Water-productivity analysis of field crops under *climate change*. The FAO approach.

Pasquale STEDUTO
Land and Water Development Division, Agricultural Department
FAO - Via delle Terme di Caracalla, 00100 Rome, ITALY
e-mail: Pasquale.Steduto@fao.org

1. Introduction

The Food and Agriculture Organization (FAO) has the mandate to raise levels of nutrition, improve agricultural productivity, better the lives of rural populations and contribute to the growth of the world economy. All factors and processes influencing agriculture are therefore of concerns for FAO, and climate is one of its foremost working domains. In the area of *climate change*, FAO participates to the debate by assessing the available scientific contributions, observing and monitoring systems, collecting unique global datasets, running special projects and providing a neutral forum for negotiations and technical services on the relationships between *climate change* and agriculture.

Meeting the demand of a raising world population, projected to grow from about 6 billion of nowadays to more than 8 billion in 2025 (FAO, 2003), requires more food production, which in turn means more water demand, and future *climate change* scenarios indicate agriculture and food security to be at risk.

Although a wide range of tools, from broad conceptual frameworks to highly complex model, is available to assess the impact of *climate change* on agricultural production, modeling crop growth under elevated CO_2 is still open to significant uncertainties. Among the major reservations are up-scaling and down-regulation (Allen *et al.*, 1996), i.e., the fact that physiological responses measured under controlled conditions, or over short-term, may overestimate the impact in the field and that the fading of responses after long exposure times may occur (acclimation).

In order to contribute in the progress of modeling crop-growth under present and future climates, and given the strict link between food production and water use, this paper reports on the FAO approach analyzing water productivity of field crops, focusing on (i) the peculiarities of the different *growth-engines* of crop models and (ii) the relevant modalities to devise the crop-growth in response to elevated CO_2.

2. The crop-models growth-engines

The unifying principles of crop growth are the processes of *capture* and *use* of solar radiation, carbon dioxide, water and nutrients. Moreover, at the heart of any crop growth model there is always a *growth-engine* that operates the production of structural biomass from the use of captured solar radiation and carbon dioxide.

The *growth engine* of all crop models has the solar energy (Rs) as primary driving force. However, Rs is also the primary driving force for water transpiration. Moreover, since both the processes of carbon assimilation and water transpiration are occurring in gaseous phase through the same pathway (stomata), and because of other conservative processes occurring in the conversion of carbon assimilation into biomass, a strict link is also established between transpiration and biomass (Fig. 1).

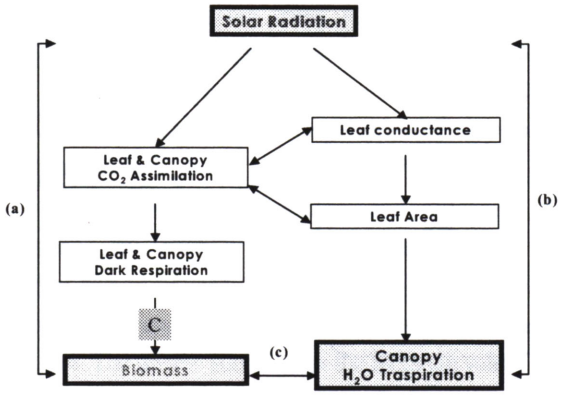

Fig.1 Basic underlining processes involved in biomass production and canopy transpiration. C is the carbon cost of converting net carbon gain into biomass of different composition. Solar radiation is the primary driving force for biomass production (path a) and canopy transpiration (path b). A strict link exists between biomass production and canopy transpiration (path c).

Depending on the path and hierarchy of the processes underlined by the crop model, three categories of growth-engines can be distinguished (Steduto, 2003): (i) *carbon-driven*, (ii) *solar-driven* and (ii) *water-driven*. Almost all *growth-engines* of the different crop models existing in literature can be grouped into one of these three main categories. Some crop models have an internal switch that allows using any of these engines.

2.1. The carbon-driven growth-engine

In this *engine*, growth results from the processing of carbon dioxide through the gross assimilation, dark respiration and conversion of the net carbon gain into structural biomass. The leaf area of the crop canopy is *discretized* in layers along the canopy height (Fig. 2a), through which diurnal light (Fig. 2b) decays while transmitted, reflected, intercepted and absorbed. In each layer, light is divided in direct and diffuse components and leaves are described in terms of area and angle (Fig. 2c). Knowing the gross photosynthetic response function to photosynthetic active radiation (Fig. 2d), the carbon assimilation of different layers and at different times of the day is then employed. Proper integration over canopy height and daytime yields the daily canopy gross carbon gain.

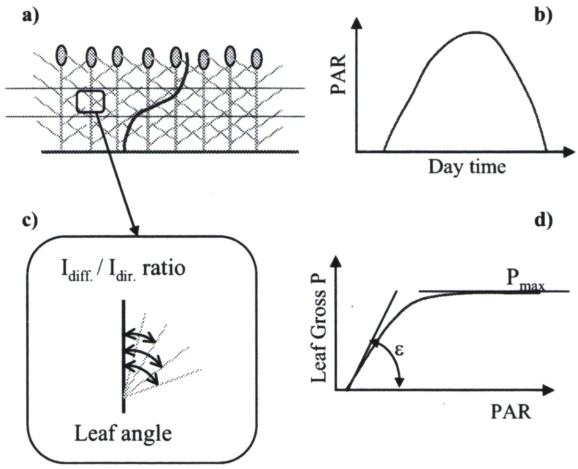

Fig. 2 Qualitative description of the gross CO_2 assimilation underlining the *carbon-driven* growth-engine; a) subdivision of the canopy height in discrete layers; b) diurnal variation of light; c) subdivision of light in direct and diffused components, and of leaf area in different class-angles; d) gross photosynthetic-rate response-function to photosynthetic active radiation (PAR).

Additional functions simulate the maintenance and growth-respiration for the same day, so that a net daily carbon gain is converted into structural biomass, accounting for the carbon cost of the different biomass composition (Penning de Vries *et al.*, 1974). We may indicate that the *carbon-driven growth-engine* follows the path (**a**) highlighted in Fig. 1.

The advantage of this type of *growth-engine* is the excellent subdivision in hierarchical levels of system organization (e.g., organs, plant, crop), where the higher-level responses result from the integration of the underling lower-level processes. In other words, its structure is heuristic, mechanistic and explanatory, in which the processes have sound physical and physiological basis.

The disadvantages of this type of *growth-engine* are ascribed to the variability of response observed at lower hierarchical level. For instance, the photosynthetic response function to photosynthetic active radiation is described by hyperbolas parameterized by the initial slope (or apparent quantum yield) and the maximum value of gross photosynthesis obtained at full light saturation (Fig. 2d). These two parameters are sensitive to temperature, nitrogen content, CO_2 partial pressure, light history on the leaf, etc. Some of these variables changes along the different layers of the canopy profile following a much more complex structure than what implemented in these type of models.

Even more significant are the uncertainties introduced by the simulation of respiration. The *growth-maintenance* modeling paradigm, where plant respiration is partitioned into the functional low-hierarchy components of construction, maintenance and ion uptake, is questioned due to the cumulating experimental evidences (e.g., Gifford, 1995; Cheng *et al.*, 2000; Albrizio and Steduto, 2003) indicating considerably different responses to environmental conditions when respiration is analyzed at higher hierarchical level of aggregation (whole canopy and long term). Therefore, there is a quite inconclusive evidence of the appropriateness of the respiration coefficients used in the *carbon-driven* type of models. These uncertainties lead to large errors in growth rates, especially in presence of large biomass.

Furthermore, the number of parameters are numerous and difficult to calibrate and validate. If new cultivars need to be simulated, then, their experimental parameterization is demanding.

To the *carbon-driven* group belong all *growth-engines* of the Wageningen crop models (Bouman *et al.*, 1996; van Ittersum *et al.*, 2003), among which we can recall: BACROS (BAsic CROP Simulator); SUCROS (Simple and Universal CROp Simulator); WOFOST (WOrld FOod STudies); SWACROP (Soil WAter and CROp Production); SWAP (Soil Water Atmosphere Plant); and many others. To this same group belong also the *growth-engines* of the American CROPGRO (CROP GROwth) crop-template model-series for soybean (SOYGRO), peanut (PNUTGRO), faba bean (BEANGRO), tomato (TOMGRO), and other crops (Boote *et al.*, 1998).

2.2. The solar-driven growth-engine

In this type of *growth-engine* there are no lower hierarchical processes expressing the intermediary steps necessary to achieve the biomass accumulation. It still follows the path (**a**) of Fig. 1 (as in the *carbon-driven*), but the underlining processes are "bypassed" (Fig. 3) and synthetically incorporated into one single coefficient called radiation use efficiency (**ε** or RUE)

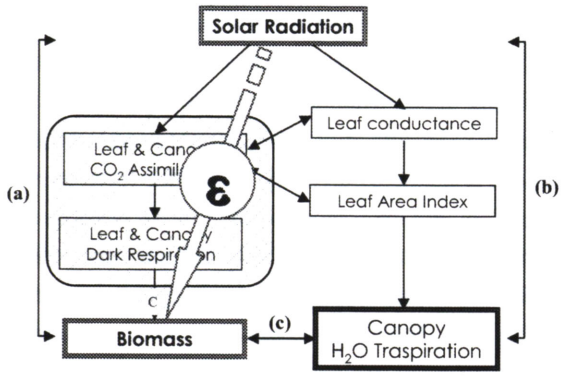

Fig. 3 The direct link between biomass production and solar radiation (intercepted) of the *solar-driven growth-engine*, through the synthetic radiation-use-efficiency parameter ε (or RUE).

In this *engine*, biomass cumulated over a time interval (t, in days) results from the product of **ε** and the cumulated solar radiation intercepted (Rs_i) over such a time interval, as indicated in Eq. (1)

$$\text{Biomass} = \varepsilon \int_0^t Rs_i \qquad (1).$$

This modeling approach has been highlighted by Monteith (1977), who demonstrated the close correlation between cumulative seasonal light interception and biomass production for several crops grown with adequate soil water supply. He formalized and fully established the experimental and theoretical grounds for the relationship (**ε**) between cumulated crop dry-matter and solar radiation.

The literature reports quite a large number of **ε** values for different crops and locations (Gallagher and Biscoe, 1978; Gosse *et al.*, 1986; Kiniry *et al.*, 1989).

The advantage of this *growth-engine* is in the robustness of **ε**, remaining substantially constant under non-stressed conditions and for a long portion of the crop season, provided no substantial changes in biomass composition occur. The relationship (Eq. 1) is simple and the variables to experimentally parameterize **ε** are relatively easy to derive.

The disadvantage of this *growth-engine* is ascribed to the inconsistent variability of **ε** observed among crops, locations and years. This is largely due to: variability in carboxylation capacity of leaves in response to nitrogen variability, stomatal response to VPD and leaf water potential; differences in the ratio between direct and diffuse light; variable sampling errors in biomass and Rs_i determinations; etc. Furthermore, apart from the case of biomass change in high energy-content compounds, the slope of the relationships loses its linearity under water stress and nutrient deficit conditions, and **ε** is not really able to discriminate between large crop groups such as C_3 and C_4. Moreover, the attempt to normalize ε for climate variability, through VPD, seems to be unreliable (Albrizio and Steduto, 2005).

These various inconsistencies and variability of responses are critically analyzed in the review of Sinclair and Muchow (1999) addressing the theoretical analysis of **ε** and its experimental determination and measure. The review summarizes the literature values of **ε** for a large number of crops and locations.

To the *solar-driven* group belong the *growth-engines* of the crop models CERES (Crop Environment REsources Synthesis) for wheat (Ritchie *et al.*, 1985), barley (Travasso and Magrin, 1998), maize (Jones and Kiniry, 1986), millet and rice (Jones *et al.*, 2003). Also belonging to this group are EPIC (Erosion Productivity Impact Calculator; *Jones et al.*, 1991), STICS (Simulator mulTIdisciplinary for Crop Standard;

Brisson *et al.*, 2003), CropSyst (Cropping System simulation model; Stöckle *et al.*, 2003) and PARCH (Predicting Arable Resource Capture in Hostile environments; Azam-Ali *et al.*, 2001). CropSyst and PARCH, though, incorporates also the *water-driven* engine, but with emphasis on the *solar-driven*.

2.3. The water-driven growth-engine

There are several underling mechanisms and processes that make the relationship between carbon assimilation and transpiration so tight that it is reflected also in the relationship between cumulative biomass and cumulative canopy transpiration. Among them are the followings: (i) the role of intercepted radiation in both of assimilation and transpiration processes; (ii) the sharing of the transport pathway by CO_2 and water vapor; (iii) the proportionality between assimilation and respiration; (Hsiao and Bradford, 1983; Steduto, 1996; Steduto *et al.*, 2005). All these mechanisms and processes are sufficiently conservative under various environmental conditions to make the relationship between biomass and cumulative crop transpiration (T_c) quite robust and stable. Steduto *et al.* (2005) report on the basic physiological features conferring constancy to the relationship between biomass and transpiration of crops.

These features allow the *water-driven* growth-engine to avoids the path **(a)** of the previous two engines (the *carbon-driven* and the *solar-driven*) and follow the path **(c)**, as highlighted in Fig. 4.

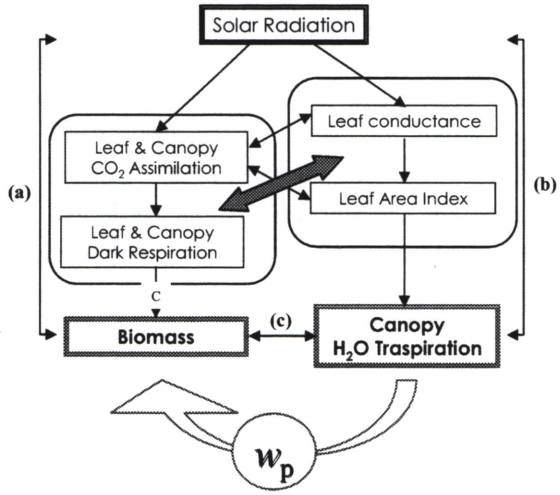

Fig. 4 The direct link between biomass production and canopy transpiration of the *water-driven growth-engine*, through the synthetic water- productivity parameter w_p.

In this *engine*, biomass cumulated over a time interval (t in days) results from the product of w_p and the cumulated canopy transpiration (T_c) over such a time interval, as indicated in Eq. (2)

$$Biomass = w_p \int_0^t T_c \qquad (2).$$

This modeling approach has been highlighted by de Wit (1958), who showed the tight linear relationship between cumulative seasonal transpiration of crops, grown with adequate soil water supply, and biomass production. Furthermore, he was able to normalize for the different climatic conditions, from year to year and from location to location, by dividing crop transpiration for the evaporative demand of the atmosphere. In this way, many crops belonging to the same group expressed the same slope of the relationship. Such a slope represents the *biomass water-productivity* (w_p), also indicated as biomass water use efficiency, or biomass/transpiration ratio. Plenty of such linear relationships can be found in the literature (Tanner and Sinclair, 1983; Hanks, 1983).

The major advantage of this *growth-engine* is in the stability of w_p also under water and salinity stress conditions, along with a low sensitivity to nutrient deficit (e.g., Steduto *et al.*, 2000; Steduto and Albrizio, 2005). Furthermore, dividing T_c by the evaporative demand of the atmosphere (ET_o), it is possible to normalize w_p for climate variability. After normalization for climate, in fact, crops group in classes having same w_p (Fig. 5).

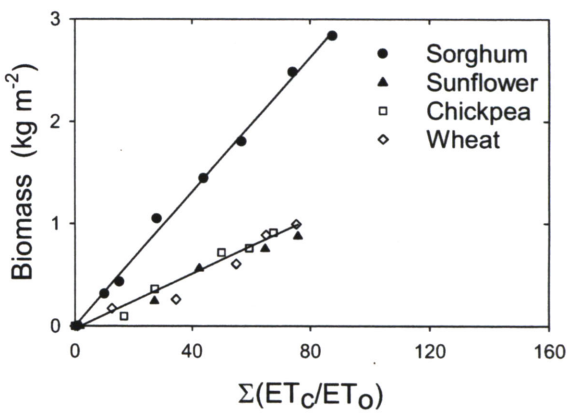

Fig. 5 Regressions between biomass and cumulative evapotranspiration normalized for reference-crop

evapotranspiration (ΣET/ETo) during the crop cycle of sunflower, sorghum, wheat and chickpea. The C_3 crops group together and distinguish from C_4 crops (from Steduto and Albrizio, 2005).

All previous considerations make the *water-driven growth-engine* highly robust for application in water-limited environments.

The major disadvantage of this approach is in the difficulty to derive actual transpiration.

Only a couple of models devise the *water-driven growth-engines* (e.g, one of the two engines of CrpSyst and PARCH). This engine, in fact, has been little implemented in mathematical computer models, in part due to such difficulties encountered in measuring actual canopy transpiration. Nevertheless, advances in instrumentation technology allow nowadays more reliable determinations of evapotranspiration (ET) and the separation between E and T.

Development of a dynamic *water-driven* model is in progress at FAO, evolving from the static *water-driven* model of Stewart (1972) implemented by Doorembos and Kassam (1979).

3. Modalities of crop-models responses to elevated CO_2

Most of the known crop-models were originally developed for simulation under present CO_2 concentration. Only after the raise in concern for *climate change* they were modified to accommodate responses to elevated CO_2. Therefore, additional parameterization was needed and, depending on the underling device simulating crop response to elevated CO_2, three modalities can be distinguished: (i) *biochemical*, (ii) *empirical-correlative*, and (iii) the most recent one based on the *water use efficiency/water productivity* (WUE/WP) *paradigm* equations. These modalities are generally implemented in the three *growth-engines* previously discussed, respectively.

3.1. The biochemical modality

This approach, typically adopted in the *carbon-driven* engine, is worked out through the enzymatic reactions of photosynthesis developed by Farquhar and von Caemmerer (1982).

Essentially, most of the biochemical knowledge of photosynthesis can be summarized in few equations representing (i) the rate of Ribulose-biphosphate (RuBP) carboxylation; (ii) the ratio of photorespiration to carboxylation and (iii) the rates of electron transport-photophosphorylation and of dark respiration in the light. These equations are then conjugated with stomatal and boundary-layer conductances and integrated within the functioning of individual leaves, leading to a final leaf-photosynthesis modeling simulating the assimilation response to light, temperature and CO_2 concentration.

While largely mechanistic, this modality suffers of a few limitations. The whole algorithmic ends up to be compounded by a large set of equations with an overall great number of parameters difficult to calibrate and validate.

Moreover, this modality aggravates the up-scaling and down-regulation problem since it extends further down the space-time scales of processes (at cellular and organelle levels, with consequent shortening also of the response times), diminishing significantly the reliability of integration up to the canopy aggregation.

Overall, this approach involves a high degree of complexity; it is very difficult to handle in practice and needs to be treated with care if confidence in results is required.

3.2. The empirical-correlative modality

This approach, mostly adopted in the *solar-driven* engine, is worked out through empirical relations that have remained largely untested in the field.

Among the main proposed modalities there are the ones of Peart *et al.* (1989) for CERES-Wheat, of Easterling *et al.* (1992) for EPIC and of Stöckle *et. al.* (1992) for EPIC and CrpSyst.

The basic assumption is that the radiation use efficiency parameter (**ε**) would change in response to $[CO_2]$ increase following an empirical hyperbolic function in a similar fashion to the photosynthetic response to CO_2.

A general function is the one of Eq. (3)

$$\varepsilon = \frac{100[CO_2]}{\left\{[CO_2] + b_1 e^{(b_2[CO_2])}\right\}} \quad (3)$$

with b_1 and b_2 being two empirical parameters that can be derived after determining experimentally, e.g. in growth chambers or FACE experiments, two value of **ε** at two level of $[CO_2]$, say 350 ppm and 700 ppm.

Notwithstanding attempts to found it on theoretical ground, Eq. (3) remains fully empirical, correlative and untested in the field.

Therefore, also in this case, the implementation of this modality needs to be treated with care if confidence in results is required.

3.1. The WUE/WP paradigm modality

This approach, mostly adopted in the *water-driven* engine, is the most recent and has been developed through the analysis proposed by Hsiao (1993).

The conceptual point of departure is the leaf gas-exchange processes formulation. Under steady-state conditions (generally the case when changes are gradual and determinations refer to period of time of the order of 5 to 15 minutes), the leaf CO_2 assimilation (A_l) and transpiration (T_l) can be expressed through the flux-gradient Eqs. (4) and (5), respectively

$$A_l = \frac{\Delta c}{r'} = \frac{c_a - c_i}{r'_b + r'_s} \qquad (4)$$

$$T_l = \frac{\Delta w}{r} = \frac{w_i - w_a}{r_b + r_s} \qquad (5)$$

where: c_a and w_a are respectively the CO_2 and water vapor concentration in the bulk atmosphere; c_i and w_i are respectively the CO_2 and water vapor concentration in the sub-stomatal intercellular air-space (or internal to the leaf); r' and r are the total resistances, respectively, to CO_2 and water vapor transport, compounded by the boundary (subscrip b) and stomatal (subscript s) resistances.

It is worth noticing that, under steady-state, the impact of the photosynthetic metabolism is not dealt with directly through the biochemistry but it is reflected in the values of A_l, c_i and c_a relative to c_i (Eq. 4).

From the diffusivity of the two gases in air (binary-diffusivity), the ratio between the resistances to water vapor transport (r) and to CO_2 transport (r') results in

$$\frac{r}{r'} = 0.625 \qquad (6).$$

The water use efficiency (WUE) of the leaf gas-exchange is defined as the ratio between assimilation and transpiration, i.e.,

$$WUE = \frac{A_l}{T_l} = \frac{\Delta c}{r'}\frac{r}{\Delta w} = \frac{r}{r'}\frac{\Delta c}{\Delta w} \qquad (7).$$

Substituting Eq. (6) into Eq. (7), and expanding, the photosynthetic water use efficiency can be expressed as

$$WUE = 0.625\frac{c_a - c_i}{w_i - w_a} \qquad (8).$$

Substantial experimental evidences shows that, for a given c_a, c_i tends to remain constant under a wide range of conditions, including water stress (Hirasawa *et al.*, 1995), temperature (Biörkman, 1981), radiation (Bolaños and Hsiao, 1991), leaf nitrogen content (Wong *et al.*, 1979), salinity (Steduto *et al.*, 2000) and CO_2 (Wong *et al.*, 1979; Morrison, 1987), although a mild tendency for c_i to decrease is observed, instead, with increase in vapor pressure deficit of the atmosphere (VPD) in plants showing stomatal response to humidity.

The tendency of the ratio c_i/c_a (generally indicated with α) to remain constant is consistent with the theory of optimal stomatal behavior in water use (Cowan, 1982) and it is attributed to the adaptation evolution of plants to environment.

Expressing, then, c_i as function of c_a (i.e., $c_i=\alpha c_a$) and substituting in Eq. (8), results in

$$WUE = 0.625(1-\alpha)\frac{c_a}{\Delta w} \qquad (9).$$

In view of the conservative behavior of α, it is advantageous to express the WUE under elevated CO_2 on a relative basis, i.e., as compared to its value under current CO_2 concentration. Following the symbolism of Hsiao (1993), indicating with the subscripts 'n' and 'o' the new (or elevated) and reference (or current) CO_2 concentrations, respectively, it is possible to express the relative change in WUE as

$$\frac{WUE_n}{WUE_0} = \frac{0.625(1-\alpha_n)}{0.625(1-\alpha_0)}\frac{c_{a,n}}{\Delta w_n}\frac{\Delta w_0}{c_{a,0}}$$

that, after cancellation (with $\alpha_n \cong \alpha_0$), reduces to

$$\frac{WUE_n}{WUE_0} = \frac{c_{a,n}}{c_{a,0}} \frac{\Delta w_0}{\Delta w_n} \qquad (10).$$

Eq. (10) indicates that the relative change in WUE is the product of the c_a ratio by Δw ratio and it represents the first paradigm equation to investigate the change in the water productivity parameter w_p under elevated CO_2. However, being Eq. (10) derived from gas-exchange of single leaves, it needs to be scaled up to canopy gas-exchange and to biomass as well.

Xu and Hsiao (2004) have shown that no real up-scaling is needed to go from leaf to canopy gas-exchange since the ratio approach of Eq. (10) allows for mutual cancellation of the similar up-scaling implications for both new and reference conditions. In other words, no need for up-scaling appears to be required in going from leaf to canopy gas-exchange, so that Eq. (10) remains valid in both cases.

Nevertheless, up-scaling is still required when extending toward biomass. In this case, additional considerations are required.

At aggregated canopy scale, biomass can be expressed as

$$\text{Biomass} = C\left(\int_0^t A_c - \int_0^t R_d \right) \qquad (11)$$

where, C is the carbon cost for different biomass composition; A_c is the net crop assimilation during day-time and R_d is the crop dark respiration during night-time; both A_c and R_d are integrated over the time interval (in days) from t_0 to t during which the Biomass has been produced.

Also about the ratio between R_d and A_c, there are cumulating experimental evidences showing its constancy under a wide range of conditions, including temperature, CO_2, and nutrients (Gifford, 1995; Cheng *et al.*, 2000; Albrizio and Steduto, 2003). Therefore, setting β the ratio R_d/A_c, so that $R_d=\beta A_c$, and substituting into Eq. (11), we obtain the following:

$$\text{Biomass} = C\left(\int_0^t A_c - \beta \int_0^t A_c \right)$$

$$\therefore$$

$$\text{Biomass} = C(1-\beta) \int_0^t A_c \qquad (12).$$

From Eq. (2) and Eq. (12) it is possible to derive the water productivity parameter (w_p) as

$$w_p = \frac{\text{Biomass}}{\int_0^t T_c} = \frac{C(1-\beta)\int_0^t A_c}{\int_0^t T_c} \qquad (13).$$

In view of the conservative behavior of β, also in this case it is advantageous to express the change of w_p on a relative basis, i.e., under elevated CO_2 as compared to its value under current CO_2 concentration. Therefore, in analogy to Eq. (10), and using the same subscript symbols, we can derive

$$\frac{w_{p,n}}{w_{p,0}} = \frac{\text{Biomass}_n}{\int_0^t T_{c,n}} \frac{\int_0^t T_{c,o}}{\text{Biomass}_o} \Rightarrow$$

$$\Rightarrow \frac{w_{p,n}}{w_{p,0}} = \frac{C(1-\beta_n)}{C(1-\beta_o)} \frac{\int_0^t A_{c,n}}{\int_0^t T_{c,n}} \frac{\int_0^t T_{c,o}}{\int_0^t A_{c,o}}$$

that, after cancellation (with $\beta_n \cong \beta_o$), reduces to

$$\frac{w_{p,n}}{w_{p,0}} = \frac{\int_0^t A_{c,n}}{\int_0^t T_{c,n}} \frac{\int_0^t T_{c,o}}{\int_0^t A_{c,o}} = \frac{\int_0^t WUE_{c,n}}{\int_0^t WUE_{c,o}} \qquad (14).$$

Eq. (14) indicates that the relative change in w_p is the product of the A_c ratio by T_c ratio, which corresponds to the WUE_c ratio of the gas-exchange at canopy level over the period of time t.

Since no up-scaling is needed from leaf to canopy gas-exchange, Eq. (10) can be inserted into Eq. (14) to derive

$$W_{p,n} = W_{p,o} \int_{o}^{t} \frac{c_{a,n}}{c_{a,o}} \int_{o}^{t} \frac{\Delta w_o}{\Delta w_n} \quad (15).$$

Eq. (15) indicates that w_p under the new condition (elevated CO_2) is obtained through weighing the reference value ($w_{p,o}$) by the product of the c_a ratio times the Δw ratio (as for Eq. 10), provided they are integrated over the time interval during which the Biomass has been produced.

For applications about the impact of *climate change* on field crops, the new values of w_p can be estimated from Eq. (15) substituting Δw with atmospheric vapor pressure deficit (VPD), as a function of air temperature and relative humidity only.

In this way, by knowing only the climatic variables (i.e., the current and future values of CO_2 concentration, air temperature and relative humidity) along with the current crop parameter w_p, derived experimentally or available from the literature, estimates of the water productivity parameter w_p under future *climate change* can be easily derived.

The previous paradigm equations are fundamental and should hold regardless of whether plants are C_3 or C_4, and under various sets of changes in environmental conditions (i.e., not only CO_2). This modality is preferred since based on the conservative behavior of α (c_i/c_a) and β (R_d/A_c), most likely as the consequence of natural evolution and adaptation of plants in resources-use optimization.

4. Concluding remarks

Concerning crop-models, FAO is working mainly with the *water-driven growth-engines*, devising the WUE/WP paradigm equations.

In addition to the specific domain of *water productivity*, the *know-how* gained over the years enables FAO to provide technical services related to *climate change* under different perspectives, such as carbon sequestration, impacts assessment, mitigation measures, reduction of greenhouse gas emissions, adaptation strategies and implementation of projects supported by the Global Environmental Facility (GEF) and other donors.

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