# FAO Model AquaCrop - Conservative behavior of biomass water productivity - a key model fundamental

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## Introduction and background

The FAO AquaCrop conceptual framework is illustrated in figure 1.

I Irrigation
*T* Air temperature
ETo Reference evapotranspiration
Ta Actual canopy transpiration
Es Soil evaporation
gs Stomatal conductance
WP Water productivity coefficient
HI Harvest Index
$CO_2$ Atmospheric carbon dioxide concentration
Ks Stress coefficient
(1), (2), (3), (4), (5): Feedbacks/Feedforwards from water stress

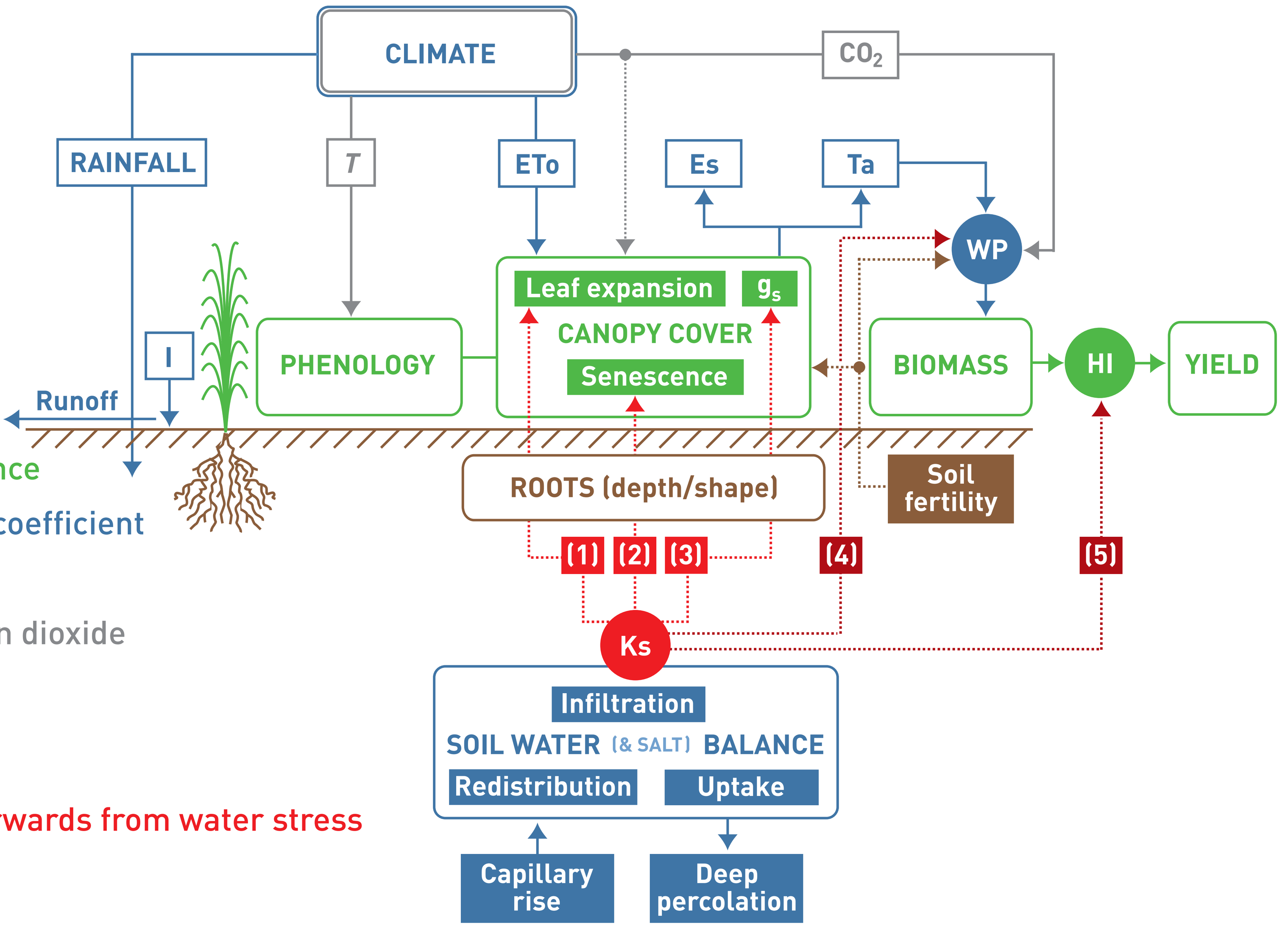


**Fig.1** AquaCrop flowchart

The *biomass water productivity* (WP) is a key model parameter at the core of the AquaCrop *growth engine*. WP main feature is its conservative behavior, i.e., it tends to remain relatively constant under different environmental conditions, provided the variation in evaporative demand of the atmosphere and the air carbon dioxide concentration ($CO_2$) are accounted for by normalization (Steduto et al, 2007)

The conceptual basis for the conservative behavior is here reviewed and the ways to normalize for evaporative demand and carbon dioxide concentration are illustrated.

This will be done by scaling up the processes from individual leaves up to crop plant communities.

## Leaf scale

At the leaf level, we define *photosynthetic water productivity* ($WP_p$) as the ratio of leaf net carbon dioxide assimilation ($A_1$) to leaf transpiration ($T_1$)

$$A_1 = \frac{\Delta c}{r'_b + r'_s} = \frac{c_a - c_i}{r'_b + r'_s} \qquad (1)$$

$$T_1 = \frac{\Delta w}{r_b + r_s} = \frac{w_i - w}{r'_b + r'_s} \qquad (2)$$

where: $\Delta c$ is the difference in $CO_2$ concentration between the atmosphere ($c_a$) and the leaf intercellular air space ($c_i$); $\Delta w$ is the water vapor concentration difference between the leaf intercellular air space ($w_i$) and the atmosphere ($w_a$); $r'_b$ and $r'_s$ are the boundary layer and stomatal resistances, respectively, for $CO_2$ transport; and $r_b$ and $r_s$ are the boundary layer and stomatal resistances, respectively, for water vapor transport.

Under steady-state conditions, *photosynthetic water productivity* of single leaves is expressed as:

$$WP_p = \frac{A_1}{T_1} = \frac{r_b + r_s}{r'_b + r'_s}\frac{\Delta c}{\Delta w} = \frac{r}{r'}\frac{\Delta c}{\Delta w} \cong 0.625\frac{\Delta c}{\Delta w} \qquad (3)$$

Normalizing for $\Delta w$ and rearranging,

$$WP^*_p = 0.625\frac{\Delta c}{\Delta w}\Delta w = 0.625\,(c_a - c_i)$$

$$= 0.625c_a - 0.625\,c_i = k - 0.625\,c_i \qquad (4)$$

where $WP_p$* is the normalized form of $WP_p$ and k = 0.625 $c_a$.

There has been substantial experimental evidence showing that for many species, $c_i$ tends to remain constant under a range of conditions (Wong et al. 1979; Pearcy 1983; Morrison 1987; Hsiao and Jackson 1999)

By considering the ratio $c_i/c_a = \alpha$ as constant, $c_i = \alpha c_a$ and Eq. 4 can be arranged as follows

$$WP^*_p = 0.625c_a - 0.625c_a = 0.625\,(1-\alpha)\,c_a = k^*c_a \qquad (5)$$

Using the widely accepted generalized values for $\alpha$ of 0.7 and 0.4 for C3 and C4 species, respectively (Morison 1987; Wong et al. 1979), k* and $WP_p$ * take on the following values:

k* = 0.1875 $\quad WP^*_p = 0.1875c_a \quad$ for $C_3$

and k* = 0.375 $\quad WP^*_p = 0.375c_a \quad$ for $C_4$

Figure 2 presents a comparison of three sets of $WP_p$* values spanning a range of $c_a$ for several field grown crops. One set was experimentally determined; one set was calculated with Eq. 4 using the experimentally measured $c_i$ that corresponded to the experimental $c_a$ values, and another was calculated from $c_a$ using Eq. 5.

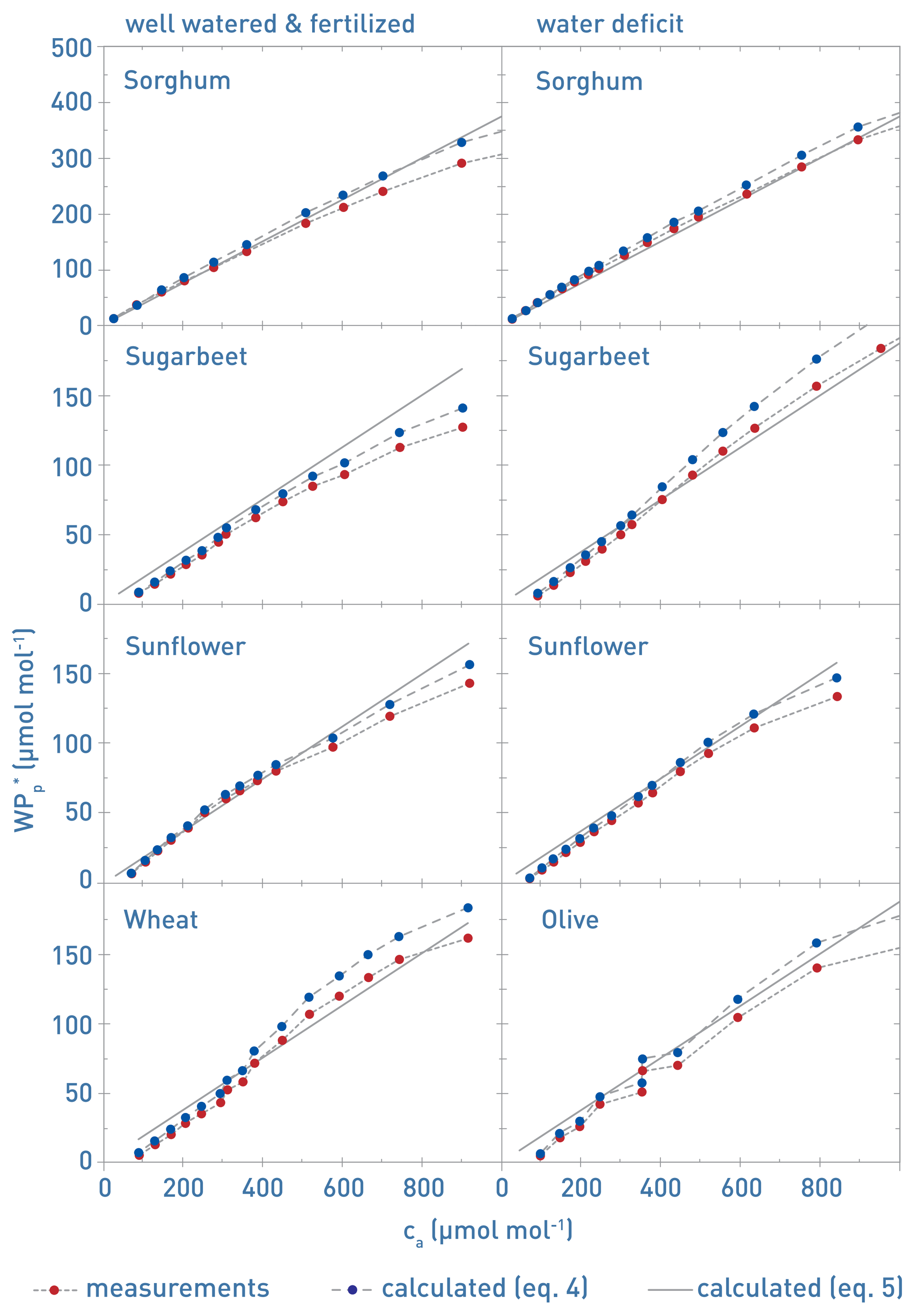


**Fig. 2** Examples of leaf photosynthetic water productivity ($WP_p$ *), normalized for $\Delta w$, as dependent on ambient $CO_2$ concentration ($c_a$), for different crops under well watered and high nitrogen (left plots) and water deficient and low nitrogen (right plots) conditions. Measurements (dotted line with red symbols) were obtained from the determination under steady state conditions of $A_l$ versus $CO_2$ response curves, using a portable leaf-photosynthesis open-system (Li-6400, LiCor, Lincoln, NE, USA) following the procedure described in Steduto et al. (2000). Dashed line (with blue symbols) and continuous lines (with no symbol) represents values calculated according to Eqs. 4 and 5, respectively. Data from P. Steduto and R. Albrizio (unpublished)

Figure 2 demonstrates the conservative behavior of water productivity at leaf scale.

## Canopy scale

The commonality and differences in the factors that affect canopy photosynthesis and canopy transpiration are summarized in Fig. 3.

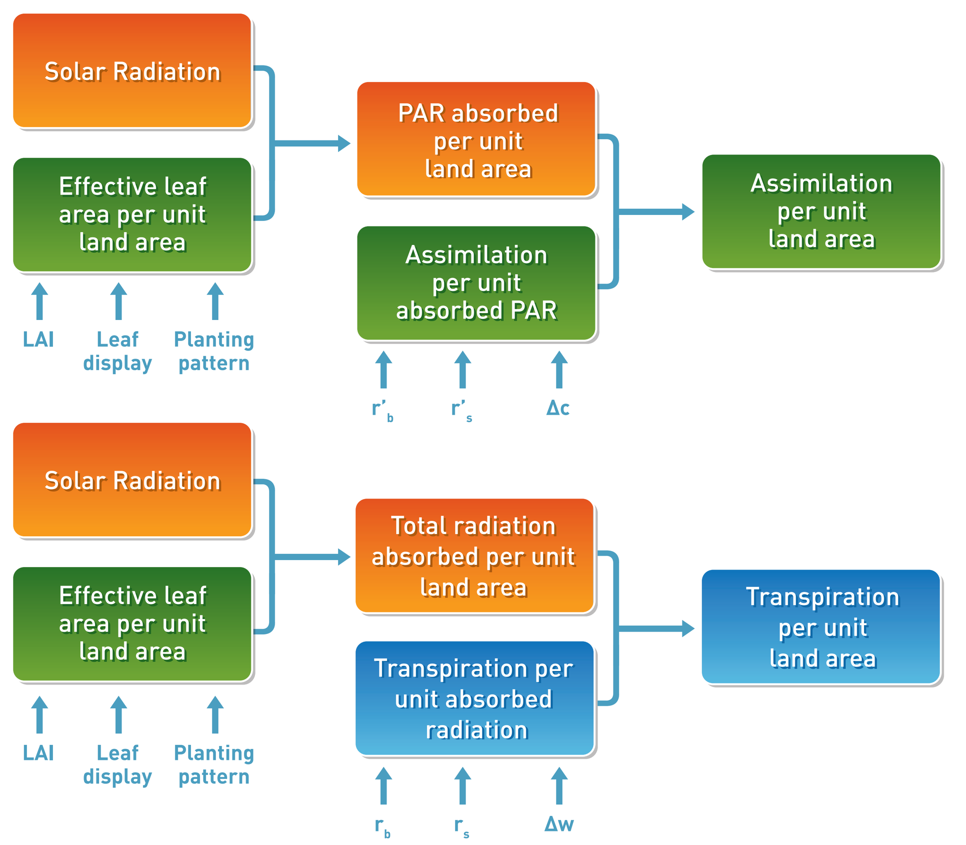


**Fig. 3** Similarities and differences in factors affecting assimilation and transpiration of canopies. Arrows indicate causal relations. All considerations are on a basis of land area. LAI is the leaf area index and PAR is the photosynthetic active radiation. All other symbols are described in previous Eq. (1) and (2). Note that because resistances to $CO_2$ and to water vapor are proportional to each other, most of the factors affecting assimilation have analogous impact on transpiration. One clear difference is the driving force for gas transport, with $\Delta c$ for assimilation and $\Delta w$ for transpiration. The ratio of PAR to solar radiation is also about constant. Modified from Hsiao and Bradford (1983) and Hsiao (1993)

Given the conservative behavior of photosynthetic water productivity at leaf scale, Figure 3 indicates that a conservative behavior of water productivity is expected also at canopy scale as illustrated by the experimental evidence of Figure 4.

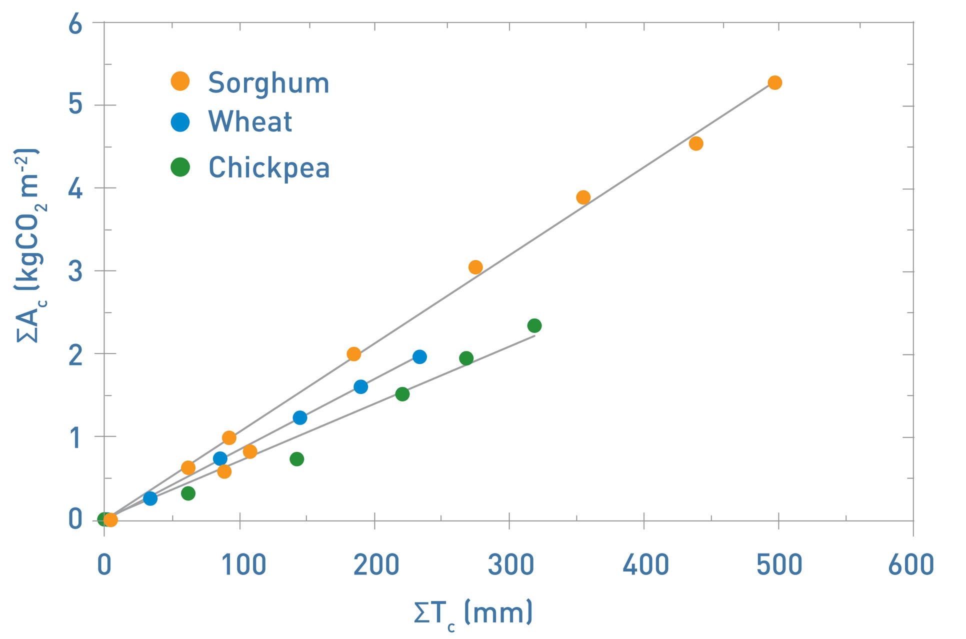


**Fig. 4** Relationships between cumulative daytime canopy net assimilation ($A_c$) and cumulative daytime canopy transpiration ($T_c$) for sorghum, wheat and chickpea. The slope of the relationships represents the *canopy photosynthetic water productivity*. Measurements were taken when the crops were all at full canopy cover, and soil evaporation was assumed to be negligible (redrawn from Steduto and Albrizio 2005)

The results of figure 4 imply that also a linear relationship between canopy assimilation ($A_c$) and canopy respiration ($R_c$) is established, as illustrated in Figure 5. Many experimental evidences are confirming the approximate fixed ratio between assimilation and respiration for a given species or genotype (Amthor, 1995, Gifford, 1995, Cheng et al.,2000) provided that chemical composition of the biomass does not change.

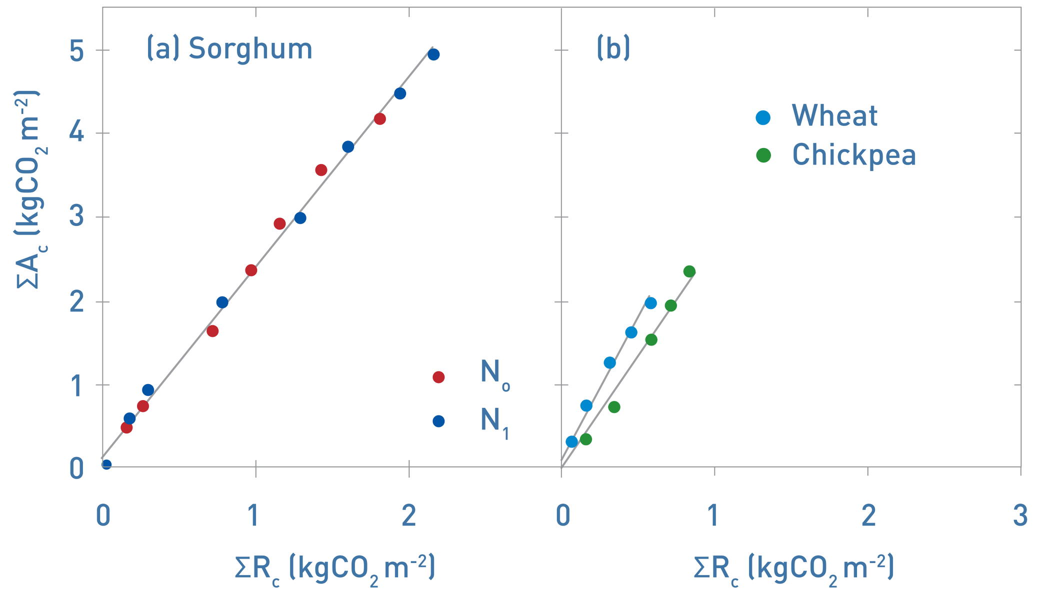


**Fig. 5** Relationship between cumulative daytime canopy net assimilation ($A_c$) and cumulative nighttime canopy dark respiration ($R_c$) for (a) sorghum and (b) wheat and chickpea. Sorghum data were obtained under two levels of nitrogen nutrition (from Albrizio and Steduto 2003).

## From net carbon gain to biomass

Given that the composition of vegetative parts of many crop species is very similar (Penning de Vries et al. 1983) and does not change substantially along the season, biomass should also be linearly related to transpiration. This is clearly evident with data obtained in the same set of experiments and depicted in Fig. 6.

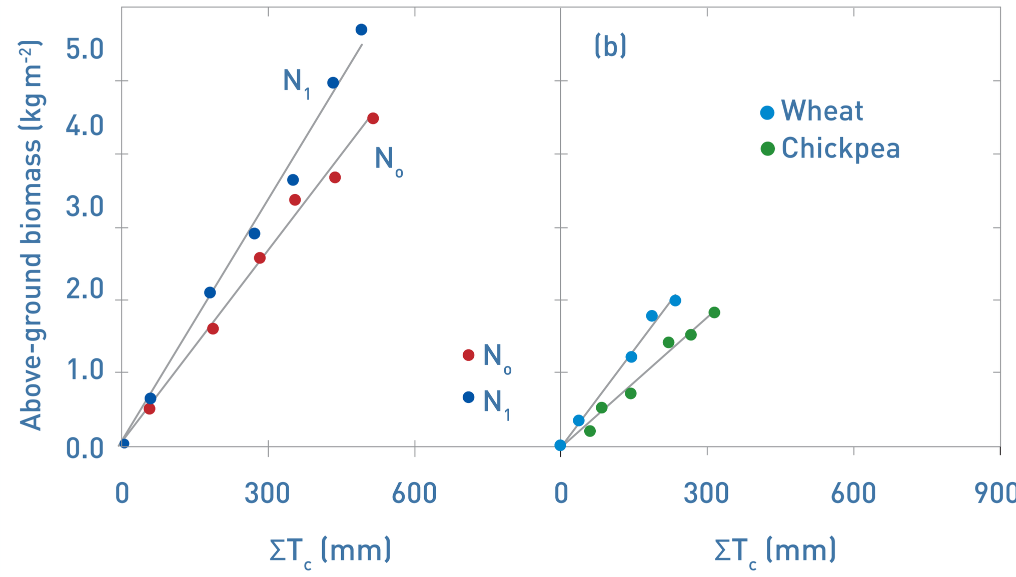


**Fig. 6** Relationship between cumulative biomass and cumulative canopy transpiration ($T_c$) for (a) sorghum and (b) wheat and chickpea. Sorghum data were obtained under two levels of nitrogen nutrition (from Steduto and Albrizio 2005).

Although the analyses and data above have addressed situations where only above-ground biomass is considered, constant *biomass water productivity* has been described for root and tuber crops such as sugar beet (e.g., Clover et al. 2001), and potato (e.g., Tanner 1981).

## Normalization of biomass water productivity for climate

The virtually constant water productivity of figure 4 and 6 are for cases whose environmental conditions did not vary markedly over periods of weeks to months. However, one expects that water productivity would still depend on the magnitude of the driving forces for water vapor and $CO_2$ transport. Thus, there is a need to normalize water productivity for the climate in order to utilize it under different space and time conditions.

The normalization of *biomass water productivity* (WP) for atmospheric evaporative demand (E) can be determined through equation 6.

$$E - \text{Normalized WP} = WP^*_E = \frac{\text{Biomass}}{\sum_{i=1}^{n} t_i \left(\frac{T_c}{ET_o}\right)_i} \qquad (6)$$

where n is the number of time intervals of same length; i is the running number designating each interval; $T_c$ is the crop transpiration; $ET_o$ is the reference crop evapotranspiration.

The normalization of WP for different atmospheric $CO_2$ concentration, originally derived by Hsiao (1993), can be determined through equation 7.

$$CO_2 - \text{Normalized WP} = WP^*_{CO_2} = Pw_o \frac{\sum_{i=1}^{n}(c_a)_i \sum_{i=1}^{n}(\Delta w_o)_i}{\sum_{i=1}^{n}(c_{a,o})_i \sum_{i=1}^{n}(\Delta w)_i} \qquad (7)$$

Where: $WP_o$ is the *biomass water productivity* at the year of reference (e.g. 2000); $c_a$ and $c_{a,o}$ are the atmospheric $CO_2$ concentration at any year and at the year of reference, respectively; $\Delta w$ and $\Delta w_o$ are the atmospheric water vapor concentration at any year and at the year of reference, respectively; i and n as described for equation 6.

The reader is referred to Steduto et al. (2007) for further insight on the conservative behavior of biomass water productivity and its normalization.

## Conclusions

Although some uncertainties, such as genotipic variation of $\alpha$ and changing shoot-root ratio, are not yet resolved, the conservative behavior of WP, i.e., its relatively narrow range of variation, represents a key model fundamental for AquaCrop. Furthermore, the normalization feature offers an invaluable opportunity to use WP across different locations, climate and seasons.

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