

Driving crop growth models: radiation- versus transpiration-use efficiency

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Abstract

Simple models of potential biomass accumulation based on radiation- or transpiration-use efficiency were compared in four locations with distinctive climates. These simple models, which have been integrated into many crop growth models that are widely used today, were found to require local calibration, with parameters obtained in one region not readily transferable to another with different climatic conditions. A proposed transpiration-use efficiency model seems to provide adequate estimations across environments when calibrated only in one location. Research will be needed to experimentally evaluate this concept and better formulate the response of transpiration-use efficiency, transpiration rates, and canopy conductance to changes in air humidity, atmospheric CO₂ concentration, and plant water availability.

Media summary

An approach requiring minimum calibration to estimate potential biomass production across diverse climates worldwide is presented and evaluated.

Key words

Simulation models, potential dry matter accumulation, radiation and water use by crops

Introduction

Carbon acquisition is the key factor driving the accumulation of biomass by crops. The first attempts to model crop biomass gain were based on the calculation of canopy net photosynthesis and subtraction of carbon required for maintenance and growth respiration. This approach, although conceptually sound, is hard to parameterize and has not rendered better predictability than simpler methods (Spitters 1990). Ideally, models of crop biomass gain should contain few parameters, which can be easily determined experimentally, and that are transferable across diverse environments. These criteria have been found important by a team of experts assembled by the United Nations Food and Agriculture Organization (FAO) to update the FAO Paper No. 33 "Yield Response to Water" (Doorenbos and Kasam 1979), including dynamic models to estimate crop biomass and yield in response to water availability worldwide (e.g. Steduto 2003).

Simple models are normally based on radiation-use efficiency or transpiration-use efficiency. Both approaches have limitations as discussed below. This paper suggests a new approach to drive biomass accumulation in crop simulation models, which appears to be more transferable across environments than currently used models.

Radiation-use efficiency

Warren Wilson (1967) introduced the following relationship between the rate of biomass production per unit ground area (B in $\text{g m}^{-2} \text{day}^{-1}$) and the amount of intercepted solar irradiance:

(Eq. 1)
$$B = e f_i S_i$$

where S_i ($\text{MJ m}^{-2} \text{day}^{-1}$) is solar irradiance, f_i is the irradiance fraction intercepted by the crop canopy, and e (g MJ^{-1}) is biomass production per unit of solar irradiance intercepted. Monteith (1977) provided a

theoretical basis for this relationship and reported an average e value of 1.4 g MJ^{-1} for four C_3 crops growing under non-limiting conditions in a temperate environment.

Values of e are simple to determine experimentally, and they are readily available for a number of crops (e.g. Sinclair and Muchow 1999). These values are conservative for unstressed crops and temperate climates with low atmospheric vapor pressure deficit (D_a), conditions under which e attains maximum values. Values of e decrease for stressed crops, thus requiring adjustments for water stress effects and other stress factors. However, a significant shortcoming of e as driver of crop growth models is that the maximum value of e cannot be transferred across environments with important atmospheric humidity differences without proper adjustments (e.g., Stöckle and Kiniry 1990; Manrique et al. 1991; Kemanian 2003).

Transpiration-use efficiency

Transpiration-use efficiency (w) is the ratio of biomass produced per unit of water transpired (T in $\text{kg m}^{-2} \text{ day}^{-1}$) by a crop. Bierhuizen and Slatyer (1965) proposed that whole canopy transpiration-use efficiency could be represented by:

(Eq. 2)

$$w = B / T = k_T / D_c$$

where k_T (Pa) is a constant for a given crop, and D_c (kPa) is the canopy-to-air vapor pressure difference. Substituting D_a for D_c and solving for biomass, the following expression is obtained:

(Eq. 3)

$$B = w T = k_T T / D_a$$

Tanner and Sinclair (1983) derived an explicit formulation for k_T . Although Eq. 3 has been shown to be a reasonable predictor of biomass accumulation for unstressed and water stressed conditions, the model becomes unreliable at low D_a values, and apparently also at large values of D_a , casting doubts about the transferability of w as defined in Eq. 2.

Dual method

Using a dual approach that combines radiation- and transpiration-use efficiency seems to overcome some of the limitations of each individual model. In this approach, biomass accumulation is modeled as the minimum from Eq. 1 and 3 (Stöckle et al. 1994; Annandale et al. 2000). The value of e is set at the maximum value for low D_a environments to define a ceiling for biomass accumulation.

Expanded transpiration-use efficiency

Tanner and Sinclair (1983) used photosynthesis and transpiration principles along with simplifying assumptions to obtain Eq. 3. Using the original equations of these authors without simplifications, allows definition of an expanded transpiration-use efficiency that might prove to be more transferable across environments (Kemanian 2003). In this approach, w is calculated hourly (Eqs. 1 and 3 are calculated daily) and separately for sunlit and shaded fractions of the canopy. Transpiration for sunlit and shaded canopy fractions is partitioned based on solar irradiance interception by each fraction as a first approximation. Canopy temperature is approximated as a function of D_a by borrowing an approach used to schedule irrigations (and determine crop water stress) using infrared thermometry (Idso 1982). The expanded w is then defined as:

(Eq. 4) 

(Eq. 5)



where k_c (g kg^{-1}) is a constant for a given crop, a [$\text{kg (glucose) kg}^{-1} (\text{CO}_2)$] is conversion of CO_2 to glucose, b [$\text{kg (biomass) kg}^{-1} (\text{glucose})$] is conversion of glucose to biomass, ϵ is water to air molecular weight ratio [$\text{kg (water) kg}^{-1} (\text{air})$], $c = 1 - C_i / C_a$, C_i and C_a (kg m^{-3}) are internal (leaf) and atmospheric CO_2 concentration, ρ is air density (kg m^{-3}), P (kPa) is atmospheric pressure, and D_c (kPa) is canopy vapor pressure deficit at either shaded or sunlit canopy temperature. The coefficient 1000 converts kg to g, and 1.5 is the approximate ratio of CO_2 to vapor transfer resistances (stomatal and boundary layer) between leaves and surrounding air. The value of c , which is normally assumed constant (around 0.3 for C_3 crops, and 0.7 for C_4 crops), has been shown to be a function of leaf vapor pressure deficit (Morison and Gifford 1983; Commstock and Ehleringer 1993), scaled here to the canopy level using D_c . The implication is that k_T in Eq. 2 is variable, not a constant.

Comparing biomass accumulation models

An experiment was conducted at Pullman, WA in 2000 to determine the parameters needed for Eq. 1 (e), 3 (K_T), and 4 (K_C). Barley was planted at the normal planting time in the region, and biomass gain, daily solar irradiance interception, and daily transpiration were determined for the period DOY 161 to 204, with LAI fluctuating from 1.3 to a peak of 6.0 (DOY 190), and ending at 5.4. A similar experiment was conducted for late-planted barley. Kemanian (2003) gives details on experimental procedures. Using data from this experiment, the following calibrated values for the given parameters were obtained ($r^2 > 0.98$ in all cases): $e = 1.1 \text{ g MJ}^{-1}$, $K_T = 6.2 \text{ Pa}$, and $K_C = 480 \text{ g kg}^{-1}$. Using these parameters, Eqs. 1, 3, and 4 were implemented in the crop growth simulation model CropSyst (Stöckle et al. 1994). In addition, an e value of 1.6 g MJ^{-1} was also used for the model based on radiation-use efficiency and the dual model, a maximum value for unstressed barley and similar crops (see review by Kemanian, 2003).

The different carbon acquisition models were compared through simulation of potential biomass accumulation in four distinctive climatic environments (Table 1). Other crop parameters required by CropSyst were determined using data from the same experiment. Thermal time requirements for phenological stages were adjusted for other locations to ensure a good representation of seasonal solar radiation capture by the crop canopy. An early planting in Paysandú (Uruguay) is the most humid location, while Pullman (late planting) provided the most arid environment. The other two locations are somewhat similar, but with distinctive radiation patterns. It is important to note important differences between pre- and post-anthesis conditions at all locations.

Table 1. Typical weather characteristics for four locations, separated for barley pre-anthesis (Pre-A) and post-anthesis (Post-A) periods.

Location	No. of Years	Daytime D_a (kPa)		Cumulative Solar Radiation (MJ m^{-2})		Mean Temperature (C)	
		Pre-A	Post-A	Pre-A	Post-A	Pre-A	Post-A
Pullman, WA (normal planting)	3	0.91	1.86	976	1007	13.1	17.9
Pullman, WA (late planting)	3	1.40	2.40	1253	917	16.1	18
Tel Hadya, Syria	11	0.67	1.79	1717	813	9.7	19.3

Paysand?, Uruguay	10	0.59	0.86	917	700	12.5	16.2
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Simulated potential biomass values were compared with typical maximum biomass accumulation (no water and/or nitrogen stress) in the different environments (Table 2). The results obtained indicate that both the model based on radiation-use efficiency or on transpiration-use efficiency with constant K_T had problems when applied to other environments using parameters calibrated for Pullman (normal planting), leading to cases of significant over or underestimation of typical maximum biomass accumulation. The dual method seems to improve the estimation of potential biomass, yet it resulted in gross underestimation for Pullman, late planting. The model using an expanded transpiration-use efficiency formulation appears promising, providing reasonable estimates in all environments, somewhat higher than typical observed values as expected for potential biomass.

Conclusions

Traditional simple models to estimate biomass accumulation based on radiation-use efficiency or transpiration use-efficiency require local calibration, with parameters obtained in one region not readily transferable to another with different environmental conditions. A dual method that combines both approaches contributes some improvement, although it leads to significant underestimation in high D_a environments. A proposed expanded transpiration-use efficiency model seems to provide adequate estimations across environments with calibration needed in only one location. This is an advantage for model applications such as that envisioned for the revised version of FAO Paper No. 33. Further research will be needed to experimentally evaluate this concept and better formulate the response of transpiration-use efficiency, transpiration rates, and canopy conductance to changes in air humidity, atmospheric CO₂ concentration, and plant water availability.

Table 2. Simulated potential barley biomass and typical maximum biomass (Mg ha⁻¹) at four distinctive locations. Simulations included four models to estimate biomass gain (RUE = Radiation-use efficiency, TUE = Transpiration-use efficiency).

	Pullman, normal	Pullman, late	Tel Hadya	Paysand?
Typical maximum biomass	12.5 - 14.0	10.0 - 11.0	10.0 - 12.0	12.0 - 14.0
RUE (Eq. 1, $e = 1.6 \text{ g MJ}^{-1}$)	21.2 ? 2.2	18.9 ? 2.0	18.3 ? 2.1	15.9 ? 2.2
RUE (Eq. 1, $e = 1.1 \text{ g MJ}^{-1}$)	13.6 ? 1.6	11.9 ? 1.5	11.2 ? 1.6	10.2 ? 1.5
TUE (Eq. 3, $K_T = 6.2 \text{ Pa}$)	12.5 ? 1.7	6.4 ? 0.5	19.8 ? 2.8	24.2 ? 2.5
Dual ($e = 1.6 \text{ g MJ}^{-1}$, $K_T = 6.2 \text{ Pa}$)	11.3 ? 1.5	6.3 ? 0.5	12.9 ? 1.0	14.4 ? 1.8
Expanded TUE ($k_c = 480 \text{ g kg}^{-1}$)	13.7 ? 1.1	11.4 ? 0.9	13.1 ? 1.5	15.6 ? 1.5

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