AquaCrop
Crop water productivity model

Version 3.1+
January 2011

Updated calculation procedures in Version 3.1+
For full description of AquaCrop consult the Reference Manual

1. Soil fertility
In previous AquaCrop versions limited soil fertility resulted not only in a reduced canopy cover but also in a shortening of the crop cycle. In Version 3.1+ the length of the growing cycle under limited soil fertility remains identical with the length under unlimited soil fertility (Fig. 1.1).

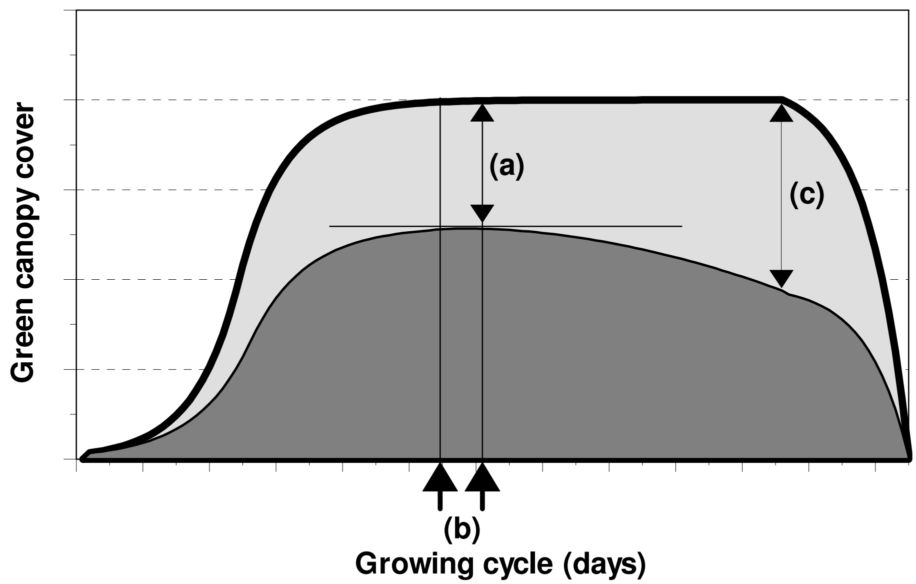

Figure 1.1
Canopy cover observed on a field with unlimited (light area) and limited soil fertility (dark area) with indication of (a) the reduction in CC_x, (b) the delay in time to reach CC_x and (c) the canopy decline once CC_x is reached

2. Effect of elevated atmospheric CO2 concentration

Eline Vanuytrecht studied the effect of elevated atmospheric CO_2 concentration on crop development by carrying out a meta-analysis on data from FACE (free air CO_2 enrichment) experiments published in peer-reviewed journals (Internal discussion note, August 2010). Relevant information was found in 53 papers on 529 independent experimental observations. The experiments focused mainly on elevated [CO_2] between 541 and 620 ppm.

In the meta-analysis, the average changes of parameters relevant for AquaCrop were computed and expressed as percentage change at the elevated [CO_2] (with ambient conditions as the reference). The analysis revealed that:

- the canopy growth coefficient (CGC), and Harvest Index (HI) hardly increased;
- transpiration was reduced by 5 %;
- the root-shoot ratio increased by 15%; and
- the biomass water productivity (WP*) increased by 23 %.

To account for the analyzed effect of elevated atmospheric CO_2 concentration, calculation procedures in AquaCrop were updated and incorporated in version 3.1plus (January 2011).

2.1 Adjustment of WP^* for atmospheric CO_2 (f_{CO2})

AquaCrop uses the normalized water productivity (WP^*) for the simulation of aboveground biomass. The water productivity is normalized for the atmospheric CO_2 concentration and for the reference evapotranspiration (ETo).

- **Version 3.0 and 3.1**

In Version 3.0 and 3.1, WP^* is adjusted when running a simulation with an atmospheric CO_2 concentration different from the reference value (i.e. 369.41 ppm measured at Mauna Loa, Hawaii at the year 2000). The adjustment is obtained by multiplying WP^* with the correction coefficient f_{CO2} as specified by Steduto et al. (2007). The coefficient considers the difference between the reference value and the actual atmospheric composition:

$$WP^*_{adj} = f_{CO2}\, WP^* \qquad \text{(Eq. 1)}$$

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1 + b\left(C_{a,i} - C_{a,o}\right)} \qquad \text{(Eq. 2)}$$

where f_{CO2} correction coefficient for WP* for CO_2;
WP^* Water Productivity normalized for climate (ETo) and [CO_2];
WP^*_{adj} WP* adjusted for actual atmospheric composition;
$C_{a,o}$ reference atmospheric CO_2 concentration (369.41 ppm);
$C_{a,i}$ actual atmospheric CO_2 concentration (ppm); and
b 0.000138 (Steduto et al., 2007).

The f_{CO2} correction (Eq. 2) yields that WP* is increased by 45 % (f_{CO2} = 1.45) for the elevated [CO_2] maintained in the FACE experiments (between 541 and 620 ppm). The correction for WP* is hence twice as much as the 23% increase of WP* obtained from the meta-analysis. Consequently the above ground biomass (B) and yield (Y) observed in the FACE experiments is overestimated when running simulations with AquaCrop Version3.0 or 3.1.

- **Version 3.1+**

It is believed that the discrepancy between the observed and theoretical adjustment (Eq. 2) of WP* is the result of various causes. One of the possible reasons is soil fertility which might not have been properly adjusted to the higher productivity under elevated CO_2 concentration in the FACE experiment. Also carbon that might have leaked out of the root system was not accounted for. Since it takes many years to develop new varieties, the sink capacity of the current crop varieties cultivated in the FACE experiments might yet not be able to take care of the elevated CO_2 concentration.

To simulate the observed B and Y for an elevated CO_2 concentration of about 550 ppm, b should have been 0.001165 in Eq.2 instead of 0.000138 (value theoretical derived by Steduto et al., 2007). By maintaining the near-linear effect of elevated [CO_2] on WP* and by assuming that some of the above mentioned causes of over prediction of B and Y will only be partly solved in the future, AquaCrop Version 3.1plus uses an adjustment midway between the theoretical approach and the somewhat smaller observed increase:

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1 + \left(C_{a,i} - C_{a,o}\right)\left[(1-w)b_{Sted} + w\left(\frac{A}{100}b_{Sted} + \left(1 - \frac{A}{100}\right)b_{FACE}\right)\right]} \qquad \text{(Eq. 3)}$$

where b_{Sted} 0.000138 (Steduto et al., 2007);
b_{FACE} 0.001165 (derived from FACE experiments);
w weighing factor;
A percentage achieved of the required crop and management adjustments.

In Version 3.1plus, the percentage A is fixed at 50 %. In future versions of AquaCrop the user will be able to alter the value of A in correspondence with adjustments achieved in the sink capacity of the crop and field management. The corrections can be as high as 100 % (i.e. Eq. 3 is identical to Eq. 2), or as low as 0% (i.e. Eq. 3 is identical to Eq. 2 but with b = b_{FACE}). In Fig. 2.1 the correction factor f_{CO2} is plotted for various atmospheric CO_2 concentrations and percentages A.

The weighing factor (w) makes that Eq.3 gradually replaces Eq.2 starting from year 2000 and becomes fully applicable at year 2100:

$$0 \leq \quad w = \frac{(i - 2000)}{100} \quad \leq 1 \qquad \text{(Eq. 4)}$$

where i is the year for which the simulation applies. By keeping the range for w between 0 and 1, Eq. 3 comes in effect only for years later than 2000 and remains valid for years beyond 2100.

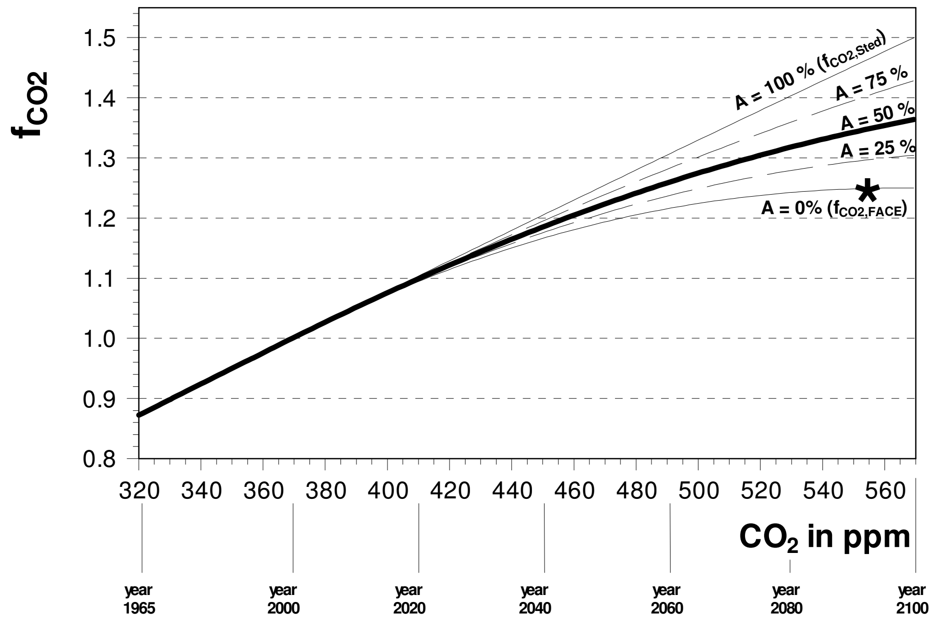

Figure 2.1
Correction coefficient for WP* as given by Eq. 3 for various atmospheric CO_2 concentrations and achieved crop and management adjustments (A expressed in percentage)

Not many FACE experiments are conducted for C_4 crops since it is believed that this crop type hardly respond to elevated atmospheric CO_2 concentrations. In the meta-analysis the (very few) data reported for sorghum and maize seems to support this observation. By assuming that the different response of C_3 and C_4 crops can be considered as valid, a correction for crop type (f_{type}) is added to Eq. 3 in AquaCrop Version 3.1plus:

$$0 \leq \quad f_{type} = \frac{(35 - WP^*)}{(35 - 20)} \quad \leq 1 \qquad \text{(Eq. 5)}$$

where WP* is the normalized water productivity of the crop (ton/ha). Eq. 5 considers the distinction between C_4 crops with a typical WP^* of 30 - 35 g/m^2 and C_3 crops with a typical WP^* of 15 - 20 g/m^2. The f_{CO2} adjusted for crop type becomes:

$$f_{CO2,type} = 1 + f_{type}\left(f_{CO2} - 1\right) \qquad \text{(Eq. 6)}$$

where f_{CO2} is given by Eq.3. In Figure 2.2 the correction factor is plotted for various atmospheric CO_2 concentrations and crops with various WP*. The correction for crop type was not yet considered in AquaCrop versions 3.0 and 3.1.

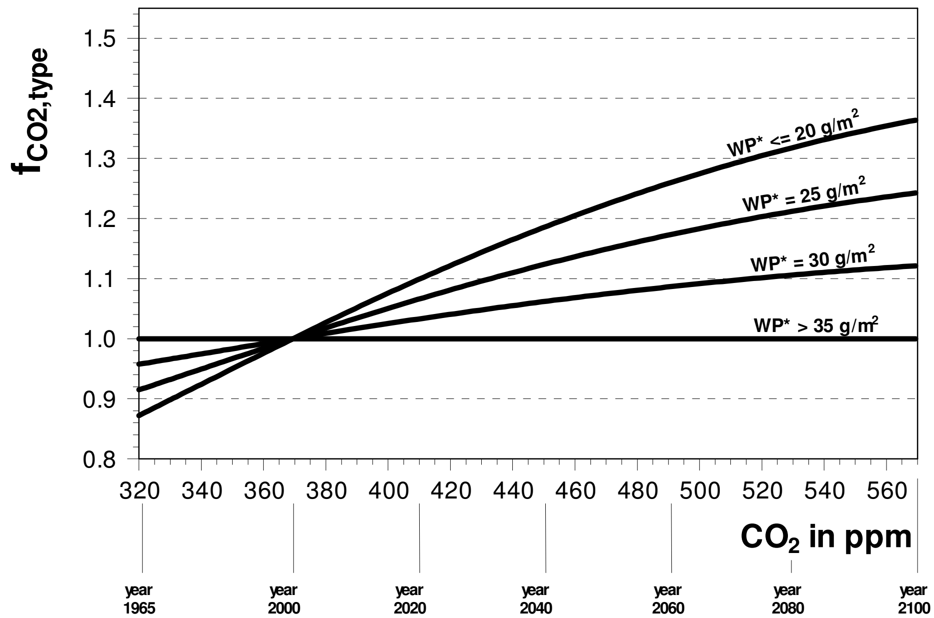

Figure 2.2
Correction coefficient for WP* as given by Eq. 6 for various atmospheric CO_2 concentration (with A = 50% in Eq. 3) and various crop water productivities (WP*).

2.2 Adjustment of crop transpiration for atmospheric CO_2 ($f_{CO2,Tr}$)

In AquaCrop versions 3.0 and 3.1, crop transpiration is calculated by multiplying the reference evapotranspiration with the crop transpiration coefficient. The crop transpiration coefficient (Kcb) considers (i) the characteristics that distinguish the crop with a complete canopy cover from the reference grass and (ii) the fraction by which the canopy covers the ground:

$$Kcb = CC^{*}\ Kcb_{x} \qquad \text{(Eq. 7)}$$

where Kcb_x coefficient for maximum crop transpiration (well watered soil and complete canopy, CC = 1);
CC^* actual canopy cover adjusted for micro-advective effects.

In AquaCrop Version 3.1+ the effect of the decrease in crop transpiration for elevated atmospheric CO_2 concentration is considered by multiplying Kcb_x with an adjustment factor ($f_{CO2,Tr} \leq 1$):

$$Kcb = CC^{*}\ f_{CO2,Tr}\ Kcb_{x} \tag{Eq. 8}$$

For an atmospheric CO_2 concentration ($C_{a,i}$) above the reference value of 369.41 ppm the adjustment is given by:

$$f_{CO2,Tr} = 1 - 0.05\left(\frac{C_{a,i} - 369.41}{550 - 369.41}\right) \tag{Eq. 9}$$

where $f_{CO2,Tr}$ correction coefficient for crop transpiration for $[CO_2]$ above 369.41 ppm;
369.41 reference atmospheric CO_2 concentration (ppm); and
$C_{a,i}$ actual atmospheric CO_2 concentration (ppm).

At an elevated atmospheric CO_2 concentration of 550 ppm, $f_{CO2,Tr}$ becomes 0.95. This corresponds with the 5% decrease in crop transpiration as derived from the meta-analysis of the FACE experiments.

3. Processing of 10-day and monthly rainfall data

The procedures for simulating surface runoff and soil evaporation when running with 10-day or monthly climatic data are updated.

- **Estimation of surface runoff**

To estimate surface runoff with 10-day or monthly Rainfall data, a specific number of rainy events is assumed during a 10-day period (the default is 2 showers per 10-day – Fig. 3.1). By dividing the total rainfall amount for the period by the number of events in that period, the rainfall amount per shower is obtained and the surface runoff can be calculated (see Reference Manual, Chapter 3, Section 3.7.4 – Runoff subroutine). The more rainy days are considered during the 10-day period, the smaller the rainfall amount per event and the smaller the runoff will be. Because the day(s) at which it rains, are unknown the Curve Number is not corrected for soil wetness and the CN value for Antecedent Moisture Class II is used.

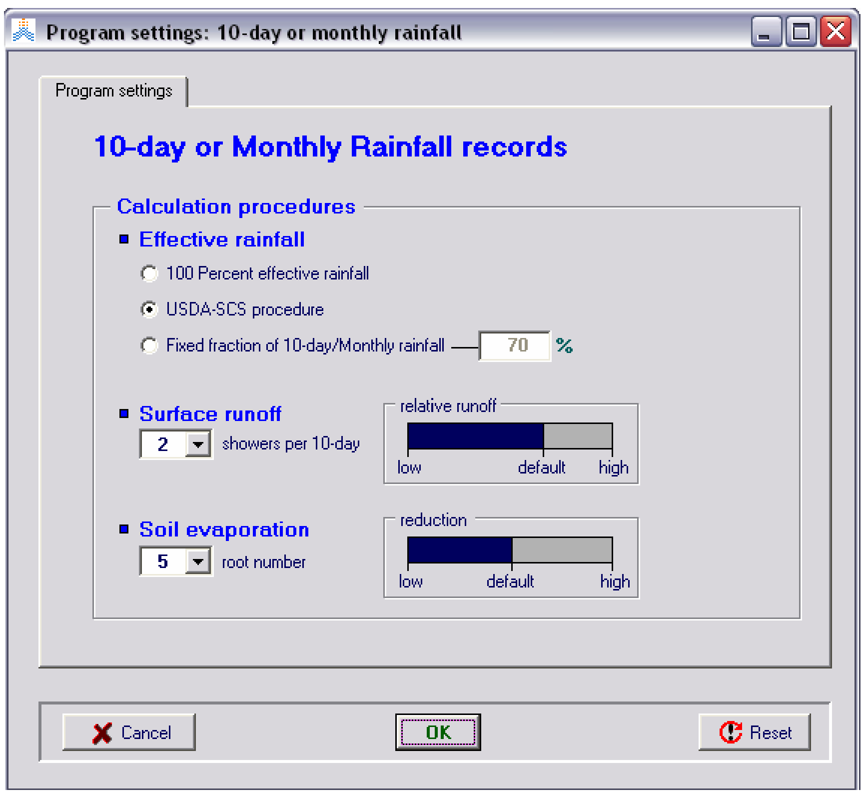

Figure 3.1
Program settings for handling 10-day or monthly rainfall data

- **Estimation of soil evaporation**

The calculation procedure for soil evaporation (E) assumes that the evaporation takes places in two stages (See Reference Manual, Chapter 3, Section 3.9 Soil evaporation). By distributing rainfall homogenously over all the days of the 10-day period or month, soil evaporation is likely to be over-estimated. Simulations (Mihutu, 2011) with rainfall data from various climatic zones indicated that the two stage calculation procedure over predicts E by some 10 to 30 % depending on soil type. The soil evaporation rate is adjusted by multiplying the estimated daily evaporation (E) with a reduction factor:

$$E_{adj} = \left(\sqrt[n]{\frac{REW + 1}{20}} \right) E \qquad \text{(Eq. 3.1)}$$

where REW is the readily evaporable water (mm) and n a program parameter which may vary between 1 (strong reduction) and 10 (light reduction). Its default value is 5 (Fig. 3.1).

The optimal setting of the program parameter can be obtained by simulating the soil evaporation for those years were daily rainfall data is available (or available in a nearby representative station). As such the characteristics of the climate (rainfall distribution and evaporating power of the atmosphere), the degree of canopy cover and the characteristics of the soil type can be fully considered.

4. Germination and net irrigation requirement

Crops can only germinate after sowing if the soil water content in the top soil is above a threshold (see Reference Manual, Chapter 3, Section 3.4.3 Germination and initial canopy cover at 90% crop emergence). If the crop cannot germinate the procedure to determine the net irrigation requirement cannot start up. The procedure consists in injecting daily, if required, a small amount of irrigation water directly in the soil profile to keep the root zone depletion just above a specified threshold (see Reference Manual, Chapter 2, Section 2.11.2 Determination of the net irrigation requirement). The total amount of irrigation water required in a period to keep the water content in the soil profile above the threshold is the net irrigation water requirement for that period.

The conflict is removed in AquaCrop 3.1+ by checking already at sowing the soil water content in the top soil. If required, water will be added to the top soil to allow the crop to germinate. This pre-irrigation is added to the net irrigation requirement.