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Evaluation of some evapotranspiration estimation models under CO_2 increasing concentrations: A review

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Abstract. The total volume of CO_2 emissions is building up dramatically, and because of the effect of this gas on the growth, physiology, and biochemistry of plants, it is becoming increasingly necessary to look into the impact of the relentless rise of carbon dioxide. Although there are several developed approaches that tried to model the canopy resistance, many of these methodologies ignored the effect of CO_2 or were not incorporated with the existing evapotranspiration calculation methodologies, mainly due to the complexity of the modeling procedure and the short time framework of the conducted studies. This review explores the few models estimating crop water requirements that account for this effect and examines their assumptions and theories. The inclusion of canopy resistance models in evapotranspiration calculation may be of questionable utility without improvements in some modeling aspects, such as the relationship between the stomatal conductance and CO_2 and the climatic variables taken in consideration in the modeling process.

Keywords. Penman Monteith, ETo, carbon dioxide, canopy resistance, surface resistance, climate change.

INTRODUCTION

According to UNDESA (2017), the world population is foreseen to grow between 20-30% by 2050, going from 7.7 billion people in 2017 to between 9.2 and 10,2 billion. Naturally, the global demand for food production is also expected to increase by almost 60% by 2025 (Alexandratos and Bruinsma, 2012; OECD, 2012). On the other side, global water consumption has already known a leap of 600% over the last century (Wada et al., 2016), and it keeps increasing by 1% yearly (AQUASTAT n.d.). Water demand is currently evaluated at 4.600 km^3 and could reach almost 6000 km^3 by 2050 (Burek et al., 2016). All this will put more pressure on the agricultural sector, which is the actual largest world consumer of freshwater, mostly for irrigation, accounting for 70% of freshwater withdrawals, up to 90% by 2050 (WWAP, 2012). Agriculture is also expected to face a fierce competition for water resources from other sectors, resulting in a decrease in its share of total water use in developing countries from 86% in 1995 to 76% in 2025 (Rosegrant et al., 2002). In addition, global warming is meanwhile affecting the water cycle and shifting weather patterns (IPCC, 2014a). Therefore, the agricultural sector is in great need of creating strategies to improve water management and, consequently, attain greater levels of water savings in order to face these aforementioned challenges (de Fraiture and Wichelns, 2010).

One of the key components to improving the management of water resources is accurately determining the water requirements of irrigated crops. These needs depend on the management strategy chosen, and are based on the demand for atmospheric water, known as evapotranspiration. Evapotranspiration (ET) is a major component of the hydrological cycle and has an important effect on the quality of water, since in the evaporation process the water is purified. This clean H_2O restores about 60% of global land surface water. For vegetated ecosystems, it is also the main component of energy balance, employing more than 50% of absorbed solar radiation (Trenberth et al., 2009). In fact, evapotranspiration is a component of the energy budget involving incoming energy and outgoing water, occurring at the crop surface. The other components of the budget are net radiation, sensible heat flux, soil heat flux, and solar radiation stored as photochemical energy. This exchange process creates an atmospheric demand that is satisfied by transferring water out of the plant system through evapotranspiration. Such phenomenon is regulated by the principle of energy conservation or energy balance: energy arriving at the vegetation surface equal energy leaving the same surface for the same time period. The energy balance equation for an evaporating surface can be written as:

$$R_n - G - \lambda ET - H = 0 \tag{1}$$

where R_n is net radiation, H sensible heat, G soil heat flux and λET is the latent heat flux. Terms can be either positive or negative: positive R_n supplies energy to the vegetation surface and positive G, λET and H remove energy from the vegetation surface. The latent heat flux (λET) is the evapotranspiration fraction and can be derived from the energy balance equation, if all other components are known. ET is an important hydrological variable for irrigation water management, hydrological modeling and water balance calculations. Penman (1963) defines ET as the combination of two separate processes occurring simultaneously, evaporation from the soil surface and transpiration from the crop. Since the evapotranspiration is strongly affected by crop type, crop development and management practices, there was a need to find a concept to express the evaporative demand of the atmosphere independently of those factors. Hence, reference evapotranspiration (ETo) was introduced for this purpose. ETo is defined as the evapotranspiration rate from a well irrigated hypothetical grass reference crop with specific characteristics. It expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider crop characteristics and soil factors. Instead, it is driven by weather parameters, which are solar radiation, air temperature humidity and wind speed. A thorough understanding of ETo is the first step to achieving efficient and effective water management and irrigation scheduling. The United Nations Food and Agriculture Organization (FAO) has adopted an updated Penman–Monteith equation (FAO-PM) as a global standard for estimating grass reference evapotranspiration (Allen et al., 1998). This equation was chosen as it provides a better prediction compared to other methods in a wide variety of geographic locations and climatic conditions (Kashyap and Panda, 2001; Yoder et al., 2005; López-Urrea et al., 2006; Suleiman and Hoogenboom, 2007; Adeboye et al., 2009; Rasul and Mahmood, 2009; Rácz et al., 2013). It includes all the different atmospheric variables that influence ET, which makes it suitable for climate change impact studies (Kingston et al., 2009; Islam et al., 2012; Priya et al., 2014). However, despite the completeness of this equation, it simulates poorly the effect of CO_2, that is represented by the "canopy resistance" or "surface resistance" term, r_c. In fact, daily r_c is fixed at 70 s m^{-1} and is considered constant regardless of climate type and change in climate patterns, thus contradicting published reports

(Long et al., 2004; Damour et al., 2010). Although Allen et al. (2006) considered that fluctuation in its value would have a negligible effect on the ETo calculation, many experimental studies disagree with their statement on hourly, daily and seasonal scales (Steduto et al., 2003; Katerji and Rana, 2006, 2011, 2014; Yan et al., 2017). This is particularly true when the crop is under well-watered conditions, i.e. when the physiological component of r_c is at its minimum. The alarming increase of CO_2 concentrations due to climate change, the physiological effects that it would have on crop plants (Tubiello et al., 2000; Long et al., 2004; Mall et al., 2017) and the uncertainties affecting the calculation of ETo using the FAO-PM equation, have prompted many researchers to develop other approaches and models to estimate reference evapotranspiration, taking into account the variability of the canopy resistance r_c. Following a short discussion on the effect of rising CO_2 on crops evapotranspiration, this paper provides an overview of these different methods, delineating their main theories and assumptions, and exploring their strengths and weaknesses.

EFFECT OF CO_2 ON CROPS EVAPOTRANSPIRATION

Our planet's atmosphere witnessed a gradual change throughout history, experiencing a wide range of CO_2 concentration. Studies suggest that this concentration may have been about 4000 to 5000 ppm some 500 million years ago (Ehleringer et al., 2005). Then, this concentration decreased to around 1000 ppm between 35 and 55 million years ago, falling abruptly to about 390 ppm during Oligocene by approximately 32-25 million years ago (Tipple and Pagani, 2007). This decline in CO_2 limited the efficiency of photosynthesis, triggering the evolution of C_4 plants from ancestral C_3 species as a clever solution to the problem of low atmospheric CO_2. Since the pre-industrial era, anthropogenic greenhouse gas (GHG) emissions have been causing new increases in the atmospheric concentrations of carbon dioxide, going from 270 ppm before 1700 to about 410 ppm in 2020, reaching unprecedented levels in at least 800,000 years. The concentration will keep increasing if no additional efforts are made to reduce emissions (IPCC, 2014a, 2014b). These increasing concentrations have important physiological effects on plants, e.g. faster rate of photosynthesis, greater leaf area, increase in biomass and yield and decrease in stomatal conductance and transpiration rate (Allen, 1990; Ainsworth and Long, 2004; van der Kooi et al., 2016). The latter effect has been confirmed by several experimental studies conducted in open-top and closed-top chambers or using the Free-Air Carbon dioxide Enrichment (FACE) method (Wullschleger et al., 2002; Shams et al., 2012). On the other hand, more biomass means more evapotranspiration because of a higher leaf area index (LAI) (Wand et al., 1999; Piao et al., 2010), potentially offsetting the effect of the reduction in stomatal conductance (Bernacchi et al., 2007). However, even under experimental conditions, there is a large uncertainty in the CO_2 induced change in stomatal conductance, especially when scaling from the single leaf to a full canopy where other factors affect the whole process (Polley, 2002). For example, CO_2 effect is significantly different between C_3 and C_4 plants and between trees and smaller plants (Taiz and Zeiger, 1991), but also seems to depend on the scale of the experiment (Jarvis and McNaughton, 1986; Bunce, 2004). In fact, most of the existing knowledge on plants response to higher CO_2 concentrations is based on small scale research experiments conducted in open field with controlled environment. Even if there are techniques such as FACE that allow the exposure of plants to elevated CO_2 concentrations under natural and fully open-air conditions, they can be difficult and expensive to construct and operate, which limits the inference space of these experiments with regards to the range of global ecosystems (Norby et al., 2016). Moreover, there could be an overestimation of the CO_2 effect due to artificial ventilation and advection from outside the FACE area (Kruijt et al., 2008). Given the complexity of the effect of CO_2-sensitivity of evapotranspiration on future climate simulations and the large uncertainty in the CO_2 induced change in stomatal conductance under experimental conditions (Kruijt et al., 2008), understanding plant responses to CO_2 is becoming increasingly important.

This review paper summarizes some of the most documented r_c models, precisely those directly used or modified to account for the effect of CO_2 on the evapotranspiration. The models presented (Table 1) have their limitations that the authors tried to underline. However, because the literature is limited regarding this particular topic, the primary purpose of this review was to provide a brief reference document for researchers and the scientific community in general on the different models developed so far and their main findings and challenges.

DESCRIPTION AND DISCUSSION OF EVAPOTRANSPIRATION APPROACHES ACCOUNTING FOR CO_2 EFFECT

Penman-Monteith method adapted to an increase in CO_2 concentrations

The standardized Penman–Monteith equation (FAO-PM) (Allen et al., 1998) is based on the Penman–Monteith equation (Monteith, 1965). It is the most widely used method and has been proven to be a good ETo estimator when compared with other methods, especially for daily computations (Chiew et al., 1995; Liu et al., 1997; Ventura et al., 1999; Jacobs and Satti, 2001; Garcia et al., 2004; Temesgen et al., 2005). For a grass reference surface and for a daily time step, this equation is expressed as:

$$ETo=\frac{0.408\Delta(R_n\text{-}G)+\gamma\frac{900}{T_{2m}+273}.u_2(e_s\text{-}e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{2}$$

where ETo is the reference evapotranspiration (mm day^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^2 day^{-1}); T_{2m} is the mean daily air temperature at 2 m height (°C); u_2 is the wind speed at 2 m height (m s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); $(e_s - e_a)$ is the saturation vapour pressure deficit (kPa); Δ is the slope of the vapour–pressure curve (kPa °C^{-1}) and γ is the psychometric constant (kPa °C^{-1}).

The canopy resistance r_c describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. It is represented in the equation above by the value 0.34 in the denominator:

$$0.34u_2=\frac{70}{208/u_2}=r_c/r_a \tag{3}$$

where r_a is the aerodynamic resistance (s m^{-1}), which describes the transfer of heat and water vapour from the evaporating surface into the air above the canopy. For a grass reference surface, assuming a constant crop height of 0.12 m and a standardized height for wind speed, temperature and humidity at 2 m, r_a becomes:

$$r_a=208/u_2 \tag{4}$$

Under the same reference conditions, and knowing that the stomatal resistance r_s of an actively transpiring C_3 grass leaf surface has a value of about 100 s m^{-1}, r_c is represented as the following:

$$r_c=\frac{r_s}{0.5\ \mathrm{LAI}}=\frac{100}{0.5\times2.88}=69\approx70\ s\ m^{-1} \tag{5}$$

where LAI is the leaf area index of the upper half of dense clipped grass, which is generally the only part actively contributing to the surface heat and vapour transfer (LAI = 24 × crop height (h) = 24 × 0.12 = 2.88)

Assuming that the $r_c \approx 70$ s·m^{-1} applies to a specific CO_2 concentration, estimating a new r_c value for higher CO_2 concentration provides a method to estimate possible impacts of higher CO_2 on ETo. Thus, the following form of FAO-PM equation should be adopted:

$$\mathrm{ETo}=\frac{0.408\Delta(R_n\text{-}G)+\gamma\frac{900}{T_{2m}+273}.u_2(e_s\text{-}e_a)}{\Delta+\gamma(1+r_c/r_a)} \tag{6}$$

Lovelli et al. (2010) and Snyder et al. (2011) used this method in a Mediterranean climate, introducing in the equation published values regarding atmospheric CO_2 on stomatal conductance (Long et al., 2004; Ainsworth and Long, 2004), and considering the temperature increment effect on the reference evapotranspiration (ETo) variation. They concluded that the effect of increasing CO_2 concentration may be annulled by an increase in air temperature and subsequent increase in evapotranspiration rate. On the other hand, Moratiel et al. (2011) found out that the CO_2 increase from 372 ppm to 550 ppm would create a reduction of the ETo increment by half, from 11% to 5% in the next 50 years, as compared to the current situation in northern Spain. By recalibrating the canopy conductance for the widely acclaimed and recommended FAO-PM equation, this approach may be particularly effective in evaluating the effects of climate change on crop water use. However, The FAO-PM model is based on the "big leaf" approximation with constant

Tab. 1. Some of the models referenced in this work

Model	Reference	Simulation Period	CO2 concentration
Penman Monteith with a modified r_c	Lovelli et al. (2010)	2071 - 2100	550 ppm
	Moratiel et al. (2011)	2007 - 2050	372 and 550 ppm
	Snyder et al. (2011)	2050	550 ppm
CO_2-factor	Easterling et al. (1992)	Analog period: 1931 - 1940	330 and 660 ppm
	Ficklin et al., (2009)	NA	550 and 970 ppm
	Islam et al., (2012)	2010 - 2099	450 ppm to 900 ppm
	Wu et al., (2012)	2071 - 2100	330 and 660 ppm
	Fares et al., (2015)	NA	330, 550, 710 and 970 ppm
F factor	Olioso et al. (2010)	2020 – 2049 and 2070 - 2099	540, 703 et 836 ppm
	Salmon-Monviola et al. (2013)	1961–1990, 2010–2039, 2040–2069 and 2070–2099	330, 430, 545 and 640 ppm
Jarvis	Medlyn et al. (2001)	NA	350–700 ppm
Katerji and Perrier	Katerji et al. (2017)	1981 – 2006 and 2070 - 2100	600 and 850 ppm

canopy resistance, which is a simplistic assumption that could limit the accuracy of the predictions of the model. Considering the driving meteorological variables at a particular site, estimates made with the FAO-PM equation rely on the correct modeling of the effective values of both aerodynamic resistance r_a and canopy resistance r_c. Hence, the fixed value for r_c may be the cause of the tendency for the FAO-PM method to underestimate the higher values of measured ETo, and to overestimate the lower ETo values in semi-arid and windy areas with a high evaporative demand (Hussein, 1999; Ventura et al., 1999; Berengena and Gavilan, 2005). As r_a can be calculated from meteorological conditions, in order to provide more accurate estimations of evapotranspiration using the FAO-PM equation, it may be necessary to parameterise r_c as a primary factor in the evapotranspiration process (Monteith, 1965). Canopy resistance r_c is a physiological parameter with an aerodynamic component (Alves et al., 1998). It is difficult to estimate it for different climatic and crop water conditions, as it is influenced by solar radiation, temperature, vapor pressure deficit and soil water content (Lecina et al., 2003; Pereira et al., 1999). Nevertheless, a simple attempt to model this resistance may yield a better estimation when the FAO-PM equation is applied over both short and tall crops (Alves and Pereira, 2000; Pereira et al., 1999) and over other types of vegetation (Chávez and López-Urrea, 2019; Margonis et al., 2017). It could also be useful to incorporate the effects of the resistance due to vegetation into climatic and hydrological models (Yang et al., 2019; Bie et al., 2015).

In this context, some studies incorporated a "CO_2-factor" into the FAO-PM equation (Easterling et al., 1992; Ficklin et al., 2009; Parajuli, 2010; Islam et al., 2012; Wu et al., 2012; Priya et al., 2014; Fares et al., 2015). Then, equation (1) can be rewritten as:

$$\mathrm{ETo}=\frac{0.408\Delta(R_n\text{-}G)+\gamma\dfrac{900}{T_{2m}+273}.u_2(e_s\text{-}e_a)}{\Delta+\gamma(1+\dfrac{0.34u_2}{CO_2\text{-}factor})} \tag{7}$$

where, in the denominator, a linear relationship for stomatal conductance as a function of CO_2 level is introduced. It was developed by Stockle et al. (1992), and based on 80 data sets comparing leaf conductance at 330 ppm and at 660 ppm of CO_2 concentration for a wide range of species including C_3 and C_4 crops:

$$g_{CO_2}=g\left[1.4\text{-}0.4\ {}^{CO_2}\!/_{330}\right] \tag{8}$$

where g_{CO2} is the leaf conductance modified to reflect CO_2 effects (m s^{-1}); g is the conductance without the effect of CO_2 (m s^{-1}); CO_2 is the actual atmospheric CO_2 concentration (ppm) and *330* represents the baseline atmospheric CO_2 concentration (ppm). The new r_c is as follows:

$$r_c=\frac{1}{g_{CO_2}\times 0.5\ LAI} \tag{9}$$

The "CO_2-factor" is based on experimental observations of a 40% linear decrease in stomatal conductance between 330 and 660 ppm CO_2 concentrations (Morison and Gifford, 1983). Islam et al. (2012) incorporated this model in the FAO-PM equation to evaluate the effects of possible future anthropogenic climate change on ETo. Results of the different simulation studies showed an increase in ETo with changing climate, but the impact of increasing temperatures was almost offset by increasing CO_2 levels. In fact, sensitivity analysis showed that the effect of a 1°C rise in temperature was offset by an increase in CO_2 levels up to 450 ppm, whereas the effect of a 2°C temperature rise was offset by CO_2 concentrations of 660 ppm, thus in close agreement with results found by Priya et al. (2014) using the same model. Authors pointed out that, due to its linearity, this "CO_2-factor" is only valid in the range of 330 to 660 ppm. For CO_2 concentrations beyond 660 ppm, factors for specific crops reported by Allen (1990) were used. The same remark was made by Ficklin et al. (2009) when increasing CO_2 concentration to 970 ppm and temperature by 6.4 °C caused watershed-wide average evapotranspiration, averaged over 50 simulated years, to decrease by 37.5%, resulting in an increase of water yield by 36.5%. They explained that the linear assumption of eq. (8) means that it is suitable for all plant species, which may lead to an overestimation of the aforementioned reduction in ETo in the presence of multiple types of land cover. They concluded that because of this broad simplification of the effects of CO_2 on plant growth, their analysis was still too uncertain for water management purposes. The presumed overestimation of ETo is because this "CO_2-factor" is based on the assumption that a doubling of CO_2 concentration would lead to a general decrease of 40% in stomatal conductance (Morison, 1987) irrespective of the land cover type. This reduction of conductance is assumed to be linear over the entire range of CO_2 concentrations between 330 ppm and 660 ppm (Morison and Gifford 1983). To overcome this issue, Wu et al. (2012) proposed an optimised equation:

$$g_{CO_2}=g\left[(1+p)\text{-}p\ {}^{CO_2}\!/_{330}\right] \tag{10}$$

where *p* is the percentage decrease in leaf conductance specific to vegetation types (Authors provided different values in their study). The modified equation inherently gave a better representation of this increasing CO_2 effects than the original equation by incorporating the CO_2 effects dynamically in more process-based details.

Olioso et al. (2010) suggested multiplying the FAO-PM ETo by another factor *F* to correct the daily values of reference evapotranspiration taking into account the effect of higher CO_2 concentrations. This factor was derived from evapotranspiration simulations of the ISBA-A-gs model (Calvet et al., 1998) at different CO_2 levels, and used in different studies (Martin et al., 2011; Lardy et al., 2012, 2014; Salmon-Monviola et al., 2013; Katerji et al., 2017):

$$F=1.1403-3.8979\times10^{-4}\times[CO_2] \tag{11}$$

The value of *F* is approximately 1 when the mean annual value of the air CO_2 concentration is equal to 370 ppm. *F* decreases or increases when the CO_2 concentration is higher or lower than this threshold. For example, the decrease in ETo is approximately 8 and 20 % when the CO_2 concentration reaches 550 and 900 ppm, respectively (Olioso et al., 2010). The factor is also based on a linear relationship between the decrease of ETo and the increase of the CO_2 concentration, which raises the same concerns previously discussed.

According to Katerji et al. (2017), the issue of the approaches mentioned above is that they are insufficient to adapt the FAO-PM equation to the increasing concentrations of CO_2. These solutions always consider the resistance r_c to be constant by neglecting its reliance on climatic variables, which means that r_c parameterisation is required to reduce the difference between the directly measured ETo values, and those estimated using the FAO-PM model.

PENMAN-MONTEITH METHOD WITH VARIABLE CANOPY RESISTANCE MODELS

Jarvis Model

Jarvis model is a phenomenological and multiplicative empirical model that interprets field measurements of stomatal conductance g_{CO2} in relation to environmental variables. It calculates g_{CO2} by multiplying the maximum conductance g_{max}, which is a value which represents the highest *g* recorded under optimal conditions (Korner et al., 1979), with a number of empirical response functions, including one for CO_2-sensitivity, and it is assumed that each variable acts independently (Jarvis, 1976; Whitehead, 1998):

$$g_{CO_2}=\frac{1}{\mathrm{r_s}}=g_{max}f(I)f(T_a)f(C_a)f(VPD)f(\Psi) \tag{12}$$

where *I* is the absorbed photosynthetic photon flux density (μmol m^{-2} s^{-1}), T_a is the air temperature (°C), C_a is the CO_2 concentration (ppm), *VPD* is the Vapour Pressure Deficit (kPa) and Ψ is the soil water potential (Pa).

Same as the aforementioned models, Jarvis model is also based on a linear function between the stomatal conductance g_{CO2} and atmospheric CO_2. In fact, Jarvis (1976) concluded that g_{CO2} decreased linearly when the increase in CO_2 concentration is within the range of 100-1000 ppm, and that it stays constant when the CO_2 concentration is <100 ppm or >1000 ppm. Also, equation (12) may underestimate g_{CO2} when relative humidity (*RH*) is high because it correlates g_{CO2} linearly to *RH* (Wang et al., 2009). In this case, a nonlinear function of *RH* or *VPD* may reduce the bias (Leuning, 1995; Wang et al., 2009).

Nevertheless, Jarvis model has been used in different forms in many studies (Hanan and Prince, 1997; Gharsallah et al., 2013; Zhang et al., 2016; Zhou et al., 2019). In the east coast region of North America, elevated atmospheric CO_2 was found to reduce ET at a rate of 0.84 mm/year between 1901 and 2008 when calculating stomatal conducatance with a Jarvis-type equation in the Dynamic Land Ecosystem Model (DLEM) 2.0 (Yang et al., 2015). Using the same model in a global scale, Pan et al. (2015) concluded that increasing atmospheric CO_2 will lessen the positive effect of warming temperature and increasing precipitation on ET by the end of the 21st century. Medlyn et al. (2001) analysed data from 13 long-term (>1 year) field-based studies of the effects of elevated CO_2 concentration (350 ppm and 700 ppm) on European forest tree species by fitting data to two models namley Jarvis and Ball (Ball et al., 1987). Their meta-analysis indicated a significant decrease (21%) in stomatal conductance in response to growth in elevated CO_2 concentrations across all studies, resulting in a decrease of ET.

Some authors think that another limit of the Jarvis model is that each response function has to be adjusted to the data to be able to provide good predictions for any type of vegetation, since they are specific for only certain crops and climate conditions and they cannot be used for general purposes (Yu and Wang, 2010). Consequently, a site-specific calibration of the empirical response functions becomes necessary. Another criticism formulated against this approach is that the knowledge of stomatal resistance r_s alone may not be sufficient to calculate ET because the FAO-PM equation requires r_c. Hence, the upscaling of r_s to the canopy level is required to calculate r_c, which could be quiet challenging (Irmak et al., 2008). Besides, Alves and Pereira (2000) questioned the validity of the multiplicative model because it only includes the physiological component of r_c but not the aerodynamic component r_a and because of the assumption of environmental variables acting independently.

Katerji and Perrier (KP) model

Based on the fact that r_c, for well-watered crops, varies during the day with different climatological variables, Katerji et al. (1983) suggested a new semi-empirical procedure to determine both resistances r_c and r_a by applying the Buckingham π-theorem (Kreith and Bohn, 2001). They established a linear relationship between the canopy resistance r_c and the climatic resistance r^* (Monteith, 1965):

$$r_c/r_a=a\,r^*/r_a+b \quad (13)$$

where a and b are empirical calibration coefficients which vary with crop type but not with site (Rana et al., 1998). Parameter values for a few crops were provided by Katerji and Rana (2014). r^* (s m^{-1}) is represented by the following equation:

$$r^*=\frac{\Delta+\gamma}{\Delta\gamma}\frac{\rho C_p D}{R_n-G} \quad (14)$$

where ρ is the air density (kg m^{-3}), C_p the specific heat of moist air (J kg^{-1} C^{-1}) and D is the vapor pressure deficit (VPD) (kPa).

However, this model still does not take into account the impact of the air CO_2 concentration value on the resistance r_c. After incorportating their model into the FAO-PM equation (PM-KP), Katerji et al. (2017) used a CO_2 correction factor (Olioso et al., 2010) with the PM-KP equation to compare it to the standard Penman-Monteith method (FAO-PM) with a fixed r_c value. PM-KP yielded better performances in forecasting the ETo directly measured by weighing lysimeters during the summer season for the measured period (1986–2006) in Apulia region in southern Italy (Katerji et al., 2017). The results demonstrated that the FAO-PM formula underestimated the measured ETo values by 20 %, whereas the underestimation is only 3 % for the PM-KP formula.

This semi-empirical KP approach has been widely used in the subsequent literature (Peterschmitt and Perrier, 1991; Alves and Pereira, 2000; Lecina et al., 2003; Steduto et al., 2003; Pauwels and Samson, 2006; Liu et al., 2012b; Margonis et al., 2017). However, one of its main limitations is the need for a specific calibration, even if it can be unnecessary under certain circumstances (Rana et al., 1998, 2001; Katerji and Rana, 2008). Furthermore, Gharsallah et al. (2013) insisted that the model's performance would probably be improved calibrating the a and b parameters for the main phenological phases of crops, making the use of this model even more complicated. A second limitation is the fact that it depends on the temporary value of the Bowen ratio β, which is not readily available (Perez et al., 2006). Besides, the KP model seems to fail under irrigated conditions in semiarid to arid regions (Allen et al., 2006).

MODIFIED MAKKINK EQUATION

Makkink model (Makkink, 1957) is a simple empirical method for ETo estimation that uses only temperature and radiation parameters:

$$ET_o=\alpha\,\frac{S}{\lambda\,(S+\gamma)}\,K\downarrow \quad (15)$$

where $K\downarrow$ is the incoming short-wave (global) radiation (W m^{-2}), λ is the latent heat of vaporization of water (J kg^{-1}), S is the temperature-dependent gradient of the saturated vapour pressure curve (Pa K^{-1}) and α is an empirical coefficient (= 0.65).

This formula does not take into consideration the effects of CO_2. To fix that, Kruijt et al. (2008) multiplied eq. (15) with a correction factor c:

$$c= S_g\times S_T\times F_T\times\Delta_{CO2} \quad (16)$$

$$S_g=(dg/g)/dCO_2 \quad (17)$$

$$S_T=(dT/T)/(dg/g) \quad (18)$$

where g is the stomatal conductance (mol m^{-2} s^{-1}), S_g is the sensitivity of g to CO_2 (ppm^{-1}), S_T is the relative sensitivity of transpiration T to g (kg m^{-2} s^{-1}), F_T is the transpiration share of evapotranspiration and Δ_{CO2} is the change in atmospheric CO_2 concentration (ppm).

After parametrizing S_g, S_T and F_T based on the literature, Kruijt et al. (2008) provided correction factors applied to a projected additional increase of atmospheric CO_2 concentrations in 2050 and 2100 by 150 and 385 ppm respectively for various vegetation categories. Results of their study suggest that direct effects of CO_2 reducing evapotranspiration can be expected to be moderate, up to 5% in the coming 50 years and up to 15% by 2100. Applying their methodology in Central and

Eastern Europe resulted in a decrease in reference evapotranspiration rates compared with runs that did not consider increases in CO_2 levels (Eitzinger et al., 2013). Similarly, Huntington et al. (2016) concluded that crop evapotranspiration is projected to increase in all basins of Western United States, especially areas where perennial crops are grown, and with smaller increases in areas where annual crops are grown.

Based on the extensive number of manuscripts on the topic reviewed by the authors, there is an abundance of models with a modified canopy resistance r_c (e.g. Shuttleworth and Wallace, 1985; Massman, 1992; Stannard, 1993; Todorovic, 1999; Irmak and Mutiibwa, 2010). However, very few of them took in consideration the change in atmospheric CO_2, hence the small number of models discussed in this study. This is essentially because when the time span of the research is short, the change in atmospheric CO_2 concentration is very small and is generally ignored (Li et al., 2014; Zhang et al., 2008). Furthermore, some of these models were not even incorporated into the FAO-PM equation to estimate ET responses to increased CO_2 concentration (e.g. Ball et al., 1987; Wang and Wen, 2010). The main issue with the previously reviewed models is that the relationship between stomatal conductance and CO_2 concentration is assumed to be a simple linear one, which is an assumption only valid within the limited range of 330–660 ppm (Li et al., 2019). In fact, those models rarely went beyond that range where data are better fitted with a nonlinear curve. This observation is consistent with the findings of Health and Russell (1954), Morison and Gifford (1983) and Wang and Wen (2010). Thus, it is crucial and indispensable to validate the accuracy and reliability of these models when applying them into the FAO-PM equation especially when the CO_2 concentration is higher than 660 ppm, and to choose the appropriate one to improve the estimation of ET under elevated CO_2 concentration.

Although some studies applied modified simple empirical equations, such as Makkink (Kruijt et al., 2008) and Priestley-Taylor (Rosenzweig and Iglesias, 1998; Hatch et al., 1999; Strzepek et al., 1999) to account for the vegetation responses to an elevated atmospheric CO_2, the FAO-PM method has been always considered to be the most reliable one for various climatic conditions due to its physically based characteristic with incorporating both physiological and aerodynamic parameters (Xu et al., 2006). However, its use of a fixed canopy resistance of 70 s m^{-1} is perceived as weakness, as surface resistance may change with climate and weather parameters, variation in day length, or differences between daytime and nighttime wind (Pereira et al., 1999). In fact, this fixed r_c hypothesis has not been verified in experimental trials carried out on irrigated grass surfaces which underlined significant variations in the canopy resistance r_c on daily and seasonal scales (Rana et al., 1994; Steduto et al., 2003; Katerji and Rana, 2006; Lecina et al., 2003; Perez et al., 2006). The same criticism applies to the models discussed above since they are replacing the constant daily values of the grass r_c with different but always constant values, or using a simple correction factor with the FAO-PM formula, which could be because of the complexity of the canopy resistance modelling (Katerji and Rana, 2006).

CONCLUSION

This paper provides an overview of surface resistance models found in literature that included the effect of CO_2 on crop evapotranspiration. The paper reports a brief explanation of the main theories and assumptions involved in the models' development and underlines their main characteristics. Using these models would help improving the accuracy of ET estimations. Yet, modeling canopy resistance is a difficult task as its value depends on vegetation type, climate, plant architecture and, in water scarcity conditions, on plant and/or soil water status (Shuttleworth and Gurney, 1990). This complexity caused the dissimilarity in results when using some of the aforementioned models in this review, which is also due to the conflicting effect that increase in CO_2 concentration has with increase in temperature. Hence, there is still a need to enhance the robustness of the resistance modeling procedure in order to be applied to different crops under different climatic conditions and under diverse future climate change scenarios. Actually, the great bulk of studies carried out on canopy resistance modelling compared the performance of these models with that of the FAO-PM approach or with different models for estimating ETo, and very few researchers have actually attempted to estimate future changes in ETo based on projected climate change scenarios and estimates of increased CO_2 concentrations. Furthermore, many models were not even tested with the FAO-PM equation, justifying Yang et al. (2019) statement that many present climate models do not account for vegetation responses to an elevated atmospheric CO_2, thus seriously questioning the claim of 'warming leads to drying' in earlier studies.

We note in conclusion that there is a growing need for improved surface resistance models, that may simulate better the changes in stomata physiological responses, thus enhancing the accuracy, reliability and applicability of ET estimates.

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