter and not a plant specific parameter has to do with the fact that this temperature is only relevant for the accumulation of heat units. For the temperature stress, the model uses the parameters 'minimum and maximum air temperature for pollination' and the 'minimum growing degree days required for full biomass production'. This last one is a plant specific parameter, the first two not. The value of 40 $°C$ is chosen as this is in non of the locations ever reached as the mean daily temperature. In this way, the heat unit equation from Aquacrop becomes exactly the same as the one of Apex. See equation A.4 and A.5 later in this appendix.

After the temperature, there are five parameters that describe the response of different plant components to the soil fertility and salinity. These parameters are all set to 25, which means that these stresses are turned off. Also the electrical conductivity parameters are turned off, resulting in a value of -9. The soil cover per plant is 200 cm^2. The model uses this, together with the number of plants per hectare (plant specific parameter), to determine the initial canopy cover. Therefore one of these two parameters can be fixed, while the other one determines per plant. The plant determinacy is linked with flowering.

For the adjusted parameters, there is one parameter remaining. As can be seen, the amount of heat units (GDD) to emergence is set on -1. For a correct simulation of evapotranspiration, it is important to keep the canopy cover intact in the winter (more on this is section A.4.2). Aquacrop

Table A.7: The parametrization of Aquacrop. An asterisk (*) at the value of the parameter means that the value of the parameter does not change the results. The caption 'n.c.' stands for 'not considered', meaning that the value of the parameter is such that Aquacrop does not considers the process it describes. The caption '5x' (or another number) is added if the description in the table covers multiple (5) parameters.

(a) Plant file (.CRO)

Adjusted parameters					
Crop type (fruit/root etc.)	=	2	Sowing/transpl.	=	*sown (1)
GDD or calend. days	=	GDD (0)	Upper temperature	=	40
Response can. exp.	=	(n.c.) 25	Response max. can.	=	(n.c.) 25
Response wtr. prod.	=	(n.c.) 25	Response can. decl.	=	(n.c.) 25
Response stom. closure.	=	(n.c.) 25	Elec. cond. soil sali.	=	(n.c.) -9
Elec. cond. strop grow	=	(n.c.) -9	Soil surf. cov. per plant	=	200.00
Crop determ. - flowering	=	linked (1)	GDD to emergence	=	-1
Plant specific parameters					
Base temperature			Min. GDD for biomass		
Length cycle in GDD			Crop coef. $Kc_{\mathrm{Tr,x}}$		
Min. eff. root depth			Max. eff. root depth		
Plants per hectare			Max. CC		
Reference HI			GDD to grow phase (3x)		
Length flow. stage GDD			CGC in GDD		
CDC in GDD			Building up HI in GDD		
Default parameters					
Depl. factor adj. by ETo	=	1	Can. exp. depl. up thresh.	=	0.25
Can. exp. low thresh.	=	0.55	Shape wtr strss can. exp.	=	3.0
Depl. frac. p_{sto} up thresh.	=	0.50	Shape wtr strss stomatal	=	3.0
Depl. fac. p_{sen} up thresh.	=	0.85	Shape wtr strss senes	=	3.0
Sum ETo exc. for senes	=	0	Depl. fac. p_{pol} up thresh.	=	0.90
Anae. point for def. aer.	=	5	Consid. soil fert/sali. strss	=	*50
Min. T (cold strss)	=	8	Max. T (heat strss)	=	40
Shape sal. strss	=	3.0	Decl. crop coef.	=	0.150
Shape root zone exp.	=	*15	Max. root wtr ext. top	=	0.024
Max. root wtr ext. bot.	=	0.006	Eff. CC on evap.	=	60
CGC in days	=	*0.10417	Max. decr. of CGC	=	(n.c.) -9
Nr. season max. decl.	=	(n.c.) -9	Shape CGC decr.	=	(n.c.) -9
CDC in days	=	*0.08000	Days to grow phase (5x)	=	*def.
Length. flow. stage days	=	*17	Excess pot. fruits	=	50
HI build up days	=	*57	Water productivity	=	17.0
Water prod. yield form.	=	100	Crop perf. CO_2	=	50
Incr. HI due to wtr strss	=	10	Coef. positive imp. HI	=	10.0
Coef. negative imp. HI	=	8.0	Max. allowable incr. HI	=	15
GDD to max. root depth	=	*700			

(b) Irrigation file (.IRR)

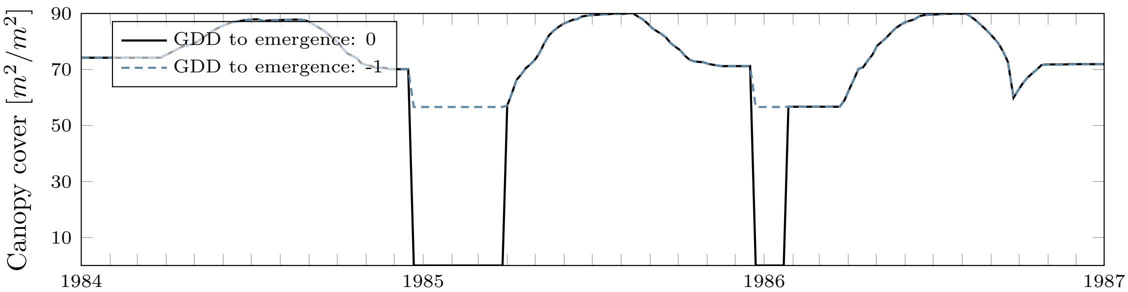
Adjusted parameters					
Plant specific parameters					
Default parameters					
Irrigation type	=	(sprnkl.) 1	Perc. soil surf. wetted	=	100
Irrigation mode	=	3	Allowable depl.	=	30

Table A.7: (continued) The parametrization of Aquacrop. An asterisk (*) at the value of the parameter means that the value of the parameter does not change the results. The caption 'n.c.' stands for 'not considered', meaning that the value of the parameter is such that Aquacrop does not considers the process it describes. The caption '5x' (or another number) is added if the description in the table covers multiple (5) parameters.

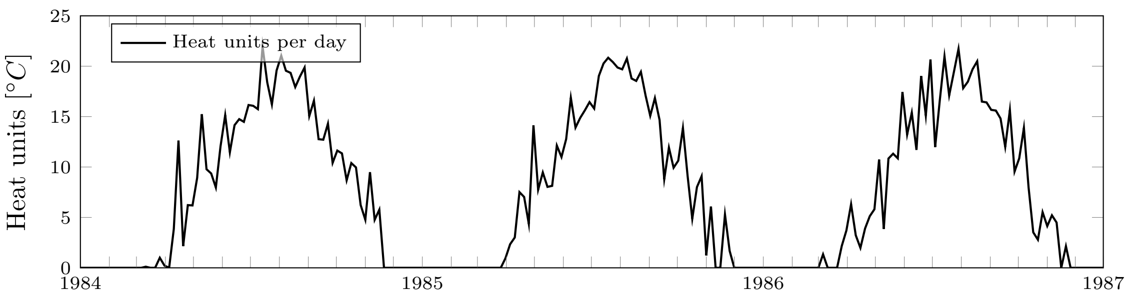
(c) Project file (.PRM)

Adjusted parameters					
Default meth. GDD calc.	=	1	CN with AMC	=	0
Plant specific parameters					
Dates simulation & plant			Soil evap. coeff. (Ke_x)		
Default parameters					
Evap. decl. factor	=	4	Thresh. CC below HI	=	5
Start depth root zone	=	70	Max. allowable root zone	=	5.00
Shape water strss - root	=	-6	Req. swc for germin.	=	20
Adj. factor SW depl.	=	1.0	Nr. days aeration	=	3
Exp. of senesc.	=	1.00	Decr. of p_{sen}	=	12
Thresh. water strss - sal.	=	0	Depth affect. by evap	=	30
Consid. depth for CN	=	0.30	Salt. diff. factor	=	20
Salt solubility	=	100	Shape factor. SWC - CR	=	16
Default min. T	=	12.0	Default max. T	=	28.0

simulates every plant as if it is an herbaceous one, meaning that the plant dies at harvest. To keep the canopy cover intact, the plant of the following year should have a canopy cover from the first day it grows, which is the day after harvest of the previous plant. To reach this, it is required to set the heat units for emergence to minus one. See figure A.4. Setting it to zero will namely lead to the problem that if the moment of harvest occurs in winter, when no heat units are acquired, the plant will not emerge until the first moment that heat units are acquired. As this can take months, this



(a) Canopy cover 1984-1986 in Gagauzia



(b) Heat units 1984-1986 in Gagauzia

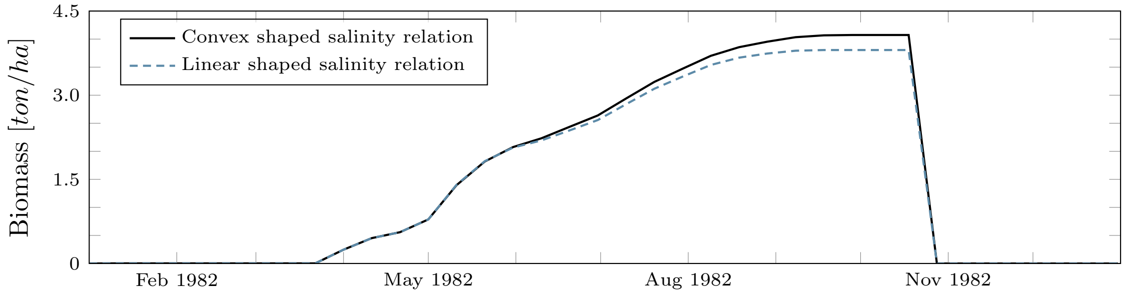
Figure A.4: The dependency of the plant development on the heat units to emergence. The top plot shows the heat to emergence set as zero or minus one. The bottom plot shows the heat units itself. As can be seen, instant emergence only occurs with a value of minus one.

would mean that the canopy cover can be zero during a few months of the year. To avoid this, the amount of heat units to emergence is set to -1.

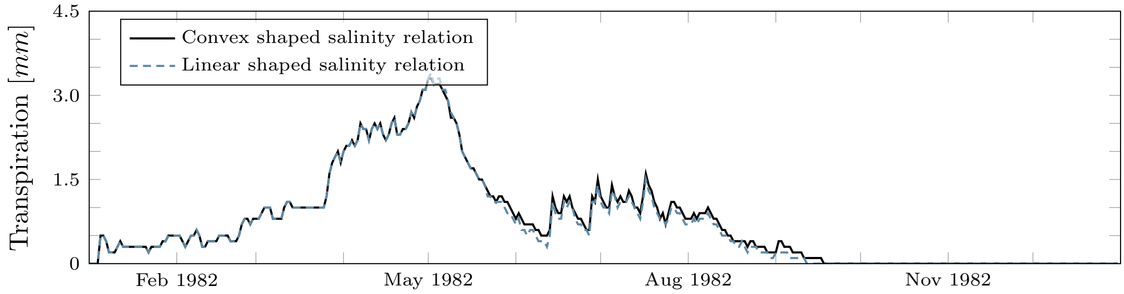
The rest of the parameters in the plant file are all left at default. These parameters are also shown in table A.7a. The parameters are not adjusted because there is simply no better estimate available for them. There are a few parameters that may require some additional clarification. To start with, the minimum (8 °C) and maximum (40 °C) temperature at which pollination start to fail from cold and heat stress, are left at their default. This seems quite unlikely, because the temperature a plant flourished best in depends strongly on the plant. While this is true, there are simply no better estimates available for these specific parameters. It is assumed that the values given by Aquacrop are conservative for a wide range of plants. The plant specific temperature characteristics are covered by the accumulation of heat units and the minimum amount of heat units required for biomass production.

A second parameter that requires clarification is the shape factor for the soil salinity stress. This is set at 3.0, its default value which describes a convex shaped relation between the salinity stress coefficient and the electrical conductivity of the soil. As salinity stress is turned off, the shape of this relation should not matter. However, a comparison between the results of simulations with different values for this shape (convex shape of 3.0 and linear shape of 0.0) show that the result do change. In figure A.5, these results are shown for the biomass and the transpiration. The reason for the difference is unclear, as the electrical conductivity threshold are both set to -9. Even when setting the electrical conductivity to values which would in practice never be reached, the model still responses to the different values of this shape parameter. As the exact reason for this still remains unclear, the value for this parameter is left at its default.

The rest of the parameters describe a wide range of processes in the model. Some of them do not change the results at all, others only slightly and some even a lot. All of these remaining parameters are left at their default value.



(a) Biomass 1982 in Gagauzia



(b) Transpiration 1982 in Gagauzia

Figure A.5: The dependency of the plant development on the shape relation between the salinity stress coefficient and the electrical conductivity of the soil. While salinity stress is turned off, the shape of the relation described by the parameter value of 3.0 (convex) and 0.0 (linear) still changes the results.

Management files (.IRR, .MAN and .OFF)

From the management files, only the irrigation file is used. This means that other management options, described by the .MAN file and the .OFF file, are not considered. For situations that require irrigation, the default irrigation file (Inet.IRR) is used. The characteristics of this file are shown in figure A.7b.

Project file (.PRM)

Finally Aquacrop has a project file, which can be considered as the master file from which the simulation is run. This file firstly contains, for every year in the file, the start and end date of the simulation and the start and end date of the cropping period. While these are important, they are plant, year and location specific. These dates are therefore discussed in section A.4.

Besides these dates, the project file also contains the program parameters. The values for these parameters for the simulations in this study are given in table A.7c. As can be seen here, most of the program parameters are left at their default value. This is mainly caused by the fact that these program parameters are very model specific and there are no general methods available to estimate them.

There are two program parameters that are adjusted. First of all, the method to calculate the heat units (GDD) is adjusted to type 1. From the three methods available in Aquacrop, this method lies closest to the heat unit equation of Apex. This method of Aquacrop, which is given by the function

$$HU(i) = \frac{T_{\text{max}}(i) + T_{\text{min}}(i)}{2} - T_{\text{base}}; \quad 0 \leq HU(i) \leq T_{\text{upper}} - T_{\text{base}}, \tag{A.4}$$

is the same as the equation in Apex, which is

$$HU(i) = \frac{T_{\text{max}}(i) + T_{\text{min}}(i)}{2} - T_{\text{base}}; \quad 0 \leq HU(i). \tag{A.5}$$

as long as T_{upper} is never reached. As can be seen in table A.7a, this upper threshold is set to 40 $°C$, a temperature that in practice is never reached. In this way, the heat unit calculations are equal for both models. Note that equations A.4 and A.5 contain the symbols used in this document and not the original symbols in the manuals of the respective models.

Also the curve number method is adjusted. In this study, it is chosen to work with a constant curve number in both models. Therefore, the program parameters describing this is adjusted. Furthermore, there is one parameter, the soil evaporation coefficient, which is plant dependent and is therefore not given here. More on this parameter can be found in section A.4.

A.3.2 Apex

In Apex the number of files for the simulation is rather large. To get a good overview of the files, four file types are distinguished in this appendix. First of all there are input files, consisting of the daily weather file (.DLY), the monthly weather file (.WP1) and the soil file (.SOL). These are all explained in the input section A.2. Furthermore, run files, database files and a print file are distinguished. In this report, database files are considered as all the files that contain a long list of different options a user can select from. For example, one can think of the plant database, from which a user can specify which plant it wants to use. Also the files that contain all the different default weather stations are considered database files. The run files are all the files that control the simulation. These include the files that state which operation is performed and when, at which date the simulation starts, what the program parameters are etcetera. And finally there is a print file, which does not control the simulation itself, but only influences the output that is being displayed. In this study at least the daily evapotranspiration and the yearly yield values should be printed. The database and run files are discussed below. Note that only the files used during the simulations in this study are mentioned. Some files, such as herd files, are not used in this study and are therefore also not discussed here. Furthermore, it is important to know that the names given with each of the files are the default names; a user might have different names for the files.

```
Crop          1       2       3       4       5       6       7       8       9      10...
#  NAME      WA      HI     TOP     TBS    DMLA    DLAI   DLAP1   DLAP2    RLAD    RBMD...
 1 SOYB   25.00    0.30   25.00   10.00    5.00    0.90   15.05   50.95    0.10    1.00...
 2 CORN   40.00    0.50   25.00    8.00    6.00    0.80   15.05   50.95    1.00    1.00...
 3 GRSG   37.00    0.50   27.50   10.00    5.50    0.80   15.01   60.95    0.50    0.50...
 4 COTS   25.00    0.60   27.50   12.50    6.00    0.95   15.01   50.95    0.50    0.50...
 5 COTP   25.00    0.40   27.50   12.50    6.00    0.95   15.01   50.95    0.50    0.50...
 6 PNUT   30.00    0.00   25.00    9.00    5.00    0.85   15.01   50.95    1.00    0.50...
 7 SUNF   49.00    0.30   25.00   10.00    5.00    0.55   15.01   50.95    1.00    2.00...
......
```

(a) The plant file (CROP.DAT)

```
    1 1.WP1          32.41  -99.68   545.6    TX_ABILENE_RGNL_AP
    2 2.WP1          32.73   -99.3   426.7    TX_ALBANY
    3 3.WP1          32.75  -99.85   520.3    TX_ANSON_3ESE
    4 4.WP1           33.6  -98.61   321.2    TX_ARCHER_CITY_1E
    5 5.WP1          32.74  -97.13   199.6    TX_ARLINGTON
    6 6.WP1          32.16  -95.83   136.5    TX_ATHENS
    7 7.WP1          30.32  -97.76   204.2    TX_AUSTIN-CAMP_MABR
    8 8.WP1          32.26  -96.64   140.5    TX_BARDWELL_DAM
    9 9.WP1          28.46  -97.71    77.7    TX_BEEVILLE_5_NE
......
```

(b) The monthly weather list file (WPM1.DAT)

Figure A.6: Example of the two different Apex database files. The plant file and the monthly weather file are shown. The first contains a list of options a user can choose from, the second contains a list of subfiles a user has to choose from. Only the first 9 lines are shown.

Database files

There are two different types of files within the category database files, see figure A.6. First of all, one can identify the tillage file (TILL.DAT), the plant file (CROP.DAT), the fertiliser file (FERT.DAT) and the pesticide file (PEST.DAT). Each of these files provides a list of options a user can choose from in one of the run files. Attached to each of the options is a list of parameters that the model requires. See figure A.6a. It is worth mentioning that non of the parameters in these files are changed. In the plant file one file is added (oil palm).

Within database files, also list files can be distinguished. These are the Apex site list (SITE.DAT), the subarea list (SUB.DAT), the soil list (SOIL.DAT), the operation list (OPS.DAT), the daily weather list (WDLST.DAT) and the monthly weather list (WPM1.DAT). Similar as with the other database files, a user also chooses from a list file. But here an option does not contain parameters of its own, but only refer to a file. See figure A.6b. In these list files, it is important that the subfiles used in the simulation are added to the list. For example, in the soil list, the name of the soil used in the simulation should be added. For the list of the daily weather file and the monthly weather file also the longitude, latitude and height (0.0 m) are entered.

Run files

Within the run files, the most important file for the simulation is the master file (APEXFILE.DAT). This file is comparable with the project file of Aquacrop and contains a list of subfiles that are required for the simulation. While this file is crucial for the simulation, it is not important to mention broadly here, as nothing is changed in this file. When a user changes file names for the simulation it can be necessary to adjust this master file.

Another important run file is the parameter file (PARMS.DAT). The parameters within this file are to some extent similar to the program parameters of Aquacrop. It contains the most coefficient for equations and S-curves. As stated in the documentation of the model, these parameters should only be changed in agreement with the model developers. As no better estimates are available for any of the over 150 parameters in this file and because of the warning given in the documentation, none of the parameters are changed.

The dimensions file (APEXDIM.DAT) sets the maximum allowable range of certain operations. One can think of the maximum number of years a user can specify operations. They do not directly influence the results, but it is important that the dimensions are set large enough so that all the simulations can be done. In practice this means that the number of years that operations can be specified should be at least 30.

Until so far the files discussed are not changed a lot. There are however five files that need more clarification. These are the run file (APEXRUN.DAT), the control file (APEXCONT.DAT), the subarea file (.SUB), the operations file (.OPS or .OPC) and the site file (.SIT). The parameters for each of these files are given in table A.8. Each of the files is discussed further below.

The run file contains seven parameters, from which four (ISIT, IWPN, IWND and ISUB) only refer to a subfile in one of the list files. For these, it is important that the corresponding subfile matches the one required for the simulation. The reference to the wind file (IWND) is not important, as no wind is considered in the simulations of this study. The parameter ISOL is set to zero, as this refers to a normal run (in contrast with using a .SOT file). The storm parameter IRFT is also set to zero; storms are not considered. Finally, ASTN is simply the name which is given to the output files. One can choose every name here that is convenient.

The control file is more comprehensive than the run file. First of all, it contains the length of the simulation (NBYR) and the start date (IYR, IMO, IDA). The input code (NGN) should be entered such that it contains precipitation, the maximum and minimum temperature and the solar radiation (therefore code 123). The estimation of the curve number (ISCN) is set to deterministic instead of stochastic. The precipitation code is set such that it represents normal conditions (no tropical storms or extreme droughts). A normal soil erosion is chosen (ISTA), because the static soil will not contain any carry over effects of the soil through the years. Identical to the choice made in Aquacrop, the curve number method is set constant in this model (NVCN). The carbon dioxide concentration (ICO2) is set as input, with an initial concentration of 340.11 parts per million (CO_2). More information on this is found in section A.2.1. The latitude is input, affecting the parameter IAZM. The final adjusted parameters are concerned with the vertical and horizontal pipe flow parameters (CPV0 and CPH0). These are both set to zero, meaning that pipe flow does not occur in either direction. The rest of the parameters are left at their default value.

The next important of the run files is the subarea file. This file contains plant specific parameters, general parameter and parameters which are left at their default, as can be seen in table A.8c. The first plant specific parameter is the soil number that is picked from the soil list (INPS). This changes per location. While the same can be said about the climate files (part of the general parameters, parameter IWTH), this study uses climate data such that the climate file is overwritten per location. A user can of course choose to also overwrite the soil file for every location or to create different climate files for each location.

There are three more plant specific parameters. The first two are the latitude (YCT) and longitude (XCT). The last one is the irrigation code (BIR). This last parameter describes at which amount of water stress automatic irrigation occurs. A parameter value for BIR of 1 means that the model irrigates as soon as even a little water stress occurs, while a parameter value of 0 means that no automatic irrigation is applied what so ever. Depending on the type of irrigation, the parameter is set to 1 if water stress is to be avoided and set at 0 if water stress is allowed.

For the general set-up in the subarea file, the parameters IOPS and IWTH describe the operation file and the climate file that are considered. The NVCN parameter is also in this file; the same value is given as in the control file. The parameter for the land use number (LUNS), which is set in the operation file (explained below) can be overwritten here. By setting it to zero this is avoided. The upland slope (SLP) is set to zero to avoid horizontal flow components. The irrigation scheduling (NIRR) is set to flexible, such that automatic irrigation can occur based on the stress that is measured. The irrigation type (IRR) is set to sprinkler irrigation. There is no minimum time between irrigation or fertiliser application (IRI and IFA). The parameter IDR allows for the simulation of drainage pipes, but as this is not in Aquacrop, the simulation of them is avoided by setting the parameter to zero. The effectiveness of the irrigation is set with the parameter EFI, which simply states the fraction of the irrigation that becomes runoff. In this study this is set to zero (no over-irrigation). Runoff can of course still occur due to rainfall. The parameters for setting the minimum and maximum amount of irrigation of a single event or a year (VIMX, ARMN and ARMX) are all set to zero, meaning that there is no minimum or maximum. The factor BFT is the fertiliser equivalent of the irrigation

Table A.8: The parametrization of Apex. An asterisk (*) at the value of the parameter means that the value of the parameter does not change the results. The caption ’5x’ (or another number) is added if the description in the table covers multiple (5) parameters.

(a) Run file (APEXRUN.DAT)

Adjusted parameters								
ISIT	=	1	IWPN	=	200	ISUB	=	1
ISOL	=	0						
Plant specific parameters								
Default parameters								
ASTN	=	*out	IWND	=	*28	IRFT	=	*0

(b) Control file (APEXCONT.DAT)

Adjusted parameters								
NBYR	=	30	IYR	=	1981	IMO	=	1
IDA	=	1	NGN	=	123	LPYR	=	0
IET	=	4	ISCN	=	1	ITYP	=	3
ISTA	=	0	NVCN	=	3	INFL	=	0
ICO2	=	2	ISW	=	3	IAZM	=	0
CO2	=	340	CPV0	=	0	CPH0	=	0
Plant specific parameters								
Default parameters								
IPD	=	*3	IGN	=	0	IGSD	=	0
IHUS	=	0	MASP	=	*0	IERT	=	*0
LBP	=	0	NUPC	=	*0	MNUL-IHY (6x)	=	*0
IGMX	=	1	IDIR	=	0	IMW-IDNT (3x)	=	*0
IPAT	=	*0	IHRD	=	0	IWTB	=	*15
IKAT	=	1	NSTP	=	0	ISAP	=	0
ICP-ISAP (3x)	=	0	RFN	=	0.8	CQN	=	0
PSTX	=	0	YWI-BTA (2x)	=	0	EXPK	=	0
QG-CSLT (27x)	=	*def.	BUS(1)-BU. (4x)	=	*def.			

(c) Subarea file (.SUB)

Adjusted parameters								
IOPS	=	200	NVCN	=	3	IWTH	=	200
LUNS	=	0	SLP	=	0	NIRR	=	0
IRR	=	1	IRI-IFA (2x)	=	0	IDR	=	0
EFI	=	0	VIMX-AR. (3x)	=	0	BFT	=	1
FMX	=	0	FIRG	=	1			
Plant specific parameters								
INPS			YCT			XCT		
BIR								
Default parameters								
IOW	=	*1	II	=	*0	IAPL	=	0
IPTS	=	0	ISAO	=	*0	IMW	=	*0
SNO	=	0	STDO	=	0	AZM-AN. (4x)	=	*0
WSA-CHN (5x)	=	*def.	SPLG-UPN (2x)	=	*def.	FFPQ-FP. (14x)	=	*def.
RSEE-BF. (16x)	=	*0	LM-IFD (2x)	=	*0	IDF1	=	*69
IDF2	=	*68	IDF3	=	*53	IDF4	=	52
IDF5	=	*68	IDF6	=	*0	IRRS	=	0
FNP4	=	500	DRT-FDSF (2x)	=	*0	PEC	=	*1
DALG-FN. (8x)	=	*0	PEC-XTP. (20x)	=	0			

Table A.8: (continued) The parametrization of Apex. An asterisk (*) at the value of the parameter means that the value of the parameter does not change the results. The caption '5x' (or another number) is added if the description in the table covers multiple (5) parameters.

(d) Operations file (.OPS or .OPC)

Adjusted parameters								
LUN	=	28						
Plant specific parameters								
Op. lines								
Default parameters								
IAUI	=	500	IAUF	=	261	IAMF	=	268
ISPF	=	266	ILQF	=	265	IAUL	=	267

(e) Site file (.SIT)

Adjusted parameters								
ELEV	=	0	RFNX	=	0.8			
Plant specific parameters								
YLAT			XLOG					
Default parameters								
APM	=	*1	CO2X-CQ. (2x)	=	0	UPR	=	1000
UNR	=	1000	FIR0	=	0	BCHL-BC. (2x)	=	*0
WSA1	=	*0						

parameter BIR. This parameter sets at which stress fertilization is triggered. As nutrient stress is unfavourable in this study, this parameter is set to 1. There is no maximum amount of fertilizer (FMX). The final parameter that is adjusted is FIRG, which states to which fraction of field capacity the simulation will irrigate. This is set at 1, meaning that irrigation will return the soil water content to field capacity as soon as water stress occurs. The rest of the parameters in the subarea file are left at their default.

The next file is the operation file. While this one is important, most of the operations are plant specific. The land use number (LUN) is adjusted. The model uses this to determine the curve number. Setting it to 28 corresponds with woods with fair hydrological conditions, which seems appropriate for all simulations in this study. Only for the grapevines this might not be fully correct, but it is chosen here to keep this a general parameter for simplicity. As the curve number of Apex is also used in Aquacrop, inconsistencies between the models do not occur regarding this. The rest of the parameters describe the automatic irrigation type, fertilization type etcetera. These are all left at default. For irrigation this is sprinkler type irrigation.

The site file is the last of the run files. In here, the latitude (YLAT) and longitude (XLOG) need to be set again. These depend on the location chosen. The elevation of the land is in all cases set at zero, since no height information is available. The parameter RFNX is the same as the parameter RFN in the control file. The value is therefore also set identical. The rest of the parameters are left at default.

A.4 Plant implementation

With all the general parameters set-up in the model, the plant parameters should be implemented as well to make a simulation possible. The plant implementation is described in this section in two steps. First of all, the green-up dates and harvest dates are derived. This is important, as the project file of Aquacrop and the operation file of Apex require this data. The second step is to determine the parameters of the plant file itself. To make a clear separation between the method to derive the plant parameters and the values of the plant parameters, this second step is divided into three sections. First additional information for Aquacrop is given, followed by additional information for Apex. These two sections describe the necessary information to get the plant data. After this, the plant data itself is presented, per plant and per model.

Table A.9: The green-up dates and potential heat units for each of the plants. The green-up dates are based on *Chapagain and Hoekstra* (2004). The potential heat units are retrieved from Apex.

Plant	Green-up date	Potential heat units
Apple tree (Sh)	January 15	2763
Apple tree (Ga)	January 15	2267
Apple tree (Wa)	January 15	1675
Grapevine	April 15	2002
Olive tree	April 15	3185
Oil palm	February 15	5966

A.4.1 Green-up and harvest dates

As calculations are done in heat units, harvest takes place a certain amount of accumulated heat units after sowing or, with woodies, green-up. So to calculate the harvest date, the accumulated heat units for a plant until harvest, the so-called potential heat units, and the green-up date should be known. To start with the last one, *Chapagain and Hoekstra* (2004) provide a database with green-up dates for all Faostat plants. An overview of the green-up dates is given in table A.9.

To determine the potential heat units of a plant, one can turn to literature. However, Apex does not support the input of potential heat units for plants which are, in the model, categorized as tree types. This applies to all plants but the grapevine. For tree type plants the model calculates the heat units itself by calculating the average daily heat units (so daily average temperature minus base temperature of the plant) and multiplying this with the time to maturity (when the plant is full-grown) (*Williams et al.*, 2016). However, attempts to check this calculation method leads to higher values of the potential heat units for the plants. Perhaps there is some unmentioned correction in the model.

The potential heat units for this study are calculated by Apex. For this, the general set-up as described in section A.3.2 is entered in the model. For the plant specific parameters, the latitude and longitude and the corresponding soil number are entered for each location. Irrigation is set to full (BIR = 1). For each of the locations, the climate as described in section A.2.1 is entered, with climate averaged data. This means that the climate data is adjusted such that in the simulation period of 30 years each January first has the same climate, each January second has the same climate etcetera. And finally, the operational lines in the operation (.OPS) file consist of a single sowing line (tillage ID number 686) with the corresponding sowing date of the plant, a time to maturity of one year and a sowing density corresponding to the one given in section A.4.3 on page 84. The plant ID number is as described in section A.4.3. An example of the operation file of the apple tree is given in figure A.7. The potential heat units are given in table A.9. For grapevine, potential heat units need to entered. A value of 2002 is chosen, as this leads to a harvest date halfway in October, which seems realistic.

With these potential heat units, the harvest dates can be calculated. This by counting the amount of accumulated heat units every day since green-up according to the heat units equation (equation A.4 or A.5, which are in practice the same for $T_{\text{upper}} = 40$). When these accumulated heat units reach the potential heat units, harvest takes place. An overview of all the harvest dates is given in table A.10. It can occur that the plant cannot be harvested before the end of the year, as is always

```
  Simulation schedule of apple trees
 28 500 261 268 266 265 267
 1  1 15  686    1   82    1    0.00    0.00    0.00    0.00  200.00    0.00    0.00
```

Figure A.7: The operation file for Apex to simulate the potential heat units for the apple tree in Shandong. The first line can contain comments and is not read by Apex. The second line contains the general parameter as described in section A.3. The third line contains the operation line with the date (15 January in simulation year 1), the tillage number (686), a machine number (1, irrelevant), the plant number for the plant file (82), the years to maturity (1) and the planting density (200).

Table A.10: The harvest dates for the plants in every year. The year number represents the year where the main part of the plant growth takes place; harvest can take place the following year. The oil palm cannot be harvested in the last year as it cannot complete its life within the year.

Year	Apple tree (Sh)	Apple tree (Ga)	Apple tree (Wa)	Grapevine	Olive tree	Oil palm
1981	10/06	10/21	09/23	03/18	01/15	01/18
1982	10/13	10/24	10/15	03/18	02/19	01/18
1983	10/09	09/23	10/05	11/21	12/18	01/18
1984	11/03	12/18	12/18	03/18	02/11	01/18
1985	10/28	12/18	10/16	10/11	12/15	01/18
1986	10/30	09/23	10/07	10/18	12/18	01/18
1987	10/27	12/18	09/20	10/03	12/27	01/18
1988	10/15	10/17	10/08	11/07	01/02	01/18
1989	10/16	10/08	10/06	10/05	11/29	01/18
1990	10/16	10/06	09/14	09/28	11/24	01/18
1991	10/23	10/19	10/02	10/05	01/11	01/18
1992	10/20	10/17	09/02	11/05	02/06	01/18
1993	10/27	11/08	12/18	03/18	03/05	01/18
1994	09/28	09/21	09/14	10/10	12/13	01/18
1995	10/17	10/04	10/07	10/16	12/11	01/18
1996	10/25	10/19	10/12	03/07	01/27	01/18
1997	09/30	12/18	09/25	10/18	12/09	01/18
1998	10/06	09/28	09/06	10/16	01/10	01/18
1999	10/06	09/19	12/18	10/08	01/06	01/18
2000	09/30	09/19	10/11	10/15	01/25	01/18
2001	10/04	09/22	09/26	10/09	01/07	01/18
2002	10/03	09/16	10/15	10/25	01/04	01/18
2003	11/01	09/26	09/09	09/18	12/05	01/18
2004	10/09	10/17	09/11	10/06	01/17	01/18
2005	10/09	10/03	09/23	09/25	12/21	01/18
2006	10/07	10/04	09/18	09/29	11/29	01/18
2007	10/03	09/02	09/16	10/24	12/28	01/18
2008	10/18	09/23	10/06	10/28	02/14	01/18
2009	10/06	09/17	09/15	09/25	12/05	01/18
2010	10/14	09/15	10/10	10/01	12/20	-

the case for oil palm. In the last year this leads to a problem, as the data only lasts to 31 December. Therefore the oil palm cannot be simulated in the last year.

It is possible that a year is characterized by very low temperatures. This could lead to a situation that the harvest date is reached after the green-up date of the following year. This is of course not possible and is avoided by setting the ultimate harvest date 4 weeks (28 days) before the green-up date of the following year. By doing this, harvest always takes place before the plant year. It is chosen to set the harvest date 4 weeks before such that the plant has time to recover from its harvest. In reality, a plant will namely not be harvested on one day and starts its new plant year directly the day after. Note that for the oil palm, the harvest date is always limited by this restriction. This is caused by the (too) high potential heat units.

A.4.2 Additional information Aquacrop

The additional information required to complete the parameter set for Aquacrop consists of a few sections. First of all, the derivations of the equations for the canopy growth coefficient and the canopy decline coefficient are explained. After this, the method to convert the harvest index of Apex to the one in Aquacrop is given. Following, a method is presented to keep the canopy cover in the winter intact, followed by the equations that describe the parameters for the plant development during the year. Finally, the rooting depth and the number of plants per hectare are described.

Derivation equation CGC

In Aquacrop, an important parameter for the canopy growth is the canopy growth coefficient (CGC). To calculate the canopy growth coefficient, it is first important to give the general equations of the relation between the canopy cover and the canopy growth coefficient. These are

$$CC = \begin{cases} CC_{\mathrm{o}} \cdot e^{t \cdot CGC} & \text{if } CC \leq CC_{\mathrm{x}}/2 \\ CC_{\mathrm{x}} - 0.25\frac{(CC_{\mathrm{x}})^2}{CC_{\mathrm{o}}} \cdot e^{-t \cdot CGC} & \text{if } CC > CC_{\mathrm{x}}/2, \end{cases} \tag{A.6}$$

in which CC $[m^2/m^2]$ is the canopy cover, CC_{o} $[m^2/m^2]$ and CC_{x} $[m^2/m^2]$ are plant properties that describe the initial and maximum plant canopy cover, CGC $[^{\circ}C^{-1}]$ is the plant specific canopy growth per heat unit (or GDD) and t $[^{\circ}C]$ is the accumulated amount of heat units.

Following the lines of *Hofstra* (2016), there are two points on the leaf development curve where it is known which equation is applicable. At the very start of the canopy cover development, where $CC = CC_{\mathrm{o}}$, it is known that the first equation applies. At the end, where $CC = 0.98CC_{\mathrm{x}}$, the second equation is applicable. See figure A.8. If the accumulated heat units corresponding to these two points are called t_{o} and t_{x}, the equations can be rewritten in terms of them as

$$t_{\mathrm{o}} = \frac{1}{CGC} \cdot \ln\left(\frac{CC_{\mathrm{o}}}{CC_{\mathrm{o}}}\right) = 0 \tag{A.7}$$

and

$$t_{\mathrm{x}} = -\frac{1}{CGC} \cdot \ln\left(0.08\frac{CC_{\mathrm{o}}}{CC_{\mathrm{x}}}\right). \tag{A.8}$$

With these two points on the leaf development curve, the distance between these points can be calculated. If the amount of heat units between these two points is called t_{growth}, the equation that applies is

$$t_{\mathrm{growth}} = t_{\mathrm{x}} - t_{\mathrm{o}}, \tag{A.9}$$

which is the same as

$$t_{\mathrm{growth}} = -\frac{1}{CGC} \cdot \ln\left(0.08\frac{CC_{\mathrm{o}}}{CC_{\mathrm{x}}}\right) - 0. \tag{A.10}$$

From this last equation we can derive

$$CGC = -\frac{1}{t_{\mathrm{growth}}} \cdot \ln\left(0.08\frac{CC_{\mathrm{o}}}{CC_{\mathrm{x}}}\right). \tag{A.11}$$

So, if the initial canopy cover, the maximum canopy cover and the amount of heat units that it takes to go from the first to the last one are known, the canopy growth coefficient can be calculated.

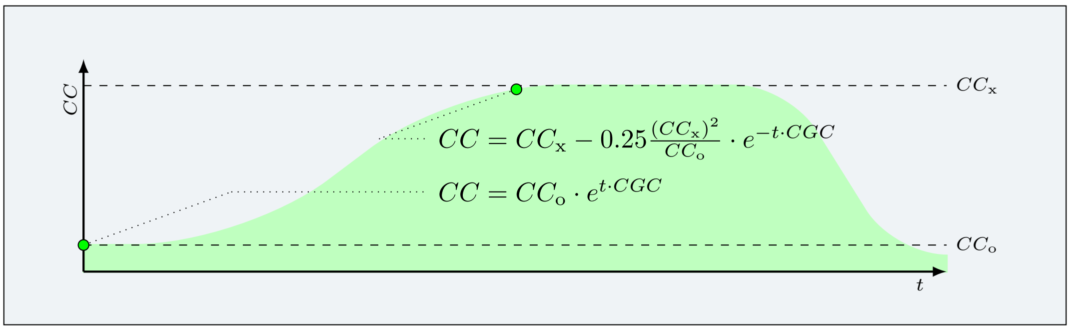


Figure A.8: The location of the canopy cover growth equations on the leaf development curve.

Derivation equation CDC

Similar as the derivation of the canopy growth coefficient, also the canopy decline coefficient (CDC) can be calculated. In the Aquacrop documentation the equation for the canopy decline is given as

$$CC = CC_{\mathrm{x}} \cdot \left[1 - 0.05\left(e^{\frac{CDC}{CC_{\mathrm{x}}} \cdot t} - 1\right)\right], \tag{A.12}$$

wherein CDC [$°C^{-1}$] is the canopy decline per heat unit. If the canopy cover at the end of the simulation is called CC_{end} and the amount of heat units accumulated between the moment of senescence and the moment of plant maturity (harvest) is called t_{decline}, the equation can be rewritten in terms of the canopy decline coefficient to

$$CDC = \frac{CC_{\mathrm{x}}}{t_{\mathrm{decline}}} \cdot \ln\left(21 - 20\frac{CC_{\mathrm{end}}}{CC_{\mathrm{x}}}\right). \tag{A.13}$$

The canopy decline coefficient can be calculated if the amount of heat units between the start of senescence and maturity is known, if the maximum canopy cover is known and if the canopy cover at the end of the simulation is known.

Harvest index for the foliage only

In Aquacrop only the foliage is simulated, with the remainder of the tree implicitly being present as biomass that is full-grown and can therefore be left out of the simulation. Since the harvest index is normally the fraction of the aboveground biomass weight that becomes yield, the harvest index has to be corrected to become the fraction of the foliage weight only. The relation can be written as

$$Y = HI_{\mathrm{st}} \cdot B_{\mathrm{st}} = HI_{\mathrm{fol}} \cdot B_{\mathrm{fol}} \tag{A.14}$$

which, if written in terms of the harvest index for the foliage, is

$$HI_{\mathrm{fol}} = HI_{\mathrm{st}} \cdot \frac{B_{\mathrm{st}}}{B_{\mathrm{fol}}}, \tag{A.15}$$

in which Y [ton/ha] is the yield, B_{st} [ton/ha] the standing (aboveground) biomass and B_{fol} [ton/ha] the weight of the foliage only. Furthermore HI_{st} [$-$] is the harvest index applicable on the whole standing biomass and HI_{fol} [$-$] the harvest index of the foliage only. Given equation A.15, the harvest index of the foliage can easily be calculated if the fraction between the standing biomass and the foliage biomass is known. In this study, this fraction is derived from literature.

Table A.11: The fraction foliage to total aboveground biomass for different woody plants. As can be seen, most information is available for plants not considered in this study. The foliage weight does not include the weight of fruits of the plant, if applicable.

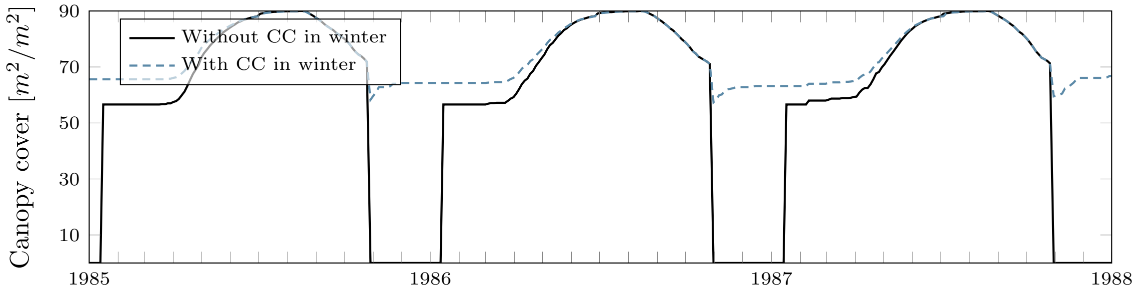
Plant	$B_{\mathrm{fol}}/B_{\mathrm{st}}$	Remark	Source
Apple tree	0.168	4 varieties, max. age 3 years, sick	*Beers and Hull* (1995)
Apple tree	0.205	producing trees, 4 temperatures	*Greer and Wunsche* (2003)
Banana plant	0.222	different nutrient treatments	*Lizarazo et al.* (2013)
Beech tree	0.162		*Konopka et al.* (2010)
Cacao plant	0.160	2 types of water stress	*Moser et al.* (2010)
Citrus tree	0.524	very high values	*Vu and Yelenosky* (1988)
Oak tree	0.115		*Konopka et al.* (2010)
Oil palm	0.368	producing trees	*Corley and Tinker* (2016)
Orange tree	0.258	from literature, range 0.449-0.116	*Morgan et al.* (2006)
Orange tree	0.271	own research	*Morgan et al.* (2006)
Pine tree	0.273		*Konopka et al.* (2010)
Pine tree	0.427	4 different water treatments	*Waghorn et al.* (2015)
Spruce tree	0.339		*Konopka et al.* (2010)
Average	0.268		

Table A.11 provides a literature overview of this fraction. As can be seen, the fractions vary considerably between different sources, even within one plant species (for example pine trees). Also, not all plants considered in this study are discussed in literature. Therefore a single fraction between the foliage weight and the standing biomass weight is derived for all plants. As the accuracy of table A.11 is little, the fraction is chosen as 0.25. As a consequence, the harvest index for the foliage will be 4 times higher than the harvest index for the whole plant. It is important to realize that this is a very rough estimate and the actual fraction will differ per plant and can deviate tremendously from this value. However, since the available literature does not allow for a better estimate we have to assume this fraction. Additional (field) research will help to derive a better fraction, possibly plant specific.

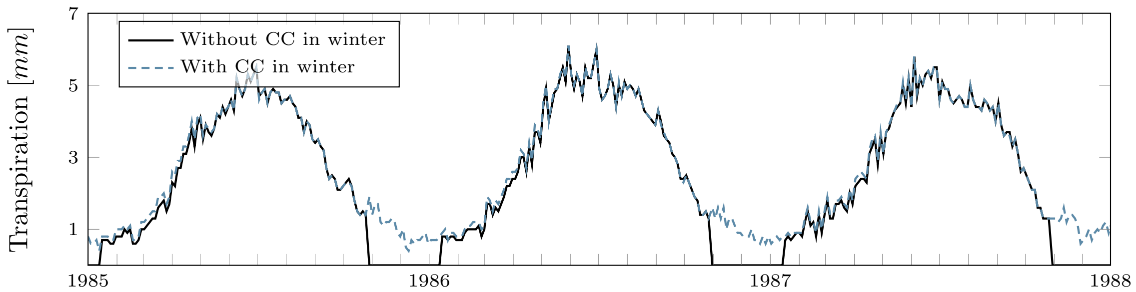
Canopy cover in winter

Aquacrop simulates the plant in this study as if it is a herbaceous plant such as a grain. This means that the plant starts growing at green-up and dies at the moment of harvest. The time between the harvest in one year and the green-up in the following year, the agricultural land can be considered wasteland as no growth takes place. As a result transpiration will become zero during these winter months.

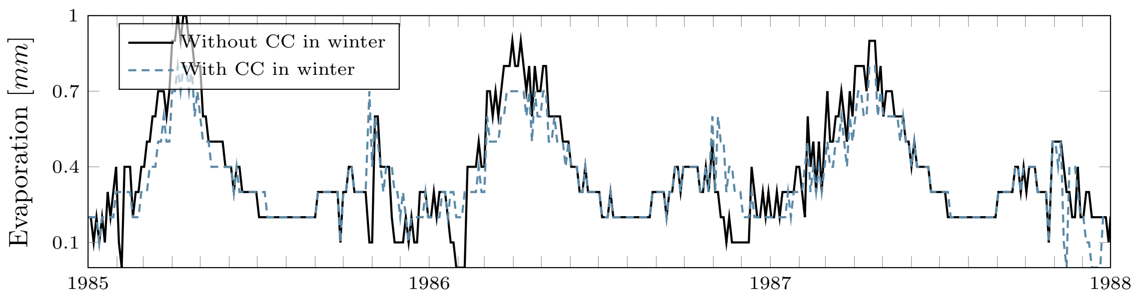
To avoid a winter period without transpiration, which is unrealistic for a perennial plant, the green-up of a new plant can take place directly after harvest. This by adjusting the green-up date



(a) Canopy cover 1985-1987 in Shandong



(b) Transpiration 1985-1987 in Shandong



(c) Evaporation 1985-1987 in Shandong

Figure A.9: The effect of winter canopy on the evaporation and transpiration. As can be seen, transpiration still occurs in the winter months when the green-up is directly after the harvest.

and guaranteeing instant emergence (by setting heat units to emergence on -1, see section A.3.1). The effect of this can be seen in figure A.9. In winter months, the green-up takes place directly after harvest, leaving the canopy cover intact. However, as a consequence, the plant development will start somewhere at the end of a certain year, instead of the beginning of the following year. The heat units accumulation in this extended growing period should be added to the amount of heat units to the growing phases, such as heat units to flowering and maturity (harvest), to avoid early senescence of the plant.

When the heat units are added to each of the growing phases, the resulting canopy cover is the one of figure A.9a. As the canopy development starts earlier, the canopy cover of the winter canopy will stay above the alternative without winter canopy deep into the life of the plant. However, as can be seen, at some point the two lines of canopy cover will join again and the remaining months of a plants life the plant development follows its original path. Because of the early emergence, the transpiration will be higher and thus the biomass and yield will be slightly higher.

Looking at figure A.9b, it can be seen that transpiration remains very close to the original one. The only significant difference is found in winter months, what was aimed for. It is hard to see in the figure, but in the rest of the year the transpiration is slightly higher than the original. The transpiration in the winter months fits quite smoothly between the transpiration at the moment of harvest and the transpiration at the original moment of green-up. In the situation shown here, there is a slight increase of transpiration visible directly after harvest, caused by the change of the transpiration coefficient $Kc_{\mathrm{tr,x}}$. More on this coefficient in the following section.

As can be seen in figure A.9c, the evaporation with the winter canopy deviates from the original situation a little. The evaporation tends to stay a little below the original one. This can be explained by the fact that the canopy cover is higher, and thus relative more transpiration and less evaporation takes place. This can also be seen with the sum of the two, the evapotranspiration, which is identical to the original one except for in the winter months. The evapotranspiration is not shown here.

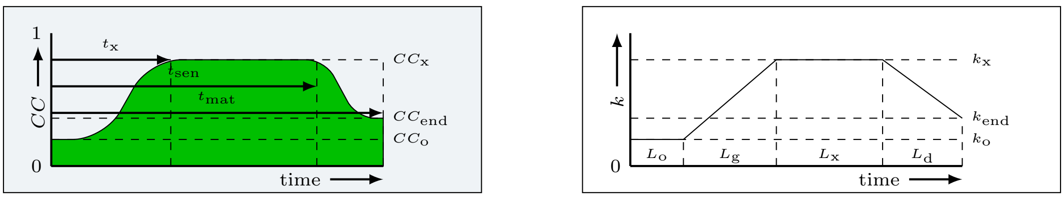
Because the winter canopy allows for a more realistic transpiration behaviour, it is implemented in the model.

Annual life cycle of a plant

As shown before, and shown again in figure A.10a, the canopy covers develops over a year. It grows from an initial canopy cover to a maximum canopy cover, where after it decreases again to its canopy cover at maturity. For each of the plants, these initial, maximum and final canopy cover have to be determined. In addition, the heat units from initial to maximum canopy cover, the number of heat units that it stays on its maximum and the number of heat units that it takes to go from maximum to final canopy cover have to be found.

To link the reference evapotranspiration with the actual evapotranspiration, a plant factor with the symbol k is generally used. This plant factor changes over the year, due to the fact that the plant develops over the year and thus the amount of transpiration that takes place from a plant changes. The change of this plant factor can be seen in figure A.10b. As can be seen, the plant factor is also characterized by an initial factor, a maximum factor and a final factor. *Chapagain and Hoekstra* (2004) give an overview of these plant factors for every Faostat plant (which include the apple tree, the grapevine, the olive tree and the oil palm). Also the length between the different phases is given by them.

With this information about the canopy cover and the plant factor, it is a small step to see that the data concerned with the plant factor can also be used to determine the different canopy covers



(a) Canopy cover (b) Plant factor

Figure A.10: The canopy cover on one hand and the comparable plant factor on the other hand.

and the time in between the phases. This is therefore also done in this study. The maximum canopy cover is determined from Apex, but the initial and final canopy cover will be of the same fraction of the maximum canopy cover as the initial and final plant factor are of the maximum plant factor. In equation form this looks like

$$CC_{\mathrm{o}} = CC_{\mathrm{x}} \cdot \frac{k_{\mathrm{o}}}{k_{\mathrm{x}}} \tag{A.16}$$

and

$$CC_{\mathrm{end}} = CC_{\mathrm{x}} \cdot \frac{k_{\mathrm{end}}}{k_{\mathrm{x}}}, \tag{A.17}$$

in which CC_{o} $[m^2/m^2]$, CC_{x} $[m^2/m^2]$ and CC_{end} $[m^2/m^2]$ are the initial, maximum and final canopy cover and k_{o} $[-]$, k_{x} $[-]$ and k_{end} $[-]$ are the initial, maximum and final plant factor. The maximum canopy cover is derived from the maximum leaf area index according to the equation from *Hsiao et al.* (2009). This equation is

$$CC_{\mathrm{x}} = 1.005 \left[1 - \exp\left(-0.6 \cdot \mathit{DMLA}\right)\right]^{1.2}, \tag{A.18}$$

wherein DMLA $[-]$ is the maximum leaf area index from Apex. It is worth noticing that this relation is derived by *Hsiao et al.* (2009) for maize and it is very doubtful if this relation has a generic applicability. However, no other relations are available. This relation is used, as it provides the logic relation that a high leaf area index will lead to a high canopy cover. It is kept in mind that this relation is not derived for the plants used in this study.

To determine the heat units to maximum canopy cover (t_{x}), the heat units to senescence (t_{sen}) and the heat units to the final canopy cover (or maturity) (t_{mat}), firstly the potential heat units are retrieved from Apex. From these potential heat units, the amount of heat units to each of the growing phases is equal to the fraction between the length of the plant factor phases to the complete length of the plant factor. The equations for each of the growing phases are

$$t_{\mathrm{mat}} = \mathit{HU}_{\mathrm{pot}} \cdot \frac{L_{\mathrm{g}} + L_{\mathrm{x}} + L_{\mathrm{d}}}{L_{\mathrm{g}} + L_{\mathrm{x}} + L_{\mathrm{d}}} = \mathit{HU}_{\mathrm{pot}}, \tag{A.19}$$

$$t_{\mathrm{sen}} = \mathit{HU}_{\mathrm{pot}} \cdot \frac{L_{\mathrm{g}} + L_{\mathrm{x}}}{L_{\mathrm{g}} + L_{\mathrm{x}} + L_{\mathrm{d}}}, \tag{A.20}$$

$$t_{\mathrm{x}} = \mathit{HU}_{\mathrm{pot}} \cdot \frac{L_{\mathrm{g}}}{L_{\mathrm{g}} + L_{\mathrm{x}} + L_{\mathrm{d}}} \tag{A.21}$$

and

$$t_{\mathrm{o}} = -1, \tag{A.22}$$

in which t_{mat} $[°C]$, t_{sen} $[°C]$, t_{x} $[°C]$ and t_{o} $[°C]$ are the accumulated amount of heat units to maturity, senescence, maximum canopy cover and emergence. $\mathit{HU}_{\mathrm{pot}}$ $[°C]$ is the potential heat units (see table A.9) and L_{g} $[days]$, L_{x} $[days]$ and L_{d} $[days]$ are the number of days that the plant factor stays at its initial value, grows from its initial value to its maximum value, stays at its maximum value and the amount of days it takes to decline from its maximum value to its final value. See also figure A.10b. t_{o} is set to -1. More information on this can be found in section A.3.1.

For flowering plants, it is also necessary to know the moment of flowering, the length of the flowering stage and the length of the phase in which harvest index is build up. These are three additional parameters that need to be set. The start of flowering is set equal to the moment of maximum canopy cover, as this coincides for many plants (*Chapagain and Hoekstra*, 2004). The length of the flowering stage is assumed to be half of the length that a plant keeps full canopy cover. The building of harvest index is assumed to stop halfway during the canopy decline, comparable with a default fruit plant in Aquacrop. In equation form these three phases look like

$$t_{\mathrm{fl}} = \mathit{HU}_{\mathrm{pot}} \cdot \frac{L_{\mathrm{g}}}{L_{\mathrm{g}} + L_{\mathrm{x}} + L_{\mathrm{d}}}, \tag{A.23}$$

Table A.12: The plant factors and the lengths between the different phases for the different plants studied in this report. These are used for Aquacrop. The values are retrieved from *Chapagain and Hoekstra* (2004). The plant factor between brackets is the corrected plant factor to avoid a constant canopy cover.

Plant	k_o	k_x	k_{end}	L_g	L_x	L_d
Apple tree	0.60	0.95	0.75	90	120	95
Grapevine	0.40	0.85	0.40	40	120	60
Olive tree	(0.55) 0.65	0.70	(0.69) 0.70	90	60	185
Oil palm	(0.80) 0.90	0.95	(0.94) 0.95	60	180	5

$$t_{fl,l} = HU_{pot} \cdot \frac{0.5 \cdot L_x}{L_g + L_x + L_d} \tag{A.24}$$

and

$$t_{HI,l} = HU_{pot} \cdot \frac{L_x + 0.5 \cdot L_d}{L_g + L_x + L_d}, \tag{A.25}$$

wherein t_{fl} [$°C$] is the amount of accumulated heat units till flowering and $t_{fl,l}$ [$°C$] and $t_{HI,l}$ [$°C$] are the length of flowering and harvest index build-up in accumulated heat units.

With the processes explained, the values of the plant factors and the lengths between phases can be given. *Chapagain and Hoekstra* (2004) provide an overview of these parameters. Their values are given in table A.12.

To use the plant factor values for Aquacrop, a complication arises; Aquacrop can not handle a constant canopy cover. For the canopy decline, the model runs normally in conditions where water stress is limited. However, when early canopy senescence is triggered, the model needs to decline and it crashes when the maximum canopy cover is equal to the final canopy cover (and thus the CDC is zero). To avoid this, the plant factor for the final phase has to be at least 0.01 lower than the maximum canopy cover.

For the initial canopy cover, the model also requires a growth. As can be seen in figure A.11, an initial canopy cover equal to the maximum canopy cover leads to strange results. The model does not crash, but because the CGC is never zero (even with $CC_o = CC_x$, see equation A.11), the model has some numerical problems. This problem occurs with the olive tree and the oil palm. At these plants, the minimum difference between the initial plant factor and the maximum plant factor should be at least 0.15 to overcome this problem. It is considered to compensate this decrease of plant factor with an increase of the canopy growth coefficient. However, as can be seen in figure A.12, an increase of the CGC also leads to irregularities in the canopy development. Also, a quite large increase of the CGC is required to create a significant effect on the development time. Therefore, no compensation of the CGC is done in this study. This will lead to somewhat lower transpiration rates in the canopy incline phase of a plants life than with the original plant factors.

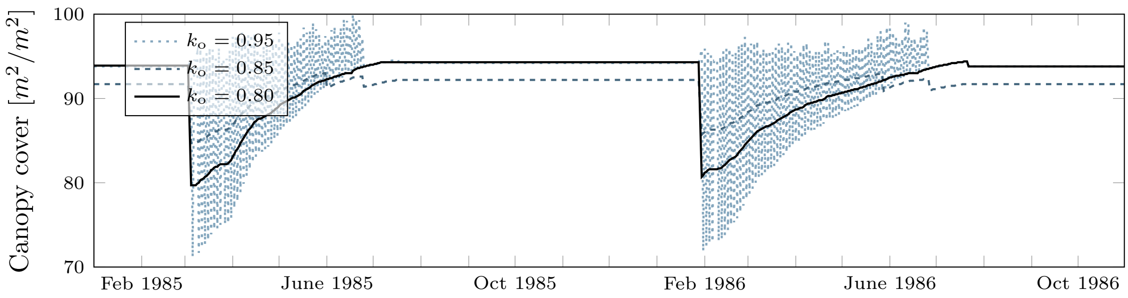


Figure A.11: The effect of the initial plant factor on the canopy cover. The maximum plant factor is in all cases 0.95. As can be seen, an initial plant factor close to the maximum one leads to numerical problems.

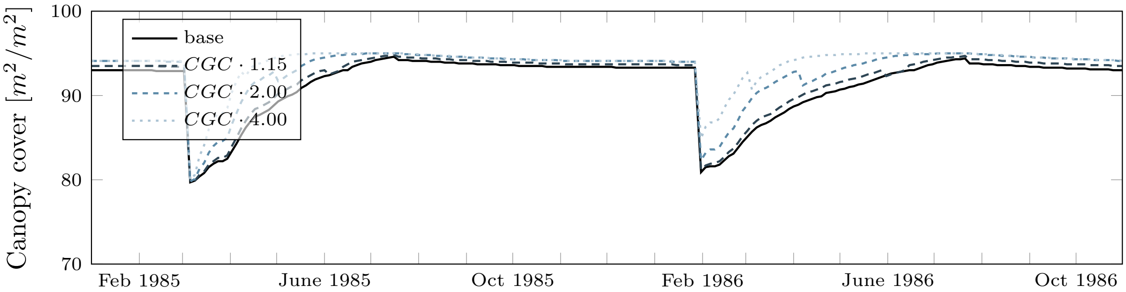


Figure A.12: The effect of a higher canopy growth coefficient on the canopy cover. As can be seen, a higher CGC leads to some inconsistent development patterns of the canopy cover.

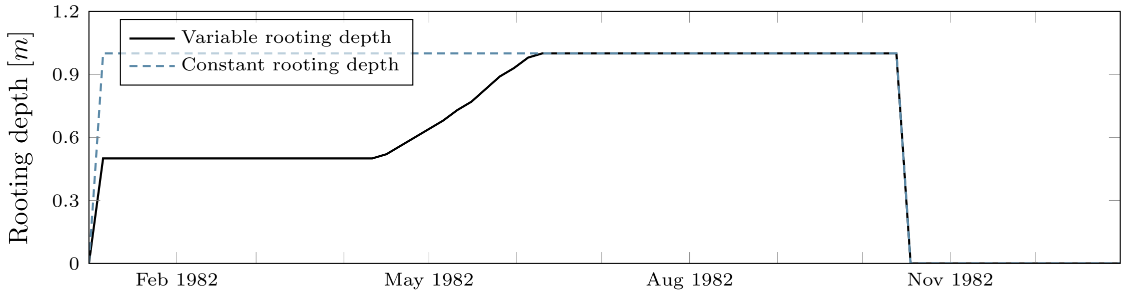


Figure A.13: A comparison between a variable rooting depth (minimum rooting depth different than maximum rooting depth) and a constant rooting depth (minimum rooting depth equal to maximum rooting depth) for Shandong in 1982.

Rooting depth

In Aquacrop, two parameters are the minimum and maximum rooting depth. These two parameters describe the initial and final rooting depth. Two additional parameters describe the time, in this case in heat units, it takes to go from the minimum to the maximum rooting depth and the shape of the root development.

For the simulations in this study, the plant is considered full grown. This means that not only the biomass is full grown, but also the roots should be fully developed from the start of the simulation. To reach this, the minimum rooting depth is set equal to the maximum rooting depth. Aquacrop recognizes this as a constant rooting depth equal to the maximum rooting depth. This can be seen in figure A.13.

To harmonize the values between Aquacrop and Apex, the maximum rooting depth is chosen from Apex. However, in Apex the maximum rooting depth is the minimum of the depth of the soil profile and the maximum rooting depth, with the reason that the roots of the plant can never be deeper than the soil profile itself. In Aquacrop, such a constrain is not available, but because of harmonization reasons the rooting depth in Aquacrop is also maximum the soil profile depth.

Plants per hectare

The amount of plants per hectare is an important parameter in Aquacrop. Together with the initial cover of a seedling it sets the initial canopy cover. From equation A.16 it is known how the initial canopy cover can be calculated. From table A.7a it is furthermore known that the soil cover per plant is set equal to 200 cm^2. To calculate the number of plants per hectare, the equation that can be used is

$$pph = \frac{CC_o \cdot 10^8}{200}, \tag{A.26}$$

wherein pph $[ha^{-1}]$ are the number of plants per hectare. The factor 10^8 comes from the fact that the soil cover per plant of 200 cm^2 should be calculated from square centimetre to hectare.

Table A.13: An overview of the Apex parameters that are important in this study.

Plant	ID	HI	TOP	TBS	DMLA	RDMX
Apple tree	82	0.10	22.00	6.00	4.00	1.00
Grapevine	123	0.02	30.00	10.00	2.00	2.00
Olive tree	136	0.10	22.00	6.00	3.20	1.10
Oil palm	250	0.12	30.00	10.00	4.45	3.00

A.4.3 Additional information Apex

For Apex, there are a few things that need to be settled before the plants can be simulated. First of all, plant parameters of Apex are presented that are important for the simulations in both Apex as Aquacrop. After this, the planting density is determined, followed by the number of years it takes for a plant to become mature, one of the Apex parameters in the operation file. After this, the tillage operations are explained and the effort to reduce the nutrient stresses is shown. Finally, the oil palm plant parameters are derived.

Apex parameters from plant file

To harmonize the models as much as possible, there are some parameters of Apex used for the creation of the plant file in Aquacrop. These parameters are the harvest index (HI), the optimal temperature for plant growth (TOP), the minimum temperature for plant growth (TBS), the maximum leaf area index (DMLA) and finally the maximum root depth (RDMX). The values of these parameters for each of the plants are given in table A.13, together with the plant ID used in Apex in the operation file. These parameters are directly derived from the Apex plant file.

Planting density

One of the parameters that need to be set in the operation file of Apex is the planting density. A higher planting density will result in a higher biomass per hectare and thus a higher yield and a higher leaf area. It seems therefore important to make a good estimate of the planting density. Apex accepts a density up to 500 plants per hectare.

The planting density is somewhat comparable with the maximum canopy cover of Aquacrop. A larger canopy cover will namely also lead to a higher transpiration and, since the biomass is derived from the transpiration (water-driven model), also a higher biomass and thus a higher yield. The maximum canopy cover in Aquacrop is derived from the maximum leaf area index of Apex. It seems therefore appropriate to also derive the planting density from this maximum leaf area index.

The planting density is determined by the equation

$$pph = \frac{DMLA}{10} \cdot 500, \tag{A.27}$$

in which pph $[ha^{-1}]$ is the number of plants per hectare and $DMLA$ $[m^2/m^2]$ the maximum leaf area index of a plant, which is a plant parameter in Apex. The 500 is the maximum planting density in Apex, and the 10 is the assumed maximum leaf area index for this study. The maximum leaf area

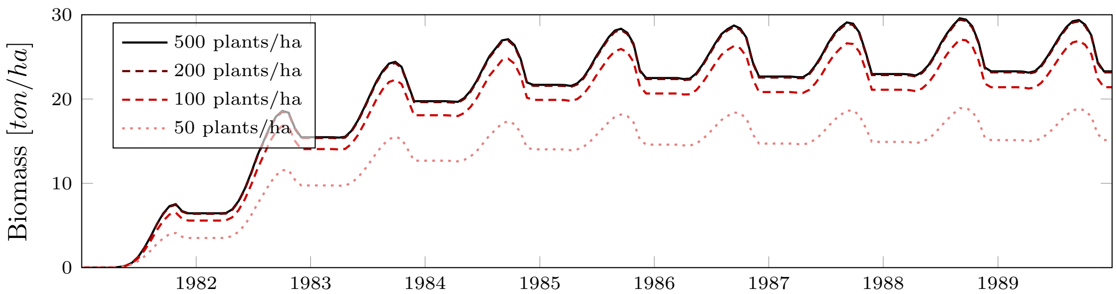


Figure A.14: The effect of the planting density on the total biomass (root weight and standing biomass) in Shandong for the apple tree.

index of 10 is based on the database of leaf area indices of *Iio and Ito* (2014), in which a leaf area index higher than 10 occurs only in less than five percent of the cases. This equation thus takes the leaf area index relative to the maximum and uses this ratio also for the planting density.

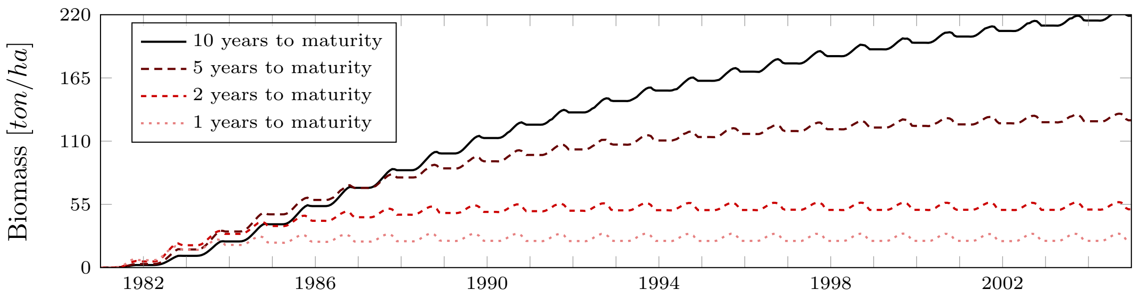
This relation seems like a rough estimate, and it is. However, as can be seen in figure A.14, the model is not as sensitive to different planting density as one would expect. It was expected that a planting density half the size would also half the biomass production (and thus the yield), but this is clearly not the case. Therefore it is chosen to use this rough theoretical approximation of the planting density in the operation files.

Years to maturity

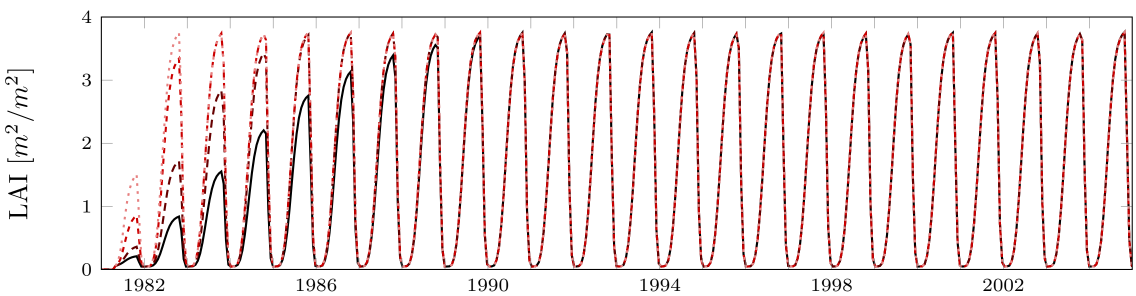
Next to the planting density, a parameter that states the number of years it takes a tree to become mature (or full-grown) is present in the operation file. This parameter needs to be set for every plant in this study, except the grapevine as this is not a tree. The effect of the time to maturity can be seen in figure A.15. The time to maturity has a strong effect on the biomass (and thus the yield), as the model keeps accumulating biomass for a tree. As the leaf area index is bounded to a maximum, the *LAI* stabilizes after the years to maturity is reached and therefore the effect of the time to maturity on the evaporation and transpiration is limited.

In Aquacrop, a mature plant has reached the end of its life and dies, but in Apex the maturity of the tree is not well defined. A tree is considered mature when the heat unit index of the plant has reached one (potential heat units is reached). Since the leaf area index develops with the heat unit index, the LAI is also at its full when the tree is mature. What the role of biomass is in this remains unclear, as this is not discussed in the documentation of the model.

In literature there is no clear overview of the time it takes for a plant to become fully grown and can thus be considered mature in Apex. An estimate is therefore made for this study, although the parameter is important for the yield (see figure A.15). For this study, it is chosen to set the time to maturity for all plants on five years. This seems reasonable, as this still allows for a clear development phase of the plant, while in most cases also reaching an equilibrium for the biomass within the 30 years of simulation, which is convenient for the analysis of the results. In reality, the time would probably be somewhat higher (see for example *Flore et al.* (1984)).



(a) Total biomass 1981-2004 in Shandong



(b) Leaf area index 1981-2004 in Shandong

Figure A.15: The effect of the time to maturity on the biomass and the leaf area index. The biomass (and thus the yield) rises when the years to maturity increase.

Tillage operations

In the operation file of Apex, the tillage operation ID numbers need to be set. For sowing operations, tillage number 686 is used, which is sowing by hand. For the harvest operations, harvest by hand is applied, which is operation 683. For the application of nutrients (see next section), tillage operation 684 is used, which is fertilizer by hand.

Reducing nutrient stresses

There are no nutrient stresses being simulated in Aquacrop. To avoid these stresses also in Apex, automatic fertilizer is set (see section A.3.2). This will start fertilizing as soon as stresses are noticed. In addition to this, some precautionary fertilization is applied every year. On the date that sowing took place, the maximum amount of fertilizer is applied in the operation file. This amount, 500 kilogram per hectare, is applied with tillage number 684, which is fertilization by hand. The type of fertilizer applied is number 53, which is nitrogen.

Implementing oil palm

The apple tree, the grapevine and the olive tree are all standard in Apex. Unfortunately, oil palm is not and it is therefore necessary to add this plant to the plant file of Apex. The parameters, all 64, need to be estimated. A lot of these parameters, however, will be irrelevant as they are applicable to processes that are not considered in this study, such as costs.

To develop the oil palm effectively, the coconut palm is used as a basis. Most of the parameters of this plant will be used for the oil palm as well. Based on *Legros et al.* (2009), there are four parameters adjusted. These are the harvest index (HI), the maximum leaf area index (DMLA), the maximum height (HMX) and the maximum root depth (RDMX) of the plant. *Legros et al.* (2009) present a harvest index for the oil palm of 0.48. This seems high, but this is the dry fruit biomass production in relation with the dry aboveground biomass production. In other words, this is the

Table A.14: The parameters of the newly created oil palm in Apex, based on the coconut palm and the apple tree, both already in the model. The asterisk (*) represent a user definable number or name.

Oil palm								
#	=	*250	NAME	=	*OILP	WA	=	24.00
HI	=	0.12	TOP	=	30.00	TBS	=	10.00
DMLA	=	4.45	DLAI	=	0.90	DLAP1	=	15.05
DLAP2	=	50.99	RLAD	=	1.00	RBMD	=	1.00
ALT	=	3.00	GSI	=	0.007	CAF	=	0.85
SDW	=	100.00	HMX	=	9.00	RDMX	=	3.00
WAC2	=	660.30	CNY	=	0.0015	CPY	=	0.0003
CKY	=	0.00	WSYF	=	0.05	PST	=	0.60
COSD	=	0.00	PRYG	=	0.00	PRYF	=	0.00
WCY	=	0.50	BN1	=	0.006	BN2	=	0.002
BN3	=	0.0015	BP1	=	0.0007	BP2	=	0.0004
BP3	=	0.0003	BK1	=	3.39	BK2	=	3.39
BK3	=	3.39	BW1	=	8.00	BW2	=	5.10
BW3	=	15.99	IDC	=	8.00	FRST1	=	0.50
FRST2	=	4.75	WAVP	=	0.40	VPTH	=	0.20
VPD2	=	20.00	RWPC1	=	0.40	RWPC2	=	0.20
GMHU	=	0.00	PPLP1	=	120.88	PPLP2	=	20.13
STX1	=	0.10	STX2	=	0.00	BLG1	=	0.05
BLG2	=	0.00	WUB	=	0.30	FTO	=	0.00
FLT	=	0.00	CCEM	=	0.00	IPDU	=	0.00
TRE1	=	0.00	TRE2	=	0.00	LAYR	=	0.00
WDRM	=	0.00	EXTC	=	0.00	GPAL	=	0.00
FNAME	=	*OILP						

harvest index for Aquacrop, as it only considers the build up of biomass within the year. Assuming the harvest index relation between the yearly biomass build and the total biomass build of a factor four (see section A.4.2), the harvest index for Apex becomes 0.12. The leaf area index they observed had an average of 4.45. The average stem height they observed was about 9 meters. The maximum root depth is set to 3 meters, as they observed most roots to be present within these 3 meters.

Only changing these four parameters will not lead to a functioning tree in Apex. To allow for plant growth, the plant population parameters PPLP1 and PPLP2 should be changed. The parameters belonging to the coconut tree are such that a plant will not grow. For these two parameters, the parameters for the apple tree are used. Furthermore, the partitioning of the total biomass into root weight and aboveground biomass need to be adjusted, as the coconut tree parameters are such that over 90 percent of the total biomass is allocated to the roots, which is unrealistic. The parameters concerned with this, RWPC1 and RWPC2, are also taken from the apple tree. An overview of all parameters of the created oil palm file is found in table A.14.

To simulate oil palms in Apex, there is one important step remaining. In this study, oil palms are simulated in Malaysia, at a latitude of 2.25 decimal degrees. Unfortunately, Apex gives strange results at such low latitudes, as the model simulates dormancy in the period where the day length is within an hour of the shortest day length. In other words, when the shortest day length is six hours, the model simulates dormancy every day that the day length is lower than seven hours. Around the equator, however, this condition leads to a situation where there is always dormancy, as the day length is always within the hour of the minimum day length. Therefore, the used latitude for oil palm is set to 45.00 decimal degrees. Another option would be to adjust the parameters file (PARMS.DAT) for the oil palm such that the dormancy criterion of an hour is reduced to any fraction of this. However, as this leads to strange model behaviour and because of the warnings given with the parameters file, the latitude is changed instead.

A.4.4 Plant data

Based on the information given in section A.4.2 for Aquacrop and section A.4.3 for Apex, all of the plant or location specific parameters of the models can be filled in. In table A.15 an overview on how to determine the parameters in each of the files.

With the information on how to get the plant specific parameters, the files to run the simulations can be created. In table A.16 an overview is given of the values for all parameters at all locations. Note that the dates and the operation lines are left out of the table. An example of a project file of Aquacrop is shown in figure A.16a. An example of a operation file of Apex is given in figure A.16b.

In Aquacrop, the green-up date (first day of cropping period in figure A.16a) is the date given in table A.9. This is only for the first year; the following years the first day of the cropping period is the day following the harvest date. This to keep canopy intact throughout the winter (see section A.4.2). The harvest date (last day of cropping period) is the date given in table A.10. The first day of the simulation is always the same as the first day of the cropping period, except for the first year, when it is equal to the first of January. The last day of the simulation is one day before harvest. When setting it equal to the harvest date, the model will start the simulation of the new season a day later, causing a day with no canopy cover and thus no transpiration. To avoid this, the harvest date is set one day early. In the last year, the last day of the simulation period is equal to the 31st of December.

For Apex, the first operation is always the sowing date of the plant. This should be entered with its corresponding time to maturity, plant number and density. On the same day of sowing, fertilizer application takes place to reduce nutrient stresses. The maximum amount of fertilizer is applied, in combination with the correct plant number, tillage number and fertilizer number. Every year this operation is repeated to prevent nutrient stress. On top of these sowing operation and fertilizer applications, harvest takes place on the dates given in table A.10. Also for harvest operations, the correct plant number, tillage number and time to maturity should be entered correctly.

Table A.15: An overview of all the plant or location specific parameters and the way they can be determined. The motivation for the method to determine them is explained in sections A.4.2 and A.4.3.

(a) Aquacrop

Aquacrop parameters		
Symbol	Parameter	Derivation
T_{base}	Base temperature	Apex paramtr. TBS (table A.13)
GD_{upper}	Min. GDD for biomass	Apex paramtr. TOP-TBS, < 20 °C (table A.13)
t_{mat}	Length cycle in GDD	Potential heat units (table A.9)
$Kc_{\text{Tr,x}}$	Crop coefficient	Maximum plant factor (table A.12)
Z_{o}	Min. eff. root depth	Min. Apex paramtr. RDMX (table A.13) and soil profile depth
Z_{x}	Max. eff. root depth	Min. Apex paramtr. RDMX (table A.13) and soil profile depth
pph	Plants per hectare	Derived from CC_{o} (equation A.26)
CC_{x}	Max. CC	Derived from Apex paramtr. DMLA (eq. A.18)
HI_{o}	Reference HI	Derived from Apex paramtr. HI (equation A.15)
t_{sen}	GDD to senescence	Derived from plant factor (equation A.20)
t_{mat}	GDD to maturity	Potential heat units (equation A.19, table A.9)
t_{fl}	GDD to flowering	Derived from plant factor (equation A.23)
$t_{\text{fl,l}}$	Length flow. stage GDD	Derived from plant factor (equation A.24)
CGC	CGC in GDD	Derived from CC_{o} and CC_{x} (equation A.11)
CDC	CDC in GDD	Derived from CC_{end} and CC_{x} (equation A.13)
$t_{\text{hi,l}}$	Building up HI in GDD	Derived from plant factor (equation A.25)
ke_{x}	Soil evap. coeff.	Maximum plant factor (table A.12)
Aquacrop remaining		
Symbol	Parameter	Derivation
–	Dates simulation & plant	See text in this section

(b) Apex

Apex parameters		
Symbol	Parameter	Derivation
INPS	Soil number	See tables A.4 and A.6
YCT	Latitude	See appendix C, table C.1. Oil palm 45.00
XCT	Longitude	See appendix C, table C.1
BIR	Irrigation fraction	1 if irrigated simulation, 0 if not
YLAT	Latitude	See appendix C, table C.1. Oil palm 45.00
XLOG	Longitude	See appendix C, table C.1
Apex remaining		
Symbol	Parameter	Derivation
–	Operation lines	See text in this section

Table A.16: An overview of the parameter values for each of the locations for the first year. In other years the heat units to certain growth stages in Aquacrop differs because of the winter canopy.

Symbol	Apple tree (Sh)	Apple tree (Ga)	Apple tree (Wa)	Grapevine	Olive tree	Oil palm
Aquacrop parameters						
T_{base}	6.0	6.0	6.0	10.0	6.0	10.0
GD_{upper}	16.0	16.0	16.0	20.0	16.0	20.0
t_{mat}	2763	2267	1675	2002	3185	5966
$Kc_{\text{Tr,x}}$	0.95	0.95	0.95	0.85	0.70	0.95
Z_{o}	1.00	1.00	1.00	1.00	1.00	1.00
Z_{x}	1.00	1.00	1.00	1.00	1.00	1.00
pph	283141	283141	283141	153817	326422	388241
CC_{x}	0.90	0.90	0.90	0.65	0.83	0.92
HI_{o}	40	40	40	8	40	48
t_{sen}	1902	1561	1153	1456	1426	5844
t_{mat}	2763	2267	1675	2002	3185	5966
t_{fl}	815	669	494	364	856	1461
$t_{\text{fl,l}}$	544	446	330	546	285	2192
CGC	0.003661	0.004463	0.006040	0.009010	0.003234	0.001846
CDC	0.001720	0.002096	0.002837	0.002933	0.000119	0.001447
$t_{\text{hi,l}}$	1517	1245	920	1365	1450	4444
ke_{x}	0.95	0.95	0.95	0.85	0.70	0.95
Apex parameters						
INPS	22455	186186	22440	210126	18516	207110
YCT	35.56	46.45	46.97	39.31	36.90	45.00
XCT	119.16	28.65	-120.76	-2.81	-5.21	103.13
BIR	1 or 0	1 or 0	1 or 0	1 or 0	1 or 0	1 or 0
YLAT	35.56	46.45	46.97	39.31	36.90	45.00
XLOG	119.16	28.65	-120.76	-2.81	-5.21	103.13

```
      4.0       : AquaCrop Version (June 2012)
29221           : First day of simulation period - 22 March 1981
29498           : Last day of simulation period - 24 July 1981
29235           : First day of cropping period - 22 March 1981
29499           : Last day of cropping period - 24 July 1981
      4         : Evaporation decline factor for stage II
0.95            : Ke(x) Soil evaporation coefficient for fully wet and non-shaded soil...
      5         : Threshold for green CC below which HI can no longer increase (% cover)
     70         : Starting depth of root zone expansion curve (% of Zmin)
      5.00      : Maximum allowable root zone expansion (fixed at 5 cm/day)
     -6         : Shape factor for effect water stress on root zone expansion
     20         : Required soil water content in top soil for germination (% TAW)
      1.0       : Adjustment factor for FAO-adjustment soil water depletion (p) by ETo
      3         : Number of days after which deficient aeration is fully effective
      1.00      : Exponent of senescence factor adjusting drop in photosynthetic activ...
     12         : Decrease of p(sen) once early canopy senescence is triggered (% of p...
      0         : Thresholds for water stress for stomatal closure are NOT affected by...
     30         : Depth [cm] of soil profile affected by water extraction by soil evap...
      0.30      : Considered depth (m) of soil profile for calculation of mean soil wa...
0               : CN is adjusted to Antecedent Moisture Class
     20         : salt diffusion factor (capacity for salt diffusion in micro pores) [%]
    100         : salt solubility [g/liter]
     16         : shape factor for effect of soil water content gradient on capillary ...
     12.0       : Default minimum temperature ($ ^\circ $C) if no temperature file is ...
     28.0       : Default maximum temperature ($ ^\circ $C) if no temperature file is ...
1               : Default method for the calculation of growing degree days
-- 1. Climate (CLI) file
   climatedata.CLI
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
   1.1 Temperature (TMP) file
   climatedata.TMP
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
   1.2 Reference ET (ETo) file
   climatedata.ETo
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
   1.3 Rain (PLU) file
   climatedata.PLU
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
   1.4 Atmospheric CO2 (CO2) file
   climatedata.CO2
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
-- 2. Crop (CRO) file
   Shandong_1.CRO
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
-- 3. Irrigation (IRR) file
   Inet.IRR
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
-- 4. Management (MAN) file
   (None)
   (None)
-- 5. Soil profile (SOL) file
   SOL_224_55.SOL
   C:\Zero\AquaCrop\Model\AquaCrop_Shandong\DATA\
-- 6. Groundwater (GWT) file
......
```

(a) Example project file of Aquacrop for the apple tree in Shandong

Figure A.16: Example of the project file of Aquacrop and the operation file of Apex for the apple tree in Shandong. Only the first 55 lines are shown.

```
  Simulation schedule of apple trees
 28 500 261 268 266 265 267
 1  1 15  686   1   82   5    0.00    0.00    0.00    0.00  200.00    0.00    0.00
 1  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 1 10  6  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 2  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 2 10 13  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 3  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 3 10  9  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 4  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 4 11  3  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 5  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 5 10 28  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 6  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 6 10 30  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 7  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 7 10 27  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 8  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 8 10 15  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 9  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
 9 10 16  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
10  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
10 10 16  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
11  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
11 10 23  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
12  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
12 10 20  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
13  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
13 10 27  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
14  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
14  9 28  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
15  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
15 10 17  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
16  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
16 10 25  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
17  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
17  9 30  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
18  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
18 10  6  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
19  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
19 10  6  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
20  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
20  9 30  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
21  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
21 10  4  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
22  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
22 10  3  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
23  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
23 11  1  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
24  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
24 10  9  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
25  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
25 10  9  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
26  1 15  684   1   82  53  500.00    0.00    0.00    0.00    0.00    0.00    0.00
26 10  7  683   1   82   5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
......
```

(b) Example operation file of Apex for the apple tree in Shandong

Figure A.16: (continued) Example of the project file or Aquacrop and the operation file of Apex for the apple tree in Shandong. Only the first 55 lines are shown.

Appendix B

Evapotranspiration function

Aquacrop calculates the actual evapotranspiration based on the input variable reference evapotranspiration. Apex on the other hand calculates evapotranspiration as a function of solar radiation. To make sure that differences in actual evapotranspiration are not caused by the underlying input, harmonization of the evapotranspiration functions between the two models is required. This harmonization is described in this chapter.

B.1 Background

Aquacrop calculates the evaporation and transpiration based on the input variable reference evapotranspiration. Reference evapotranspiration is evapotranspiration from a normalized surface, consisting of a grass with a height of 0.12 meter and an albedo of 0.23. The advantage of using such a reference evapotranspiration is that it describes the potential evapotranspiration independent of the plant type, plant development and management (*Allen et al.*, 2006). The reference evapotranspiration depends on atmospheric variables as temperature, radiation, wind, humidity and more. *De Graaf et al.* (2014) provides a dataset of reference evapotranspiration from 1958 to 2010. This dataset is calculated according to the Penman-Monteith method.

Instead of using a reference evapotranspiration, Apex calculates evapotranspiration itself. For this, it needs variables that also play a role for the reference evapotranspiration. As Apex has different evapotranspiration functions, the exact climatic variables the model needs depend on the function used. Apex can calculate the evapotranspiration based on Penman, Penman-Monteith, Priestley-Taylor, Hargreaves and Baier-Robertson. As the reference evapotranspiration dataset is derived with Penman-Monteith, an obvious way to harmonize the models is to calculate the evapotranspiration in Apex also with this method.

Unfortunately, the Penman-Monteith equation, and also the Penman equation, cannot be used in this study. The climate variables necessary for these equations are namely temperature, solar radiation, wind speed and relative humidity. Only the first two are available in this study. The other three evapotranspiration methods only require temperature and solar radiation. These can therefore be used.

Apex calculates the evapotranspiration in first place as potential evapotranspiration. This is independent of any plant characteristics. To harmonize the evapotranspiration between the models, the potential evapotranspiration from Apex is used as reference evapotranspiration input in Aquacrop. In this way, the evapotranspiration functions in Aquacrop and Apex are harmonized in the sense that they are derived from the same evapotranspiration function (Priestley-Taylor, Hargreaves or Baier-Robertson) and therefore show the same trends and possible irregularities.

B.2 Evapotranspiration functions

To choose from the three evapotranspiration functions, the equations for these functions are given below. Following this, the root mean square error is determined for each of the functions and for each of the locations considered in this study in comparison with the dataset provided by *De Graaf* *et al.* (2014). Finally, the evapotranspiration rates are visualized for each of the evapotranspiration functions.

B.2.1 Calculation procedure

The evapotranspiration function in Apex for Priestley-Taylor is

$$ET_{\text{p}}(i) = 1.28 \cdot \frac{R_{\text{net}}(i) \cdot (1 - \alpha_{\text{grass}})}{H_{\text{vap}}(i)} \cdot \frac{s}{s + \gamma}, \tag{B.1}$$

in which $ET_{\text{p}}(i)$ $[mm/day]$ is the potential or reference evapotranspiration on the day i, $R_{\text{net}}(i)$ $[MJ/m^2/day]$ the net radiation on that day, α_{grass} $[-]$ the albedo of grass (0.23), $H_{\text{vap}}(i)$ $[mm/kg]$ the latent heat of vaporization on day i, which is a function of the daily maximum and minimum temperature, $s(i)$ $[kPa/°C]$ the slope of the saturation vapor pressure curve on day i, which is a function of the daily maximum and minimum temperature, and γ $[kPa/°C]$ the psychometric constant, which depends on the elevation of the location. Going deeper in this equation, the net solar radiation can be described by

$$R_{\text{net}}(i) = f(R_{\text{max}}(j), \alpha_{\text{grass}}, R_{\text{out}}(i), R_{\text{sol}}(i), \tag{B.2}$$

wherein $R_{\text{max}}(j)$ $[MJ/m^2/day]$ is the maximum radiation determined by the day of the year j and the latitude. This calculation assumes a clear sky. Also, R_{out} $[MJ/m^2/day]$ is the outgoing solar radiation, which is determined by by the daily maximum and minimum temperature. $R_{\text{sol}}(i)$ $[MJ/m^2/day]$ is the mean daily solar radiation, which is provided by the user. This is different than the maximum solar radiation as clouds will cause less radiation to reach the earth surface.

In Apex, the Hargreaves evapotranspiration function is determined by the equation

$$ET_{\text{p}}(i) = 0.0032 \cdot \frac{R_{\text{max}}(j)}{H_{\text{vap}}(i)} \cdot \left(\frac{T_{\text{max}}(i) + T_{\text{min}}(i)}{2} + 17.8\right) \cdot (T_{\text{max}}(i) + T_{\text{min}}(i))^{0.6}, \tag{B.3}$$

in which $T_{\text{max}}(i)$ $[°C]$ and $T_{\text{min}}(i)$ $[°C]$ are the maximum and minimum temperature on day i.

Finally, Baier-Robertson is incorporated in Apex as

$$ET_{\text{p}}(i) = 0.288 \cdot T_{\text{max}}(i) - 0.144 \cdot T_{\text{min}}(i) + 0.139 \cdot R_{\text{max}}(j) - 4.391. \tag{B.4}$$

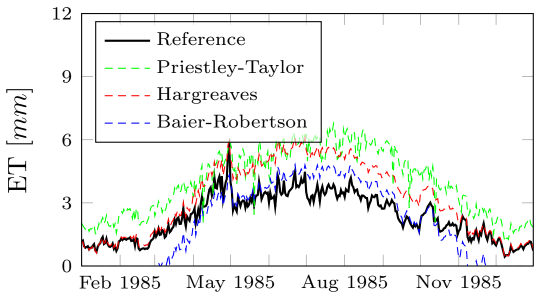
B.2.2 Performance according to RMSE

To compare the evapotranspiration function with the dataset of *De Graaf et al.* (2014), the root mean squared error is used. By calculating this it will become clear which evapotranspiration function of Apex lies closest to *De Graaf et al.* (2014). This is useful to know, as this reference evapotranspiration is checked for irregularities. The root mean square error rates the performance of the function according to

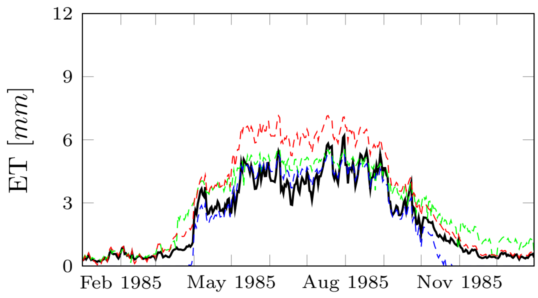
$$\text{RMSE} = \frac{1}{n} \cdot \sum_{n=0}^{n=i} (ET_{\text{ref}}(i) - ET_{\text{p}}(i))^2, \tag{B.5}$$

where RMSE $[(mm/day)^2]$ is the root mean squared error and $ET_{\text{ref}}(i)$ $[mm/day]$ is the reference evapotranspiration from *De Graaf et al.* (2014). A perfect fit between the reference from *De Graaf et al.* (2014) and the evapotranspiration from one of the function would lead to a RMSE of zero. The higher the number, the further the calculated evapotranspiration lies from the reference.

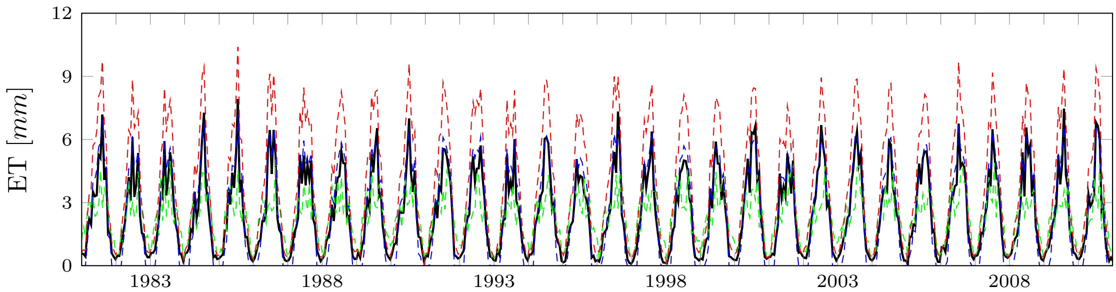
In table B.1 an overview of the calculated values of the root mean squared error is given for all locations used in this study. As can be seen, the Baier-Robertson clearly lies closer to the reference case than Priestley-Taylor and Hargreaves. On average, this method has a daily deviation from the reference dataset of 0.74 millimeter per day. Priestley-Taylor and Hargreaves have almost the double deviation. Based on this criteria alone, the Baier-Robertson method will be chosen as it lies closest to the reference evapotranspiration provided by *De Graaf et al.* (2014).



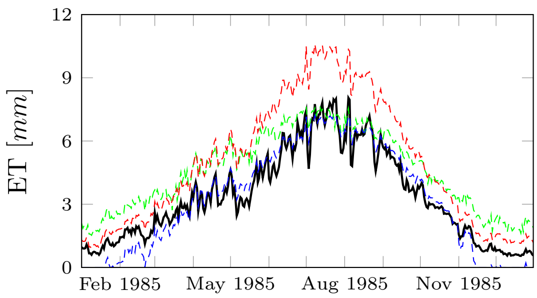
(a) Shandong 1985



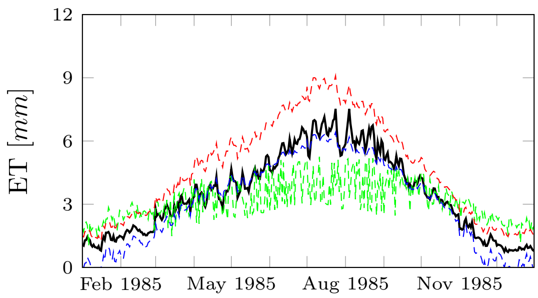
(b) Gagauzia 1985



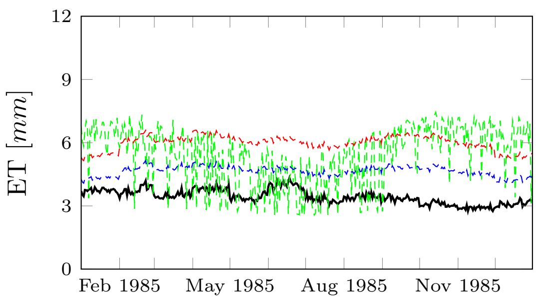
(c) Washington 1981-2010



(d) Castilla-La Mancha 1985



(e) Andalusia 1985



(f) Johor 1985

Figure B.1: The performance of the evapotranspiration functions in Apex for the whole period 1981-2010 in Washington and for 1985 at the other locations.

Table B.1: The root mean squared error (RMSE) for each of the locations for all evapotranspiration functions in Apex. The values are calculated in comparison to the reference evapotranspiration given with Penman-Monteith by *De Graaf et al.* (2014).

Location	Priestley-Taylor	Hargreaves	Baier-Robertson
Shandong	1.57	1.12	0.94
Gagauzia	0.81	1.20	0.62
Washington	1.25	1.66	0.58
Castilla-La Mancha	1.32	1.85	0.60
Andalusia	1.48	1.28	0.63
Johor	2.45	2.42	1.16
Average	1.48	1.59	0.75

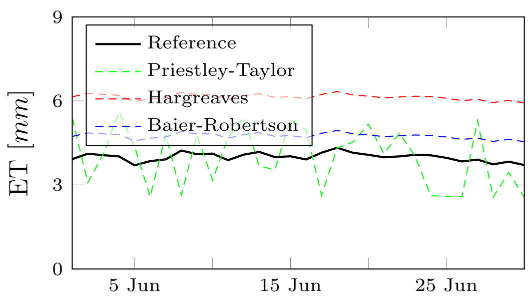
B.2.3 Visual performance

Figure B.1 shows the performance of the evapotranspiration functions. For Washington, the whole period 1981 to 2010 is shown, while for the rest of the locations only 1985 is given here.

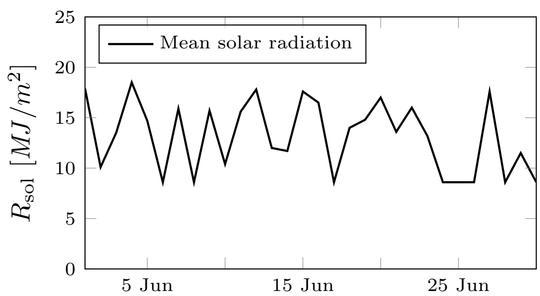
Priestley-Taylor seems to simulate the evapotranspiration quite close to the reference evapotranspiration in Shandong, Gagauzia, Washington and Castilla-La Mancha. However, in Andalusia and Johor the functions shows some very unstable behaviour. The other models do not show this. Comparing the equation of Priestley-Taylor (equation B.1) with the equations of Hargreaves (equation B.3) and Baier-Robertson (equation B.4), Priestley-Taylor stands out as it depends on a solar radiation that is corrected for cloud cover. As can be seen in figure B.2, the dynamic behaviour of the Priestley-Taylor evapotranspiration indeed shows the exact same trend as the mean solar radiation. So it is indeed this solar radiation that causes the rough behaviour of this function. This net solar radiation is derived with the method described by *Allen et al.* (1998). The reason that the solar radiation shows irregular behaviour has to do with the fact that the cloud cover can fluctuate a lot over the days. Maybe there is some physical phenomena that causes more cloud fluctuations in these regions. Another explanation is that there are problems with the data.

Looking at the function of Hargreaves, there is a rather consequent overestimation of evapotranspiration in comparison with the other functions in the summer months. In the winter months the model lies close to the rest. In Johor, where the seasons are not really visible, the overestimation is rather constant.

Baier-Robertson estimates the evapotranspiration closest to the reference evapotranspiration for all locations. However, it can also be seen that in winter months the evapotranspiration reduces to zero which can be problematic when using this evapotranspiration function. Zero reference evapotranspiration would namely also result in zero net evapotranspiration. The water use of the plant will be underestimated in the winter months with this function. The reason that the evapotranspiration becomes zero has to do with the fact that equation B.4 will go negative.



(a) Evapotranspiration Johor June 1985



(b) Mean radiation Johor June 1985

Figure B.2: The evapotranspiration and solar radiation for Johor. The unstable behaviour of Priestley-Taylor is caused by the input variable mean solar radiation.

B.2.4 Selecting a function

If we choose an evapotranspiration function based on the root mean squared error alone, the Baier-Robertson method would be preferred as this has the lowest RMSE value. However, from figure B.1, it can be seen that the Baier-Robertson method tends to go to zero in winter months. The second choice based on the RMSE will be Priestley-Taylor, but this models shows very unstable behaviour at some locations because of the mean solar radiation that is provided to the model.

While Hargreaves has the highest RMSE and thus estimates the evapotranspiration furthest from the reference evapotranspiration, this function is chosen in this study. This because Hargreaves is the only function that estimates a consequent, useful evapotranspiration during the whole year and at all locations. This is considered more important that the fact that the RMSE is deviating quite a lot from the reference case.

Appendix C

Location of plants

In this study four plants are simulated with Aquacrop and Apex. The selection of the plants is based on their phenological characteristics (evergreen and deciduous broadleaved trees and shrubs) and their climatic range. These four plants are the apple tree, the grapevine, the olive tree and the oil palm. To keep the amount of computing time and data processing time manageable, three of the four plants are simulated on only one location. The fourth plant, the apple tree, is simulated on three locations to make additional comparisons between the model possible.

To select representative locations for the plants, a climate map and a soil map are used. These are firstly explained. Based on these the locations are selected. Hereafter, literature values of yield and evapotranspiration are presented to serve as a reference for the simulated values. Finalizing this appendix, three soils are selected for additional comparisons.

C.1 Climate and soil maps

To narrow down a location from a whole region and to select multiple locations for the apple tree, climate and soil maps are used. Figure C.1 shows the soil map used for the selection of locations. This soil map is characterised by 253 different soil types. Types are characterized by different sand, silt and clay contents. From these contents, other soil parameters can be derived for a topsoil layer and a subsoil layer. For details about the soils the reader is referred to the source of this soil map (*De Lannoy et al.*, 2014).

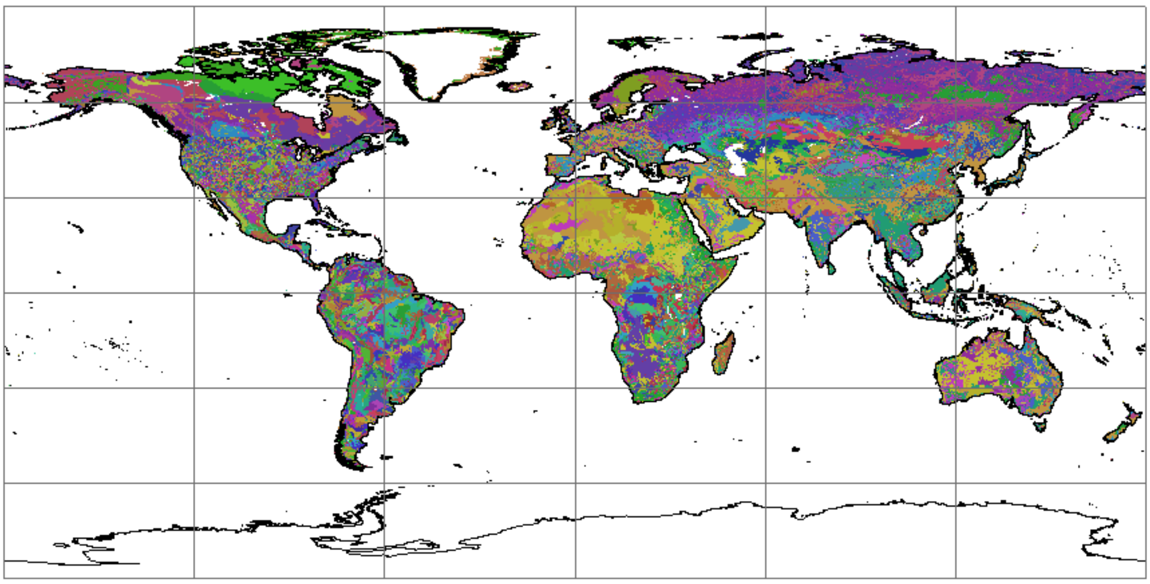


Figure C.1: The soil map used in this study, characterized by 253 different soil types and accompanying soil parameters (*De Lannoy et al.*, 2014).

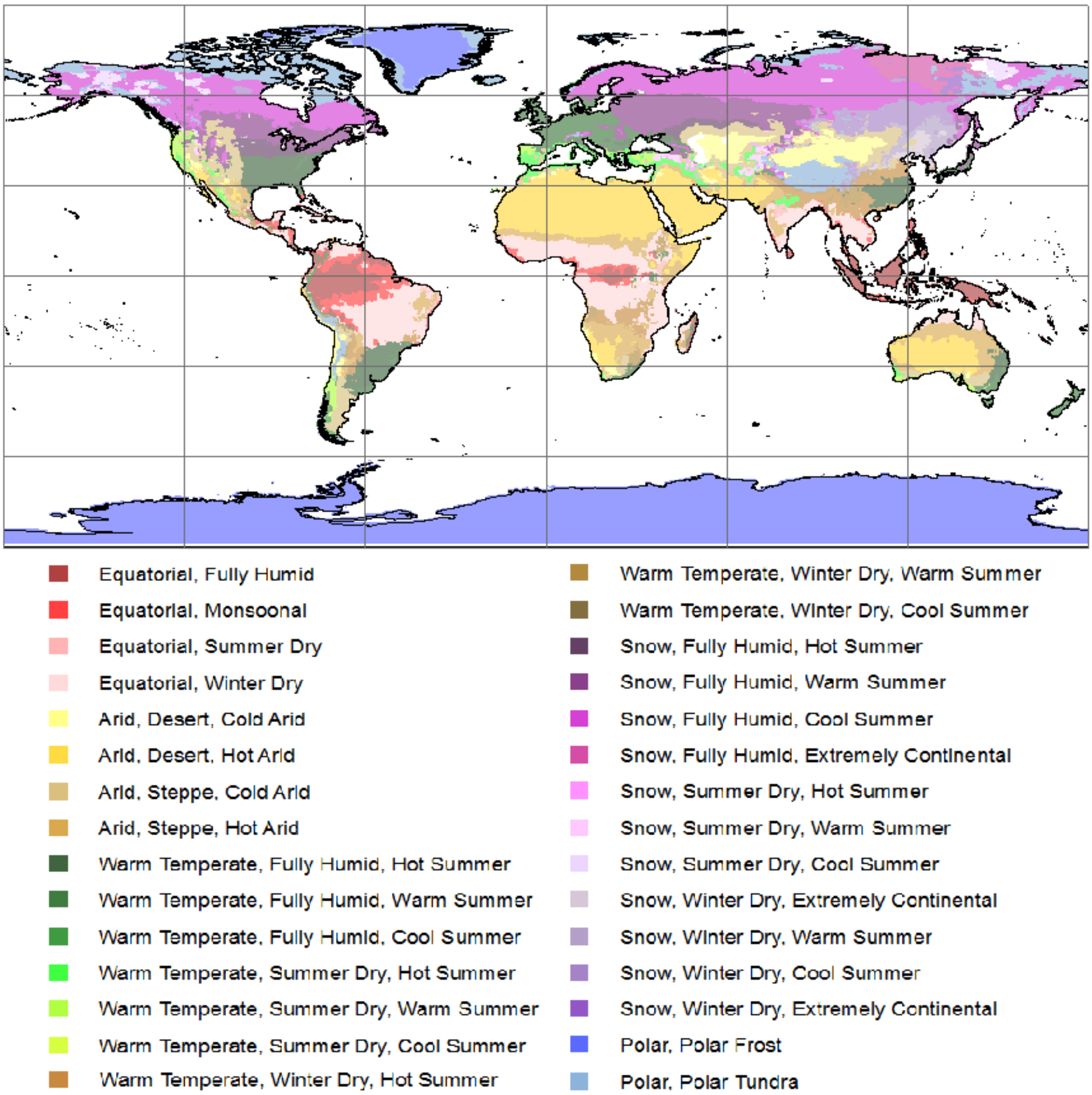


Figure C.2: The climate map used to select the locations. It is based on the Köppen-Geiger classification for the years 1951 to 2010 (*Kottek et al.*, 2006).

In figure C.2 the climate map is given. This map shows 30 climate classes based on Köppen-Geiger. This classification has five different main classes (equatorial, arid, warm temperate, snow and polar). Based on the timing and the magnitude of the precipitation and the temperature these five classes are subdivided.

When a main production region for a plant is determined, the location is further specified based on these climate and soil maps. For this, the dominant climate and soil type in the region is determined and a longitude and latitude where these two collide are selected.

C.2 Location selection per plant

Now that it is known how locations are selected in the core production region in the world, the locations can be determined. Per plant, the sections below describe the location choice. An overview of the locations is given in table C.1.

Table C.1: The locations and their characteristics. The longitude and latitude are in decimal degrees. The climate class refers to the first letters of the climate types in figure C.2, where the part between brackets is the general Köppen-Geiger climate code. The topsoil and subsoil are retrieved from *De Lannoy et al.* (2014).

Plant	Country	Province	(Lon,Lat)	Climate	Top-/subsoil
Apple tree	China	Shandong	(119.16,35.56)	WWH (Cwa)	224/55
Apple tree	Moldova	Gagauzia	(28.65,46.45)	WFW (Cfb)	186/186
Apple tree	USA	Washington	(-120.76,46.97)	WSW (Csb)	224/40
Grapevine	Spain	Castilla-La Mancha	(-2.81,39.31)	ASC (BSk)	210/126
Olive tree	Spain	Andalusia	(-5.21,36.90)	WSH (Csa)	185/16
Oil palm	Malaysia	Johor	(103.13,2.25)	EF (Af)	207/110

C.2.1 Apple tree

For apple trees, three locations are selected. A global map of apple production is given in figure C.3a. This map shows at which locations the tree is cultivated and at which density. A high density means that there is a large amount of apple trees per unit of area. As can be seen on the map, the core production of apples in the world takes place in the east of China. This region is therefore also chosen as the first simulation location for the apple tree. The exact location based on the dominant climate and soil type in the region is given in table C.1. The corresponding province is Shandong.

To select two alternate locations, there are a few possibilities. First of all, northern India shows a dense apple production. However, the soil types in this region are very fractured and this country is therefore skipped. Another rather dense apple production is visible north west of the Black Sea, in Moldova. This region has a slightly colder climate and a very different precipitation pattern in comparison to the climate in Shandong. There is a distinct dominant soil type. The details of this location are found in table C.1. Furthermore there is some dense apple production visible in the west part of the United States, in Washington. This region is selected as the third region for the apple tree.

C.2.2 Grapevine

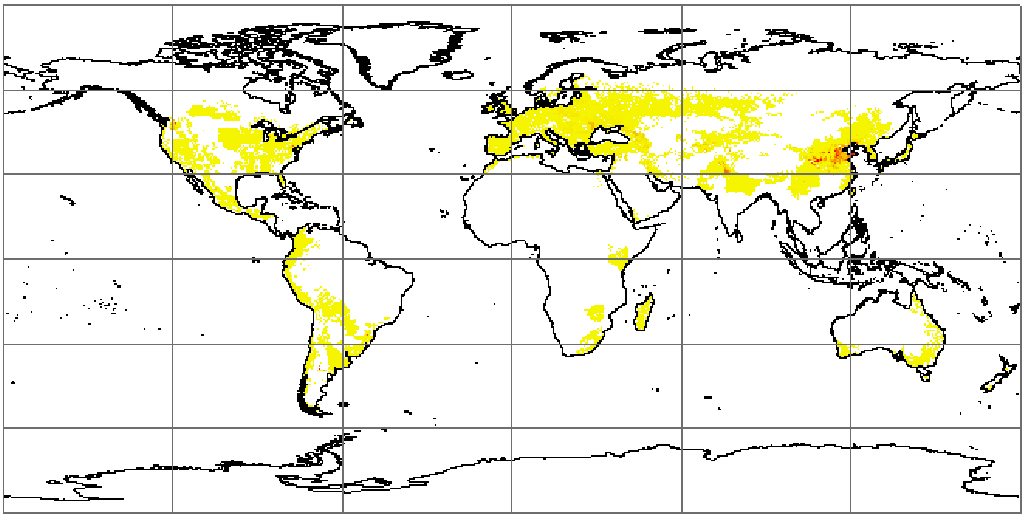
Looking at figure C.3b, there are a few locations with a rather dense production of grapevines. In California in the United States, in eastern Europe and especially around the Mediterranean grapevines are cultivated quite a lot. There is one region in the world that clearly stands out, namely Castilla-La Mancha in Central Spain. This region is therefore chosen for the grapevine. The specific coordinates of the locations, the climate type and the soil type can be found in table C.1.

C.2.3 Olive tree

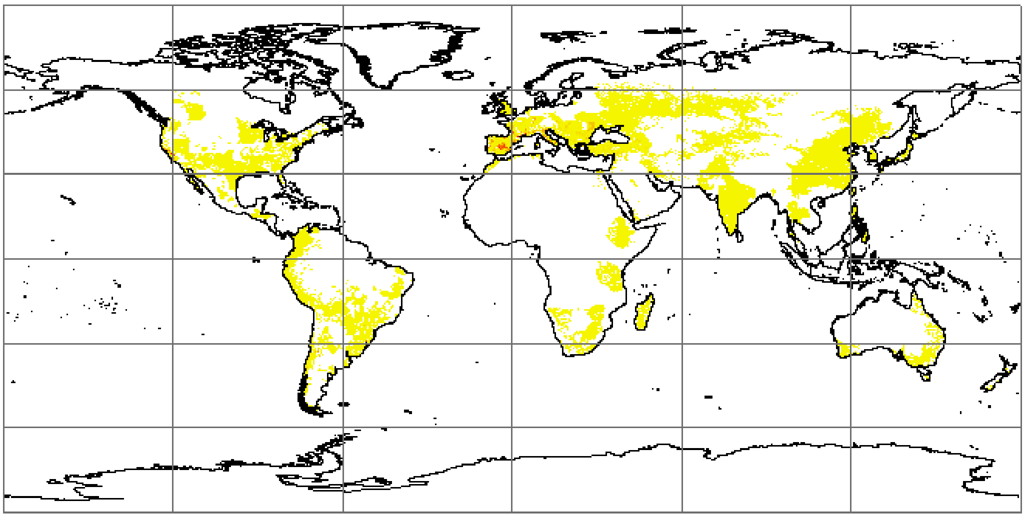
Looking at the map for olive trees in figure C.3c, it can be seen that these trees are grown mainly around the Mediterranean. Spain, Morocco, Tunisia, Italy and Israel are visible as rather dense areas. As it is the densest area, the region Andalusia in Spain is chosen as the dominant location of olive production. The details of the location are given in table C.1.

C.2.4 Oil palm

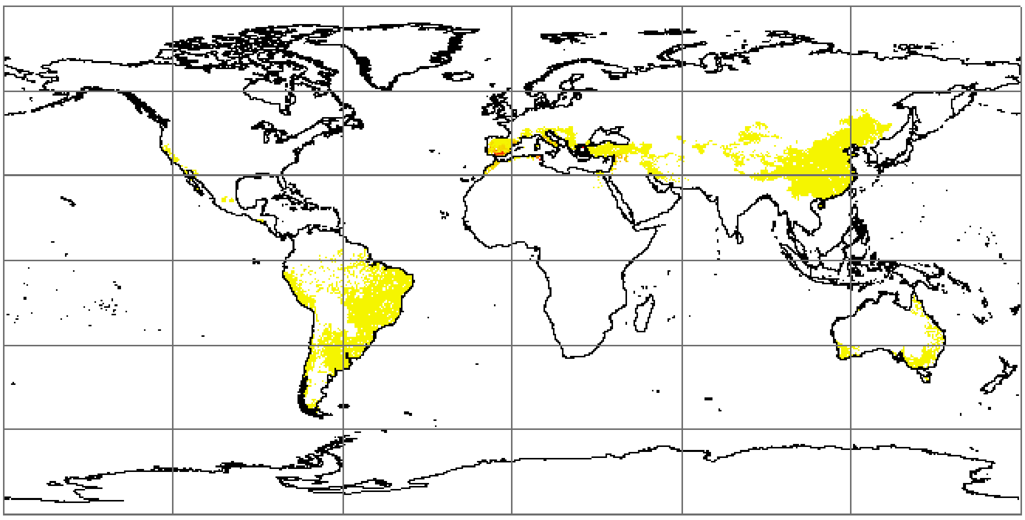
The cultivation of oil palms is mainly reserved for the regions around the equator. In the warm temperate climates there is some production, but the core production lies in Nigeria and Malaysia. Looking at these locations, Nigeria stands more-or-less on its own when it comes to dense production of oil palms. Malaysia, on the other hand, is neighboured by the production in Indonesia. Within Malaysia, the west part has a clear denser production than the east part. Therefore this part is chosen as the representative location for oil palm production. Within West Malaysia, the region of Johor in the south is chosen. The characteristics at this location can be found in table C.1.



(a) Apple tree

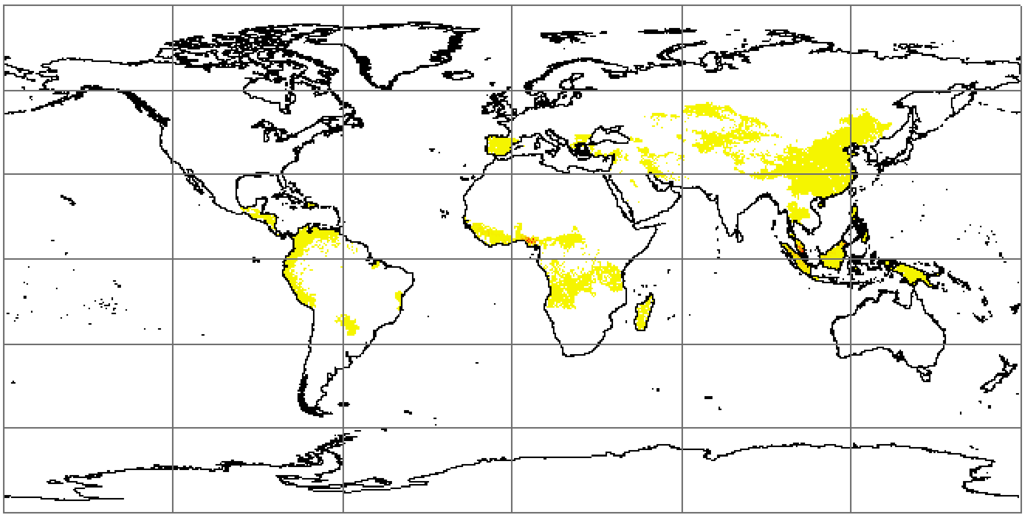


(b) Grapevine



(c) Olive tree

Figure C.3: Per plant the places in the world where they are cultivated. The colours show the density of occurrence (red = high, yellow = low). The maps are retrieved from *Monfreda et al.* (2008).



(d) Oil palm

Figure C.3: (continued) Per plant the places in the world where they are cultivated. The colours show the density of occurrence (red = high, yellow = low). The maps are retrieved from *Monfreda et al.* (2008).

C.3 Reference yield and evapotranspiration

To compare the simulated yields and evapotranspiration rates with reality, it is necessary to find some reference values from literature. In table C.2a, these references are shown for the yield. As can be seen, the main source for the yield is the database of *Faostat* (2015). This database provides yearly values of the yield on a country level. With these yearly values, the average yield over the period in which the plant is considered full-grown can be calculated. More information about the full-grown period per plant is found in chapter 3.

For some plants, more location specific information is available. For the apple tree, *USDA* (2016) provide a database of the yields per year in Washington. The full-grown years of this source are therefore used. For the apple tree in Shandong, the grapevine and the olive tree, alternate sources where also available, but not for the full-grown period considered in this study. For the period the data was available, the average is calculated. For these years the average is also calculated with the data of *Faostat* (2015). Comparing the two gives a factor that *Faostat* (2015) over- or underestimates the location specific data. This factor is applied on the complete full-grown period by *Faostat* (2015), resulting in a scaled dataset.

The yield values in literature are reported in fresh weight, while the models simulate yield in dry weight. To convert these to each other, the rough estimation proposed by *Raes et al.* (2012) is used, which states that the dry weight is a quarter of the fresh weight. While this is a very rough approximation and its applicability is probably not very accurate for all plants considered in this study, no better estimate is available. The values in table C.2a show the dry values of the yield.

The reference values for the evapotranspiration are found in table C.2b. *Mekonnen and Hoekstra* (2010) provide water footprint data, often on a province level. However, to calculate evapotranspiration from the water footprint, also yield is required. *Mekonnen and Hoekstra* (2010) used the yield of Faostat for the calculation of water footprint. To calculate the evapotranspiration from the water footprint, this study also uses the yield data from *Faostat* (2015). As these are available on a country level only, also the country level water footprints are used. The evapotranspiration rates are found by multiplying the water footprints with the yields. For the apple tree in Washington, *USBR* (2016) provide evapotranspiration data. For the oil palm, *Yusop et al.* (2008) provide evapotranspiration data as well. The average of them and *Mekonnen and Hoekstra* (2010) is used.

Table C.2: An overview of the yields and evapotranspiration rates found in literature. The values are as much location specific and for the correct full-grown years as possible. The values of evapotranspiration are based on the water footprint from *Mekonnen and Hoekstra* (2010) in combination with the yields of *Faostat* (2015). More on this in the text.

(a) Yield

Plant	Y [*ton/ha*]	Remark
Apple tree (Sh)	4.29	*Peng et al.* (2008) and *Lagos et al.* (2009) provide data for 2004-2008 in Shandong. This is scaled to country data 1994-2010 of *Faostat* (2015)
Apple tree (Ga)	0.97	No better estimate than country data 1994-2010 of *Faostat* (2015)
Apple tree (Wa)	9.54	*USDA* (2016) provide 1995-2010 data for Washington
Grapevine	0.97	*Polytechnic University of Madrid* (2005) provide data for 1992-2002 in Castilla-La Mancha. Scaled to country data 1981-2010 of *Faostat* (2015)
Olive tree	0.93	*Galán et al.* (2008) provide Andalusia average for 1990-2004, scaled to country data 2001-2010 of *Faostat* (2015)
Oil palm	5.00	No better estimate than country data 1998-2009 of *Faostat* (2015)

(b) Evapotranspiration

Plant	ET [*mm/year*]	Remark
Apple tree (Sh)	767	No better estimate than country average of *Mekonnen and Hoekstra* (2010)
Apple tree (Ga)	548	No better estimate than country average of *Mekonnen and Hoekstra* (2010)
Apple tree (Wa)	880	*USBR* (2016) provide data 1988-1999 for Washington
Grapevine	454	No better estimate than country average of *Mekonnen and Hoekstra* (2010)
Olive tree	603	No better estimate than country average of *Mekonnen and Hoekstra* (2010)
Oil palm	1397	Country average of *Yusop et al.* (2008) and *Mekonnen and Hoekstra* (2010)

C.4 Additional soils for further analysis

To compare the influence of different soils on the models, three additional soils are manually selected from *De Lannoy et al.* (2014). These soils are chosen such that they cover the most extreme soil properties. The three selected soils are the topsoil/subsoil combination 8/8, 234/234 and 82/172.

Soil 8/8 is characterized by an average saturated hydraulic conductivity, a high field capacity and wilting point and a silty to clayey texture. Soil 234/234 has a high saturated hydraulic conductivity, a low field capacity and wilting point and is rather sandy. Soil 82/172 has a similar texture as soil 8/8, but has a very low saturated hydraulic conductivity and an average field capacity and wilting point. The exact parameter values of each of the three soils are found in *De Lannoy et al.* (2014).