1 Technical Article

2 Title: Six crop models differ in their simulation of water uptake.

3 G.G.T. Camargo^{1*} and A.R. Kemanian²

4 ¹Department of Agricultural and Biological Engineering, The Pennsylvania State University,
5 Agricultural Engineering Building, University Park, PA, 16802, USA (ggc107@psu.edu) and

6 ²Department of Plant Science, The Pennsylvania State University, Agricultural Sciences and
7 Industries Building, University Park, PA, 16802, USA (kxa15@psu.edu).

8 * Corresponding author

9 **ABSTRACT**

10 Root water uptake is an essential component of crop models since it affects plant growth and,
11 through its effect on the soil water balance, multiple soil and nutrient cycling processes. Several
12 methods to simulate water uptake exist; however, the differences among them have not been
13 evaluated. We compared the water uptake methods implemented in six crop models: APSIM,
14 CropSyst, DSSAT, EPIC, SWAP and WOFOST. These methods range from simple empiric
15 approaches (WOFOST) to mechanistic approaches based on the water potential gradient and root
16 distribution in the soil-plant system (CropSyst). We compared the six models' water uptake
17 algorithms in scenarios with different evaporative demand, soil texture, and water distribution
18 with depth. The main difference among methods derived from the degree to which each model
19 enabled the use of water in the subsoil (below ~0.5 m). In a rooted, 1-m deep silt loam soil in
20 which the root density decreased geometrically with depth and which was subjected to an
21 evaporative demand of 5 mm d⁻¹ for 60 days, APSIM, EPIC, DSSAT and SWAP transpired
22 about 83% of the total plant available water while SWAP and CropSyst transpired about 65% of
23 it. When methods were compared with initially dry bottom soil layers, cumulative transpiration
24 became similar for all methods, while the opposite initial condition exacerbated differences. All
25 methods, except CropSyst, increased transpiration as the evaporative demand rose to relatively
26 high rates (10 mm d⁻¹) because they lack a feedback mechanism that reduces transpiration when
27 the demand exceeds the plant's ability to conduct water. CropSyst, DSSAT, EPIC and SWAP
28 developed a "drying front", as usually observed in field conditions, while APSIM and WOFOST
29 showed relatively uniform water depletion with depth in the soil profile. In conclusion, the
30 models differ meaningfully in their simulation of water uptake and careful consideration of these
31 differences is needed to properly use and interpret the outcome of model simulations.

Key words: crop model comparison, water uptake, water stress, root distribution

1. Introduction

Root water uptake affects plant growth and development and, indirectly through its control over soil moisture, multiple soil and landscape processes such as nutrient cycling and transport. Therefore, it is critically important in agroecosystem models to get the water uptake “right”. Simulation models quantitatively encapsulate the putative controls of soil, plant and the atmosphere on water uptake. Nonetheless, no single agreed-upon model to simulate water uptake exists in the academic community, and different approaches are used in comprehensive models as described in several reviews (Cardon and Letey, 1992; Mathur and Rao, 1999; Hopmans and Bristow, 2002; Green et al., 2006; Saseendran et al., 2008; de Willigen et al., 2012). Few studies have systematically evaluated how the differences among models alter the progression of the soil drying front and cumulative water uptake (van den Berg et al., 2002). This lack of comparative studies and the associated lack of understanding of the specific differences among models cast uncertainty on the interpretation of outputs from different models when simulating distinct climate or management scenarios.

There is renewed interest in exploring differences among models, as exemplified by the Agricultural Model Improvement and Intercomparison Project (AgMIP, Rosenzweig et al., 2013). Model intercomparison studies typically compare the output of several crop growth models in relation to experimental data and focus on a limited set of measured variables (Asseng et al., 2013; Bassu et al., 2014). Understanding the differences among simulation models through this approach is challenging because modeling systems are made up of many interconnected modules that affect the overall results. To understand differences in simulation approaches for a

particular process, it seems more effective to extract the relevant algorithms and compare them directly while keeping other system attributes constant.

We have applied this approach to compare the water uptake methods used in six prominent crop models. The models selected for this comparison were: 1) Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003), 2) CropSyst (Stöckle et al., 2003), 3) Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003; Boote et al., 2008), 4) Erosion Productivity Impact Calculator (EPIC) (Williams, 1990; Williams et al., 2014), 5) Soil, Water, Atmosphere Plant (SWAP) model (Feddes et al., 1978; van Dam, 2000) and 6) World Food Studies (WOFOST) model (Supit et al., 1994). These models were selected because they represent a wide range of methods to simulate water uptake, from relatively simple methods based on soil water content and considering roots only as present or absent (WOFOST), to methods based on the gradient of water potential and conductances to water flow in the soil-plant system (CropSyst). To compare the methods, the water uptake algorithms were extracted from the models' code or manuals.

We compared the models across scenarios that differed with respect to fundamental controls on plant water uptake: soil texture (to vary the moisture release curve), evaporative demand, and water distribution in the soil profile. Water distribution scenarios differed with respect to initial plant available water (PAW), initial water distribution through the soil profile, and arrangement of the soil profile in layers of uniform thickness or of geometrically increasing thickness with depth. Soils were dried by plant water uptake without recharge. We used differences in the temporal pattern of water use and in the derived shape of the drying front progression to interpret the differences among water uptake methods.

To facilitate the presentation, the results and discussion sections answer a series of questions: (1) Does soil texture affect the differences in water uptake among methods? (2) Do methods vary in their response to increasing transpiration demand? (3) How do the methods respond to different initial soil moisture and its distribution in the soil profile? (4) Does the soil layering method (uniform or geometrically increasing layer thickness with depth) affect the results within and among methods? In the following section, we present a description of each method and the methodology used to evaluate them.

2. Materials and Methods

2.1. Description of water uptake methods

The methods reviewed in this study use algorithms that operate at the macroscopic scale: water uptake is simply a sink term in the water balance of a soil layer. Representation of this sink term varies among methods and can be classified into two types. In one type, water uptake is a function of the difference in water potentials (ψ , J kg⁻¹) and the conductances (C , kg s m⁻⁴) between adjacent components in the soil-plant system. Assuming a water density (ρ_w) of 1,000 kg m⁻³, the unit J kg⁻¹ is numerically equivalent to kPa. In this method, accurately representing water flow (kg s⁻¹ m⁻²) depends on the appropriate calculation of potential gradients and conductances. The second type represents the system functionally through the water content (θ , m³ m⁻³), the root depth (z_r , m), and root density (ρ_r , m m⁻³) or root fraction (f_r , unitless) of the system. There is no calculation of a potential gradient to drive a flux, but an empiric relationship between θ and the ability of the plant to uptake water, which is modulated by ρ_r to a varying degree in each model. Of the methods used for this study, CropSyst and SWAP belong to the first type and the other methods belong generally to the second type. Both types require empiric

data for model parameterization. Table 1 describes the variables used in all algorithms and Table 2 summarizes the controls that drive each water uptake method. The equations used to compute water uptake for each method follow. As we shall see, these methods produce different emergent properties.

Table 1. Abbreviations used to represent the variables in each model (A: APSIM; C: CropSyst; D: DSSAT; E: EPIC; S: SWAP; and W: WOFOST).

Variable	Model	Explanation	unit
c_2	D	Constant	--
C_p	C	Total plant water conductance	kg s m^{-4}
ET_o	All models	Daily evapotranspiration demand	mm d^{-1}
f_i	All models	Radiation interception fraction	--
f_r	C, S	Root fraction	--
f_{it}	--	Fraction of thermal time progression	--
i	All models	Day counter	d
j	All models	Soil layer	--
kl	A	Soil-root water availability parameter	--
$kl\text{-}std$	A	Standard soil-root water availability parameter	--
p	W	Soil water depletion factor	--
R_{Li}	--	Rate of change of fractional light interception	--
R_{rd}	--	Rate of change of fractional root depth	--
s_1, s_2	E	Water stress logistic curve parameters	--
T_a	All models	Actual transpiration (simulated, but limited by the soil water content or water potential)	mm d^{-1}
T_p	All models	Potential transpiration for a given day	mm d^{-1}
T_h	S	High transpiration demand	mm d^{-1}
T_l	S	Low transpiration demand	mm d^{-1}
T_x	C, D	Maximum water uptake for a given crop	mm d^{-1}
U_{rl}	D	Water uptake per unit of root length	$\text{m}^3 \text{m}^{-1} \text{d}^{-1}$
U_{rlx}	D	Maximum water uptake per unit root length	$\text{cm}^3 \text{cm}^{-1}$
u_k	E	Previous layer water uptake sum	mm
WA	A, E	Water available	mm
WT	E	Soil limitation of water uptake of each layer	--
WS	A	Water supply	mm d^{-1}
Z	All models	Cumulative soil depth	m
z_r	All models	Root zone depth	m
Γ	E	Exponent of parameter of soil limitation to water uptake	--
Δz	A, E	Soil layer thickness	m

ζ_e, ζ_s	E, S	Stress factor	--
η	E	Compensation factor	--
θ	A, D, E, W	Water content	$\text{m}^3 \text{m}^{-3}$
θ_t	W	Threshold or critical water content	$\text{m}^3 \text{m}^{-3}$
θ_{fc}	E, W	Water content at field capacity	$\text{m}^3 \text{m}^{-3}$
θ_{pmp}	A, D, E, W	Water content at permanent wilting point	$\text{m}^3 \text{m}^{-3}$
Λ	E	Water uptake distribution parameter	--
ρ_w	A, C, D, E, S	Water density	kg m^{-3}
ρ_r	D	Root density per layer	m m^{-3}
$\rho_{r\text{-std}}$	D	Standard root density	m m^{-3}
ψ_L	C	Leaf water potential	J kg^{-1}
ψ_{Lpwp}	C	Leaf water potential at permanent wilting point	J kg^{-1}
ψ_{Lsc}	C	Leaf water potential at the onset of stomatal closure	J kg^{-1}
ψ_s	C, S	Soil water potential	J kg^{-1}
ψ_{sfc}	C, S	Soil water potential at field capacity	J kg^{-1}
ψ_{sht}	S	Soil water potential for stress in high transpiration demand	J kg^{-1}
ψ_{slt}	S	Soil water potential for stress in low transpiration demand	J kg^{-1}
ψ_{spwp}	S	Soil water potential at permanent wilting point	J kg^{-1}
ψ_{ssat}	S	Soil water potential at saturation	J kg^{-1}
ψ_{ss}	S	Soil water potential for stress	J kg^{-1}
Ω	E	Soil moisture-dependent limitation to water uptake	--

Table 2 Root, soil and water stress controls driving each water uptake method.

Model	Plant properties	Soil properties	Combined plant-soil properties	Soil water status
APSIM	f_i	$\theta_{pwp}, \theta_{fc}$	Kl	θ
CropSyst	$f_h, \psi_L, \psi_{Lsc}, \psi_{Lpwp}, C_p, f_r, T_x$	ψ_{spwp}, ψ_{sfc}	--	ψ_s
DSSAT	f_h, ρ_r, U_{rlx}	θ_{pwp}	--	θ
EPIC	f_i	$\theta_{pwp}, \theta_{fc}$	s_1, s_2, η, Λ	θ
SWAP	f_h, f_r	$\psi_{spwp}, \psi_{sfc}, \psi_{ssat}$	ζ_s	ψ_s
WOFOST	f_i	$\theta_{pwp}, \theta_{fc}$	θ_t	θ

2.2. Description of water uptake methods

APSIM

In APSIM, water uptake (T_a , mm d^{-1}) is determined from potential transpiration demand (T_p , mm d^{-1}), soil water available (WA , mm d^{-1}), and water supply (WS , mm d^{-1}) for each i^{th} day and soil layer j^{th} as:

$$T_{p_i} = f_i ET_{o_i} \quad (1)$$

$$WA_{i,j} = (\theta_{i,j} - \theta_{pwp,j}) \Delta z_j \rho_w \quad (2)$$

$$WS_{i,j} = WA_{i,j} kl_j \quad (3)$$

$$T_{a_{i,j}} = \begin{cases} 0, & T_{p_i} = 0 \\ T_{p_i} \frac{WS_{i,j}}{\sum_{j=1}^n WS_{i,j}}, & T_{p_i} < \sum_{j=1}^n WS_{i,j} \\ WS_{i,j}, & T_{p_i} > \sum_{j=1}^n WS_{i,j} \end{cases} \quad (4)$$

113

114

$$T_{a_i} = \sum_{j=1}^{j=n} T_{a_{i,j}} \quad (5)$$

115

116 where f_i is the daily intercepted solar radiation fraction, ET_o is the daily reference
 117 evapotranspiration (mm d^{-1}), θ_{pwp} is the water content at permanent wilting point ($\text{m}^3 \text{m}^{-3}$), Δz is
 118 the soil layer thickness (m), and kl is the rate of water extraction, an empiric soil-root factor for
 119 the fraction of available water that can be supplied to the plant from each rooted soil layer.
 120 Conceptually, once a soil layer is colonized, it will supply water at a decaying rate. This means
 121 that kl represents a maximum supply determined by ρ_r and the resistance to water flow
 122 (Passioura, 1983; Monteith, 1986), and the change in soil water capacitance ($d\theta/d\psi$) as θ
 123 decreases. The challenge is to determine the right kl progression with depth for a given crop and

soil, and to represent variations in k_l due to dynamic stresses. To the best of our knowledge, k_l in APSIM is not affected by abiotic or biotic stresses.

CropSyst

The CropSyst water uptake method is a simplification of the water uptake algorithm described by Campbell (1985). Water flux in the soil-plant system depends on the difference in water potential between the soil (ψ_s , J kg⁻¹) and the leaf (ψ_L , J kg⁻¹), and a total soil-root-shoot conductance which is dominated by the plant (C_p , kg s m⁻⁴). The plant conductance is calculated by inverting the transpiration equation using a maximum expected transpiration (T_x , mm d⁻¹), the soil water potential at field capacity (ψ_{sf_c} , J kg⁻¹) and the leaf water potential at the onset of stomatal closure (ψ_{Lsc} , J kg⁻¹):

$$C_p = \frac{T_x}{\psi_{sf_c} - \psi_{Lsc}} \quad (6)$$

To compute transpiration, both ψ_s and ψ_L need to be computed. The average soil water potential ($\overline{\psi_s}$, J kg⁻¹) is calculated based on a representative root length fraction for each soil layer ($f_{r,j}$):

$$\overline{\psi_s} = \sum_{j=1}^n f_{r,j} \psi_{s,i,j} \quad (7)$$

The root fraction can be conceived as a representative root “activity” of each layer. In practice it can be adjusted dynamically depending on the actual ρ_r and ψ_s . Parameterization with CropSyst shows that an approximately linear decrease in f_r works best in soils with no limitations to root exploration (Jara and Stöckle, 1999), even if the actual f_r is strongly exponential with most of the roots in the soil surface. This reflects plant control of root conductance, likely through aquaporins (Tyerman et al., 1999; Moshelion et al., 2014) and root hair growth (Mackay and

Barber, 1985). For simplicity, it has been assumed in this study that f_r is that calculated based on ρ_r and Δz (i.e. the root fraction).

The ψ_L is calculated using T , C_p and $\bar{\psi}_s$. If ψ_L is lower than ψ_{Lsc} , ψ_L is recalculated (Eq. 8) to represent stomata closure and the corresponding reduction in T (Eq. 9). If ψ_L falls below that of permanent wilting point (ψ_{Lpwp}), then $T_a = 0$:

$$\psi_{Li} = \max \left\{ \min \left(\bar{\psi}_{Si} - \frac{T_i}{C_{plt}}, \frac{C_p \bar{\psi}_{Si} (\psi_{Lsc} - \psi_{Lpwp}) + \psi_{Lpwp} T_i}{C_{plt} (\psi_{Lsc} - \psi_{Lpwp}) + T_i} \right), \psi_{Lpwp} \right\} \quad (8)$$

Finally, T_a is calculated using ψ_s and ψ_L , C_p and T_p :

$$T_{ai} = \begin{cases} T_{pi}, & \psi_{Li} > \psi_{Lsc} \\ T_{pi} \frac{\psi_{Li} - \psi_{Lpwp}}{\psi_{Lsc} - \psi_{Lpwp}}, & \psi_{Li} < \psi_{Lsc} \\ 0, & \psi_{Li} \leq \psi_{Lpwp} \end{cases} \quad (9)$$

$$T_{ai,j} = C_p (\psi_{Si,j} - \psi_{Li}) \frac{T_{ai}}{T_{pi}} \quad (10)$$

Choudhury and Idso (1985) presented a non-linear response of stomatal conductance to ψ_L , but a linearized version as used in CropSyst (Jara and Stöckle, 1999) works as well and makes computations simpler. This set of equations has an implicit feedback mechanism that reduces T_a if the demand is higher than T_x even in relatively moist soils. Because it is assumed that C_p remains constant, a high demand causes ψ_L to fall below ψ_{Lsc} , reducing T_a below T_p (Eqs. 8 and 9). For this research $T_x = 10 \text{ mm d}^{-1}$, $\psi_{Lsc} = -1,100 \text{ J kg}^{-1}$ and $\psi_{Lpwp} = -2,000 \text{ J kg}^{-1}$. These parameters need to be measured or calculated based on observations. A $T_x = 10 \text{ mm d}^{-1}$ is a reasonable upper bound for the atmospheric demand in temperate to semi-arid environments. The $\psi_{Lpwp} = -2,000 \text{ J kg}^{-1}$ is the average value for loss of turgor of transpiring leaves found by Brodribb et al. (2003), and is close to the average turgor loss ψ_L found by Bennett et al. (1987) in

field grown maize (*Zea mays* L.) and soybean (*Glicine max* L.) (-1,490 and -2,260 J kg⁻¹, respectively), and is also close to the minimum ψ_L that we observe in wilting annual crops (e.g. -2,300 J kg⁻¹ for wheat, *Triticum aestivum* L, Kemanian personal communication). The value for ψ_{Lsc} has to be higher than ψ_{Lpwp} ; it varies among species and growing conditions. For example, sensitive plants like potatoes have a relatively high threshold (-400 J kg⁻¹, Campbell et al. (1974)) while isohydric plants like maize and anisohydric plants like sunflower can have fully open stomata at $\psi_L < -1,000$ J kg⁻¹ (e.g. Tardieu and Simonneau (1998)).

DSSAT

In DSSAT, root water uptake is calculated in two steps. First, water uptake per unit of root length is computed in each soil layer (U_{rl} , m³ m⁻¹ d⁻¹) as an exponential function that depends on: (i) eight parameters provided in the algorithm and determined empirically (Eq. 11a and 11b), (ii) ρ_r , and (iii) the θ for each soil layer:

$$U_{rl_{i,j}} = \begin{cases} \min\left(\frac{0.0013e^{(\min(c_{2j}(\theta_{i,j}-\theta_{pwp_j}),40))}}{7.01 - \ln(\rho_{r_{i,j}}/10^4)}, U_{rlx}\right), & \theta_{i,j} > \theta_{pwp_j} \\ 0, & \theta_{i,j} \leq \theta_{pwp_j} \end{cases} \quad (11a)$$

$$c_{2j} = \begin{cases} 120 - 250\theta_{pwp_j}, & \theta_{pwp_j} \leq 0.3 \\ 45, & \theta_{pwp_j} > 0.3 \end{cases} \quad (11b)$$

173 with the maximum water uptake per unit of root length $U_{rlx} = 0.03 \text{ cm}^3_{\text{water}} \text{ cm}^{-1}_{\text{root}}$. Second, the
 174 maximum potential water uptake for the profile (U_x , mm d^{-1}) is obtained by multiplying $T_{a,rl}$
 175 times ρ_r for each layer and summing over the soil profile:

$$U_{x_i} = \sum_{j=1}^n U_{rl_{i,j}} \Delta z_j \rho_{r_{i,j}} \quad (12)$$

176 The actual plant water uptake is the minimum of T_p (the demand for the day) and U_x :

$$T_{a_i} = \min(T_{p_i}, U_{x_i}) \quad (13)$$

177 If $T_p < T_{a_x}$ then $T_{a_{i,j}}$ are adjusted by the ratio T_p/T_{a_x} .

178 These equations state that the moister the soil and the higher the ρ_r , the higher the uptake
 179 per unit root length. It can be shown that the U_{rl} decreases when the ratio θ/θ_{pwp} falls below
 180 ≈ 1.4 . For example for a soil with $\theta_{pwp} = 0.1 \text{ m}^3 \text{ m}^{-3}$, the reduction becomes noticeable at $\theta = 0.15$
 181 $\text{m}^3 \text{ m}^{-3}$; if $\theta_{fc} = 0.3 \text{ m}^3 \text{ m}^{-3}$ (a loam soil) this means that stress is triggered by PAW $\approx 25\%$. The
 182 proposed response to ρ_r indicates that the uptake per unit length increases as ρ_r increases, a
 183 curious proposition because as ρ_r increases there is less volume of soil per unit length, and one
 184 would expect a reduction in the uptake per unit length. Regardless, this effect is minor in most
 185 conditions: to reduce U_{rl} by 50%, ρ_r needs to be reduced by a factor of 500. In summary, these
 186 equations essentially reduce the water uptake when θ is in the vicinity of 25% of PAW, with
 187 some adjustments by ρ_r . As seen below, this is the typical threshold of most empiric models.

188 **EPIC**

189 The EPIC water uptake method requires no input of root morphological parameters. It
 190 simply assumes that water is used preferentially from the top layers, and the potential water
 191 supply rate decreases exponentially downward. An allowance is made for the user to determine
 192 how much the lower layers can compensate for the water that is not obtained from drier upper

layers. The formulation uses a water uptake exponential distribution parameter ($\Lambda = 10$), T_p , θ , z , soil layer thickness (Δz , m), the water uptake from previous soil layers (u_k , mm d⁻¹), a compensation factor (η), and a stress factor (ζ_e):

$$T_{a_{i,j}} = \min \left(\frac{T_{p_i}}{1 - e^{-\Lambda}} \left(1 - e^{-\Lambda \frac{z_j}{z_r}} \right) - \eta \sum_{k=1}^{k=j-1} u_k - (1 - \eta) T_{a_{i,j-1}}, (\theta_{i,j} - \theta_{pwp}) \frac{\Delta z_j}{\rho_w} \right) \zeta_{e_{i,j}} \quad (14)$$

$$\zeta_{e_{i,j}} = 1 - \frac{w_{i,j}}{w_{i,j} + e^{s_1 - s_2 w_{i,j}}} \quad (15)$$

$$w_{i,j} = \max(5, 10^{\gamma_{i,j}}) \quad (16)$$

$$\gamma_{i,j} = 3.18 - 1.66 \times \log \left(\frac{\theta_{i,j} - \theta_{pwpj}}{\theta_{fc_i} - \theta_{pwpj}} \right)$$

where s_1 and s_2 are parameters of a logistic curve (9 and 0.005, respectively), and w represents the soil limitation to water uptake of each layer. This limitation by water stress slowly decreases the ability of the soil to fulfill the demand when the soil approaches θ_{pwp} . While the shape is user-defined, earlier versions of EPIC used 25% PAW as a typical threshold. This limitation is unrelated to the evaporative demand. The η used in this study was 0.5 (J.R. Williams, personal communication). Thus, once the top layer cannot supply all the water potentially demanded from that layer, the deficit can progressively be taken from deeper layers. This can almost compensate for the deficit, but never completely, unless $\eta = 1$. In EPIC, abiotic stresses can limit uptake in each soil layer (e.g. temperature or pH); for simplicity we assumed that the soil does not impose any stress other than water stress.

SWAP

210 The SWAP water uptake method is based on T_p , f_r and an empiric stress factor
 211 relationship ζ_s :

$$T_{a_{i,j}} = \zeta_{s_{i,j}} f_{r_{i,j}} T_{p_i} \quad (17)$$

212 The stress factor ζ_s is calculated based on a soil water potential near saturation ($\psi_{ssat} = -10 \text{ J kg}^{-1}$)
 213 and a lower water potential threshold that depends on the transpiration demand. When the
 214 demand is low ($T_l = 1 \text{ mm d}^{-1}$), the threshold (ψ_{ss}) is $\psi_{slt} = -500 \text{ J kg}^{-1}$, and when it is high ($T_h =$
 215 5 mm d^{-1}), the threshold is $\psi_{sht} = -400 \text{ J kg}^{-1}$ (Diamantopoulos et al., 2011). These water
 216 potentials correspond to approximately 21 and 26% of PAW for a silt loam soil, respectively.

217 The stress factor ζ_s is:

$$\zeta_{s_{i,j}} = \begin{cases} \frac{\psi_{s_{i,j}} - \psi_{spwp}}{\psi_{ss_i} - \psi_{spwp}}, & \psi_{spwp} < \psi_{s_{i,j}} < \psi_{ss_i} \\ 1, & \psi_{ss_i} \leq \psi_{s_{i,j}} \leq \psi_{sfc} \\ \frac{\psi_{s_{i,j}} - \psi_{ssat}}{\psi_{sfc} - \psi_{ssat}}, & \psi_{sfc} < \psi_{s_{i,j}} < \psi_{ssat} \\ 0, & \psi_{s_{i,j}} \leq \psi_{spwp} \\ 0, & \psi_{s_{i,j}} \geq \psi_{ssat} \end{cases} \quad (18)$$

218

$$\psi_{ss_i} = \begin{cases} \psi_{slt}, & T_{p_i} \leq T_l \\ \psi_{sht}, & T_{p_i} \geq T_h \\ \psi_{sht} + \frac{T_h - T_{p_i}}{T_h - T_l} (\psi_{slt} - \psi_{sht}), & T_l < T_{p_i} < T_h \end{cases} \quad (19)$$

219

220 where ψ_{spwp} is the soil water potential at permanent wilting point. In this method, the water
 221 supply from each layer depends on f_r and ψ_s , which resembles CropSyst. Unlike the latter, no
 222 plant resistance to water flow is included in the water flow path, but must be implicitly included
 223 in f_r . As explained below, this feature has been considered in later versions of this model (de

Jong van Lier et al. (2008)), but the plant conductance or resistance term has not been explicitly included.

WOFOST

The WOFOST water uptake method, the simplest of all methods, calculates water uptake as a function of the rooting depth and the water available in that rooting depth without regard to the soil water distribution with depth. Water uptake depends linearly on the average θ through the rooting depth and a threshold θ (θ_t , $\text{m}^3 \text{m}^{-3}$):

$$T_{a_i} = \min \left(T_{p_i}, T_{p_i} \frac{\theta_i - \theta_{pwp}}{\theta_{t_i} - \theta_{pwp}} \right) \quad (20)$$

$$\theta_{t_i} = (1 - p_i)(\theta_{fc} - \theta_{pwp}) + \theta_{pwp} \quad (21)$$

where p is the soil water depletion factor calculated as 0.56, 0.43, 0.34 for $T = 5, 7.5, 10 \text{ mm d}^{-1}$ respectively, and drought category 4 for grain crops as explained in (Supit et al., 1994). In this model, the higher the demand, the higher the θ_t at which transpiration is limited by θ .

In summary, the methods described differ in the drivers (ψ or θ) and controls of water uptake and consequently in the number of parameters that they require. APSIM has a number of parameters proportional to the number of soil layers, although if k_l is assumed constant for some layers or assumed to vary in a simple pattern, the number of parameters can be just one or two (Table 3). CropSyst has the lowest number of required input parameters (ψ_{Lsc} , ψ_{Lpwp} , and T_x) but requires an estimate of f_r . DSSAT, EPIC and WOFOST have eight required parameters: DSSAT to calculate c_2 , U_{rl} and U_{rh} ; EPIC to calculate A , ζ and γ , and WOFOST to state the drought category and to calculate p . SWAP requires four parameters (ψ_{slt} , ψ_{shl} , T_l , T_h). Thus, simple

methods such as WOFOST do not necessarily require fewer parameters than more mechanistic methods.

Table 3 Parameters (param.) in the compared water uptake methods. The integer j is the number of soil layers.

Model	Parameters	Equation	No. of parameters
APSIM	$kl \times j$	Eq. 3	j
CropSyst	$\psi_{Lsc}, \psi_{Lpwp}, T_x$	Eq. 5, 8	3
DSSAT	c_2 (4 param.), U_{rl} (3 param.), U_{rlx}	Eq. 10, 11	8
EPIC	$\eta, \Lambda, \zeta(s_1, s_2), \gamma$ (4 param.)	Eq. 14, 15, 16	8
SWAP	$\psi_{slb}, \psi_{shb}, T_b, T_h$	Eq. 18	4
WOFOST	Drought category, p (7 param.)	Eq. 22	8

2.3. Comparison of water uptake methods

We compared the water uptake methods using two complementary approaches, one with a dynamic canopy and root system establishment and one with a static canopy and root system. For the dynamic approach, we created scenarios in which a virtual crop was allowed to develop a canopy starting from zero light interception and, simultaneously, develop a root system. Both the canopy cover (f_i) and the root depth (z_r) and ρ_r progression were affixed and independent of the water uptake method under consideration. To facilitate the comparison, water stress (i.e., when water uptake was less than the transpiration demand) did not affect canopy or root growth. For the static approach, we compared the methods using an established root system and canopy, or in other words, assuming that the comparison starts with a canopy intercepting all of the incoming light and with the root system fully established.

The scenarios consider variations in soil texture (four textures, Table 4), soil layering (layers of uniform or geometrically increasing thickness with depth, Table 5), transpiration

demand (only the static approach), and initial θ . The length of the simulation was 100 and 60 days for the dynamic and static simulation scenarios, respectively. The soil was 1-m deep, divided in 10 layers with uniform texture, and the rooting system had a maximum depth of 1 m. Pedotransfer functions using soil texture were used to calculate bulk density, θ_{fc} , ψ_{fc} , θ_{pwp} , ψ_{pwp} , saturated θ and ψ , and the air entry ψ_s (Table 3) (Campbell, 1985; Saxton and Rawls, 2006). To feed the pedotransfer functions, organic matter was assumed to be 50% of that at saturation as defined by Hassink and Whitmore (1997).

Table 4 Soil texture, water content and plant available water (PAW) for the scenarios evaluated. The PAW is the difference between field capacity (θ_{fc}) and wilting point (θ_{pwp}) water content expressed in mm of water for a 1-m deep soil.

Soil	Clay content	Sand content	θ_{fc}	θ_{pwp}	PAW
	%	%	$\text{m}^3 \text{m}^{-3}$	$\text{m}^3 \text{m}^{-3}$	mm
Silt loam	5	20	0.28	0.05	230
Silty clay	45	10	0.40	0.27	130
Sandy clay	40	53	0.35	0.25	100
Loamy sand	7	81	0.13	0.06	70

For the dynamic approach we assumed a constant daily ET_o of 5 mm d^{-1} with no soil evaporation. The variables f_i , z_r and ρ_r changed continuously. The rate of change of fractional light interception (R_{Li}) and that of root depth (R_{rd}) were calculated for each day using a method analogous to that in Olson et al. (2012):

$$R_{rd} = \frac{15e^{5-15f_{tt}}}{(1 + e^{5-15f_{tt}})^2} \quad (22)$$

$$R_{LI} = \frac{20e^{6-20f_{tt}} - 15e^{15f_{tt}-16}}{(1 + e^{6-20f_{tt}} + e^{15f_{tt}-16})^2} \quad (23)$$

where f_{tt} is the fractional thermal time progression and was assumed to increase by 0.01 per day. The equation for R_{LI} is the derivative of a double exponential that represents a sharp increase in f_i early in the season, stabilizes at a maximum value ($= 1$) and decreases when the cumulative fractional thermal time approaches 1 (senescence). The z_r and f_i were determined each day accumulating their respective rates of change. In addition, it was assumed that $z_r = 0.2$ m at leaf emergence. Fig. 1 shows a graphical representation of f_i and z_r progression.

Figure 1. Root depth and fractional solar radiation interception progression. (*one column*)

In this approach, to dynamically vary ρ_r and k_l as the root front progressed, we used a standard ρ_{r-std} and k_{l-std} that apply to a fully established root system, by assuming that when fully rooted, the top layer of 0.1 m had an average ρ_{r-std} of 50,000 m m⁻³ as reported for maize in Jara and Stöckle (1999), and that ρ_{r-std} decays by a third every 0.1 m (Table 5). For soil layers where the rooting front did not reach the layer lower bound, ρ_r and k_l were adjusted proportionally to

the progression depth in that layer. APSIM's k_l decreased linearly from 0.085 to 0.055 (Meinke et al., 1993; Hammer et al., 2009).

For the static approach, and to compare soil textural and transpiration demand effects, we created six scenarios that combine four soil textures (Table 4) and three T demands (5, 7.5 and 10 mm d⁻¹). The soil was initialized with $\theta = \theta_c$ throughout the soil profile. The transpiration demand was set to values representing average, high, and very high transpiration depending on the scenario of interest. We used 5 mm d⁻¹ as the average because this is the reference ET_o (Allen et al., 1998) for a relatively average day in summer in mid latitudes, i.e. a day with 25 °C maximum and 10 °C minimum temperature, 25 MJ m⁻² solar radiation, 1.25 kPa of vapor pressure, and 2.5 m s⁻¹ wind speed. Higher radiation, drier air, or higher wind speed can increase the evaporative demand. During the simulations the soil was allowed to dry due to plant transpiration assuming no vapor loss at the soil surface and no recharge.

Table 5 Layer thickness distribution, root density and fraction, and APSIM's k_l used in simulations for a soil with constant or geometric variation of layer thickness. The total root length is *ca.* 15 km m⁻².

Soil layer	Layer thickness m	Root density m m ⁻³	Root fraction --	k_l --
<i>Constant</i>				
1	0.1	50,000	0.336	0.085
2	0.1	33,500	0.225	0.081
3	0.1	22,445	0.151	0.077
4	0.1	15,038	0.101	0.073
5	0.1	10,076	0.068	0.069
6	0.1	6,751	0.045	0.066
7	0.1	4,523	0.030	0.062
8	0.1	3,030	0.020	0.058
9	0.1	2,030	0.014	0.054
10	0.1	1,360	0.009	0.050
<i>Geometric</i>				

1	0.009	60,156	0.036	0.087
2	0.013	57,531	0.051	0.086
3	0.020	53,811	0.072	0.086
4	0.030	48,682	0.098	0.085
5	0.045	41,900	0.126	0.083
6	0.067	33,477	0.151	0.081
7	0.101	23,938	0.162	0.078
8	0.151	14,515	0.147	0.073
9	0.226	6,898	0.105	0.066
10	0.339	2,291	0.052	0.055

To analyze the impact of the initial θ in both magnitude and distribution throughout the profile, we compared seven new scenarios: (1) 100% PAW uniform, (2) 50% PAW uniform, (3) 100% PAW in top half and 50% PAW in bottom half, (4) 50% PAW in top half and 100% PAW in bottom half, (5) alternating 100% and 50% PAW, (6) 100 to 10% PAW gradually decreasing from top to bottom, and (7) 10% to 100% PAW gradually increasing from top to bottom of the soil profile. The T demand was 5 mm d^{-1} and the soil of silt loam texture. WOFOST was not evaluated in these scenarios since it does not account for soil layering. The parameters modified in the dynamic and static approach are summarized in Table 6.

Four output variables were used to evaluate differences among water uptake methods: T_a , the ratio of actual to potential transpiration (T_a/T_p), and θ and ψ in the soil profile. These variables are critical inputs to other modules in the corresponding simulation models, including crop growth.

Table 6. Parameters modified in the dynamic or static approaches.

Approach	Dynamic	Static
<i>Parameters varied</i>		
Variable potential transpiration T_p , mm d^{-1}	5	5; 7.5; and 10
Variable soil texture	Silt loam	Silt loam, silty clay, sandy clay, and loamy sand
Initial plant available water (PAW)	100%	100% all profile 50% all profile

		100% top half and 50% bottom half of profile
		50% top half and 100% bottom half of profile 100% and
		50% alternating layers
		from 100% (top) to 10% (bottom) gradually decreasing
		from 10% (top) to 100% (bottom) gradually increasing
Variable soil layering	--	Uniform or Geometric

3. Results

3.1. Dynamic simulation of water uptake

Since the dynamic simulation was initialized with the soil at θ_{fc} , cumulative transpiration increased steadily and without limitation while the canopy was expanding (Fig. 1); by day 40 the roots reached the soil profile bottom. Once water extraction amounted to 60 - 100 mm, the methods differed in the degree to which a drying soil limited water uptake (Fig. 2). Three methods, CropSyst, WOFOST and especially SWAP, reduce transpiration relatively early in comparison with the other methods. APSIM and DSSAT had an intermediate onset of water stress, approximately 10 days or nearly 50 mm after SWAP. EPIC used most of the available water before transpiration was limited. Once a drying soil limited transpiration, the T_a/T_p ratio decayed with a concave shape in all methods except EPIC (Fig. 2).

Figure 2. Cumulative actual transpiration (T_a , mm d⁻¹) and T_a divided by potential transpiration (T_p , mm d⁻¹) for the APSIM, CropSyst, DSSAT, EPIC, SWAP and WOFOST water uptake methods. (*one column*)

Water uptake differed in the dynamic simulation due to substantive variation in the explicit or implicit mechanisms of water uptake embedded in each algorithm, and in some cases due to the parameterization. These differences produce striking divergence in the shape of the water extraction front. The θ (Fig. 3) and ψ (Fig. 4) across the soil profile differed between the water uptake methods with two major groupings. CropSyst, EPIC and SWAP, and to a lesser extent DSSAT, developed a drying front; APSIM and WOFOST had a more uniform water uptake across the profile. This development of a drying front is expected in a method like CropSyst because of the way in which root density affects the root conductance: when the water potential is uniform across the soil profile, more water will be taken from the layer with more root length. Similar considerations apply to SWAP. In a method like EPIC, the drying front

reflects the concept of the functional algorithm that takes up water from top to bottom with an implicit consideration of root geometry. In DSSAT the water use also has the semblance of a drying front (Fig. 4), albeit less marked than that in CropSyst or SWAP. This is because the wetter the soil and the higher the root density, the higher the water uptake from that layer, thus replicating through different means a similar water use pattern to that of CropSyst, SWAP, or EPIC. In Cropsyst and SWAP, the sharpness of the drying front can be manipulated by changing the distribution with depth of f_r . Similarly, in DSSAT it can be modified by changing the root density. In EPIC, it can be manipulated by changing the parameter A (a lower value makes the drying front less prominent).

In the case of APSIM, a drying front can be represented if k is progressively reduced with depth. That is not, however, what emerges from published studies (Meinke et al., 1993; Robertson et al., 1993; Hammer et al., 2009). Nonetheless, a drying front can also be generated by a slower progression of the rooting front caused either by the genotype or by restrictive soil layers.

The WOFOST method, though extremely simple, seems to represent the cumulative water use reasonably well; the pattern of cumulative water use cannot be easily distinguished from other methods (Fig. 2). The distribution of the water use with depth is, however, clearly unrealistic, as illustrated the water potential profile (Fig. 4). The distribution of water affects many processes in the soil, from water infiltration and redistribution through the profile, to heat transfer and nutrient cycling. Therefore, this method can only be applicable, with reservations, to relatively simple water balances.

374

375 **Figure 3.** Soil water content (θ) in the soil profile in three different days for the APSIM,

376 CropSyst, DSSAT, EPIC, SWAP and WOFOST water uptake methods. (*two columns*)

Figure 4. Soil water potential (ψ_s) in three different days for the APSIM, CropSyst, DSSAT, EPIC, SWAP and WOFOST water uptake methods. (*two columns*)

3.2. Static simulations of water uptake

3.2.1. Does soil texture affect the differences in water uptake among methods?

The answer is yes. Clearly, the higher the PAW, the longer the plant canopies can transpire at a rate set by the atmospheric demand. When the soils have low storage, all methods show a sharp decrease in transpiration and are difficult to distinguish from each other (Fig 5, loamy sand soil). In the silt loam soil, the results can be grouped as follows: CropSyst and SWAP exhibited more conservative water use, and DSSAT, EPIC, APSIM and WOFOST exhibited less conservative water use. This is, however, somewhat dependent on the

parameterization: a more linear f_r distribution with depth causes CropSyst and SWAP to approach the other methods (data not shown). At the end of the simulation, the group of less conserving methods used about 83% of the total PAW (191 mm) regardless of T_p . In the other group, CropSyst transpired about 60% and SWAP transpired 70% of total PAW (Fig. 6).

3.2.2. Do methods vary in their response to increasing transpiration demand?

Methods differed sharply in their response to an increased demand. Most methods except CropSyst increased transpiration as the demand increased. In Cropsyst, increasing the transpiration demand causes a low ψ_L , which in turn causes stomatal closure and, therefore, a reduction in transpiration (Campbell, 1985; Jara and Stöckle, 1999). Thus, this algorithm has a built-in feedback system that causes water stress under high transpiration demand, even if the soil is relatively moist. Other methods tend to simply supply more water as the demand increases, for there is no mechanistic feedback to reduce transpiration. In SWAP, the threshold ψ_s that triggers a reduction in transpiration does increase the higher the evaporative demand, thus incorporating an interaction of soil water status and evaporative demand.

In the silt loam and loamy sand soils, the EPIC method had the highest water uptake, using most of the water available in a layer and then moving to the next layer until depleting most of the water in the soil profile. This study did not include the water uptake reduction factors for different soil layers that are implemented in the EPIC model since they cannot be separated from the model (for example, the effect of suboptimal soil temperature). Including these factors would reduce, but never increase, the overall water uptake, perhaps bringing the cumulative water uptake in line with the other methods.

411 The APSIM method was the first method to start reducing T_a in the loamy sand soil even
 412 though it continued transpiring, consuming 93% of PAW. Interestingly, the DSSAT water uptake
 413 method behaved similarly to CropSyst and SWAP in loamy sand, sandy clay, and silty clay soils,
 414 but it became less conservative in the silt loam soil when PAW was larger. This similar behavior
 415 between CropSyst and DSSAT (at least for some soil textural classes) was also observed by Jara
 416 and Stöckle (1999) when they compared daily water uptake methods with measurements of sap
 417 flow and θ for maize. The water uptake in DSSAT is related to θ_{pwp} , but not to the pore space
 418 between θ_{pwp} and θ_{fc} or directly to ψ_s , or to the transpiration demand as in other methods. As a
 419 result, the methods are likely to perform differently across scenarios and will not produce a
 420 consistent ranking of water uptake.

Figure 5. Simulated transpiration (T_a , mm d⁻¹) divided by potential transpiration (T_p , mm d⁻¹) for six water uptake methods and six scenarios with different soil texture and transpiration demand.

(two columns)

Figure 6. Cumulative actual transpiration (T_a , mm) for six water uptake methods and six scenarios with different soil and potential transpiration (T_p , mm d⁻¹). (two columns)

To evaluate water depletion through the soil profile, θ (Fig. 7) and ψ (Fig. 8) were plotted for 15, 30 and 45 days in a silt loam soil with a T demand of 5 mm d⁻¹. CropSyst, DSSAT, EPIC and SWAP generated θ and ψ_s curves that were similar to typical measured soil water depletion profiles (Cabelguenne and Debaeke, 1998; Jara and Stöckle, 1999; Doussan et al., 2006). CropSyst was the only method to allow the soil to go beyond the putative permanent

wilting point in the top layers, resembling observations by Cabelguenne and Debaeke (1998). This feature is hard to detect in simulations that include soil evaporation, for this process can easily drive θ well below θ_{pwp} .

The almost-uniform water depletion across the soil profile in the APSIM method reflects k_l 's linear distribution. Fitting k_l with experimental data would change the shape of θ and ψ in the soil profile, but when using k_l as prescribed in Hammer et al. (2009) the water extraction in this 1-m soil is rather uniform. The WOFOST method shows a uniform θ throughout the profile since it does not account for soil layering, treating the soil as a single large 1-m thick layer

Figure 7. Soil water content (θ) in day 15, 30 and 45 of a simulation in a silt loam soil with 5 mm day⁻¹ transpiration demand using six water uptake methods. (*two columns*)

Figure 8. Soil water potential (ψ) in day 15, 30 and 45 of a simulation in a silt loam soil with 5 mm day⁻¹ transpiration demand using six water uptake methods. (*two columns*)

3.2.3. How do the methods respond to different initial soil moisture and its distribution in the soil profile?

Varying the amount and distribution with depth of available water revealed with more clarity the different mechanisms that are, wittingly or not, embedded in each method. Fixing the transpiration demand to 5 mm d⁻¹, the less conservative methods (APSIM, DSSAT and EPIC) removed more water from lower soil layers than CropSyst and SWAP (Fig. 9 and 10). The water uptake of all methods was similar in scenario 6 where PAW decreases downward from 100% to 10%; however if PAW increases with depth from 10% to 100%, APSIM, DSSAT and EPIC

transpired cumulatively and on average for the three methods 104 mm while CropSyst and SWAP transpired 69 mm. While these behaviors can be manipulated through parameterization, the differences reflect intrinsic differences among methods.

Changing the initial PAW of soil layers from 100% to 50% (from scenario 1 to 2 in Fig. 9) reduced total cumulative T from 144 mm to 83 mm for CropSyst and SWAP (43% reduction), and from 190 mm to 95 mm for APSIM, DSSAT and EPIC (50% reduction). The less conservative methods exactly follow the average reduction in PAW of the soil, with lesser influence of the soil water distribution on water uptake. Similar results occurred when using a sandy clay soil texture. This makes these methods somewhat similar to WOFOST.

Thus, the drier the upper soil layers, the more the methods differed; when the lower layers were dry, the methods rendered similar results (Fig. 10 SC6). This is an important point. For example, during the progression of a dry spell these methods will produce different crop water uptake (as well as growth and nutrient uptake). Observations in the field indicate that dry upper soil layers limit overall water uptake, even when the moist subsoil is colonized with roots (Skinner, 2008). This behavior is closer to that simulated by CropSyst and SWAP. In these models, different species will show a decrease in transpiration as the upper layer dries in proportion to the depth and distribution of roots in the soil profile: the deeper the roots and the more homogenous their distribution with depth, the lesser the effect because of the weighting of the root resistance by ρ_r .

Figure 9. Simulated transpiration (T_a , mm d^{-1}) divided by potential transpiration (T_p , mm d^{-1}) for a silt loam soil with varying initial soil moisture distribution with depth. Soil layers have equal thickness. The initial moisture patterns are based on different plant available water (PAW). Five water uptake methods, APSIM, CropSyst, DSSAT, EPIC and SWAP, were compared in this simulation. (*two columns*)

Figure 10. Cumulative transpiration (T_a , mm) simulated for a silt loam soil with varying initial soil moisture distribution with depth. Soil layers have equal thickness. The initial moisture patterns are based on different plant available water (PAW). Five water uptake methods, APSIM, CropSyst, DSSAT, EPIC, and SWAP were compared in these simulations. (*two columns*)

3.2.4. Does the layering method change the results within and among methods?

Changing the layers from uniform thickness to a geometrically distributed thickness, and properly weighting the root density (or any depth-dependent property), only caused differences in water uptake in DSSAT (only the silt loam soil) and EPIC, with the latter being more sensitive to soil layering. The other methods were remarkably robust, yielding similar results regardless of the layering scheme or soil texture (Fig. 11). This result was difficult to predict in the case of DSSAT and reflects the threshold response to moisture (Eq. 10). Below a given moisture threshold, the uptake per unit root length (U_r) decreases, thus creating “steps” in the simulated T_a/T_p once that moisture threshold is reached. The somewhat discontinuous change in the rate of water use (Fig. 5) reflects sharp transitions between limited and unlimited water use in a layer that, interestingly, are smoothed out and difficult to detect if only considering the cumulative transpiration.

In the case of EPIC, the compensation among layers, while qualitatively logical, shows limitations. This method seeks to make up the water deficit in the top layers from the layers below, but it does not weight the layer thickness. If the top layers are relatively thin, the limitation emerges quickly, and the ability to compensate is limited by a fixed factor (η) that bounds the volume that can be compensated. If η varied with depth, for example, $\eta = 1$ for top layers and $\eta = 0.5$ for the bottom layers, this effect might be ameliorated, but at a cost of increasing the number of parameters and without a clear guidance about what parameterization is reasonable. Thus, when using EPIC, the method must be calibrated and used with a relatively stable soil layering criterion.

Figure 11. Simulated transpiration (T_a , mm d⁻¹) divided by potential transpiration (T_p , mm d⁻¹) for sandy clay and silt loam soil textures with equally and geometrically distributed soil layer thickness. Five water uptake methods, APSIM, CropSyst, DSSAT, EPIC and SWAP, were included in this comparison. Initial plant available water (PAW) was 100%. (*two columns*)

4. Discussion

The methods presented have in common the goal of representing a reduction in water uptake as the soil dries or in some cases when the evaporative demand increases. The methods, however, vary widely in the approach used to accomplish that goal. The more process-based methods (CropSyst and to some extent SWAP) rely on the water potential gradient as the driver for liquid water flow in the soil-plant system. Because the soil capacitance decreases drastically as the soil dries, the water uptake becomes limited by both the supply and by a gradual reduction of the stomatal conductance. As suggested by Campbell and Norman (1998), this occurs because the plant hydraulic conductance is adapted to match the evaporative demand to the soil supply. In these methods, the reduction in water uptake as the soil dries is an emergent and not an imposed

property of the system. Even if the ψ_L were allowed to decrease beyond ψ_{Lpwp} , water uptake will be progressively limited by the reduction in soil water capacitance.

The approach in APSIM is commendable for its simplicity, but requires knowledge of a combined plant-soil property: the k_l constant per layer. This problem is analogous to defining the correct f_r for CropSyst or SWAP: as stated before, this variable, more than representing f_r represents the effective root activity. In addition, it is somewhat surprising that WOFOST's simple method provides cumulative T estimates similar to other methods, despite the direct summation through the soil profile to calculate θ .

In methods such as DSSAT, EPIC, and WOFOST, in which the surrogate “driving force” for liquid water flow is the soil water content θ , the threshold θ that starts limiting water uptake is imposed through equations that translate empiric knowledge. This threshold θ is typically between 25 to 35% PAW (Turner et al., 1985), and there is a theoretical basis to expect such a threshold (e.g. Campbell and Norman, 1998): the soil water capacitance drops sharply when about $\frac{2}{3}$ to $\frac{3}{4}$ of PAW has been used. . No threshold θ is needed in APSIM, CropSyst or SWAP, because the effect is accounted for either through mathematical expediency (APSIM's exponential decay) or by using Ψ instead of θ . That the threshold θ is higher when the transpiration demand is higher is an emergent property in CropSyst, but it can be at least partially represented in other methods by capping transpiration in a simulation (Sinclair et al., 2005).

There is an interaction between the water uptake method and water distribution in the soil profile in determining transpiration. One of the main differences between conservative and less conservative water uptake methods is the use of water from lower layers of the soil profile. These differences are important and may lead to over-estimation of water uptake in less conservative methods, or conversely, an underestimation of water uptake in the more

conservative methods. These risks are highest when the top soil layer is dry and the bottom layer is moist. Eitzinger et al. (2004) compared the DSSAT, SWAP, and WOFOST water uptake methods with experimental data and reported an overall tendency of the methods to over-estimate water uptake in silty loam, sandy loam, and silt clay loam soils, which is consistent with the DSSAT and WOFOST results presented here, but not with the results for SWAP, which may be due to a different parameterization of SWAP.

All water uptake methods but EPIC and DSSAT provided stable simulations when the soil layer thickness was held constant (0.1 m) or varied geometrically with depth. The robust response of APSIM, CropSyst, SWAP and WOFOST is encouraging since soil databases provide information usually on a horizon by horizon basis. This information is translated into model input files in which the soil layers are split based on needs or practical considerations. Most users expect that models are relatively insensitive to this layering, as long as the integrated properties are conserved. With EPIC in particular, it seems clear that users need to calibrate and use the model with a stable soil layering.

To consider mechanisms that compensate for the reduced water uptake from dry layers with increased water uptake from wet layers, de Jong van Lier et al. (2008) modified the SWAP water uptake method. They used Gardner's (1958) matric flux potential as a driving force for the flux and included the resistance to water flow from the bulk soil to the edge of the root. This approach is also suggested in Campbell (1985) using directly $d\psi/dz$ as the driving force; the matrix flux potential is recommended to handle infiltration. However, de Jong van Lier et al. (2008) neglected the plant conductance to water flow, which leads to overestimation of water uptake (Faria et al., 2010). This was addressed by introducing a correction factor of 0.05 that multiplies the flow estimated with their method, which implicitly assumes that the soil has a

conductance about 20 times higher than the root. In doing so, the authors are effectively acknowledging the control of the root conductance over the water flow.

Comparatively, the method described by Campbell (1985) and used in CropSyst makes this assumption the core of the model, as the plant conductance is orders of magnitude lower than that of the soil in most conditions (Campbell, 1985). Jarvis (2011) also modified SWAP to include water redistribution, which produced a more uniform water content across the soil profile. This resulted in drying profiles similar to those generated with APSIM (Fig. 3 and 7), though APSIM does so with fewer parameters. SWAP is therefore a simplified version of Campbell's (1985) method, and is better used assuming that f_r can be adjusted empirically; the inclusion of the root conductance simply leads to Campbell's (1985) method.

CropSyst and SWAP are relatively sensitive to the soil moisture distribution with depth, while the other methods are built so that compensation among layers operates through one of the following: averaging of the soil moisture in the profile (WOFOST), explicit compensation (EPIC), or implicit (emergent) compensation (DSSAT). The APSIM method allows for a conceptually simple calibration if a soil profile is allowed to dry without recharge so as to calculate the progression of the rooting front and the water extraction rate (Meinke et al., 1993). In practice, however, obtaining such parameters can be challenging.

We expect that over time the method to simulate water uptake will converge towards the water potential and conductance to flow framework as proposed by van den Honert (1948), refined by Campbell (1985), and with adaptations used in CropSyst and in other modeling exercises (Tardieu and Simonneau, 1998). This approach requires further work, particularly to account for the variation in C_p (e.g. Sperry et al., 2003). As described here, the response of stomatal conductance to ψ_L lumps what in reality is the response to ψ_L (or associated metabolic

response) and C_p . In other words: the method may simulate total water uptake and water uptake per layer correctly, but may not necessarily simulate ψ_L or C_{pl} accurately. This is relevant only if these quantities need to be known, which depends on the objectives of the modeling exercise. In the methods based on soil water content, the simultaneous change in the soil-plant water potential gradient and the soil water capacitance are not explicitly considered. In these methods, any improvement in simulating water uptake may come from more empiric adjustments that, with skill, may render useful simulations, but will not emerge from the application of the principles governing liquid water flow in the soil-plant system.

Given the differences among methods to simulate water uptake, it is reasonable to expect that differences among models exist in nearly every module in these comprehensive agroecosystem models. Kumudini et al. (2014) already documented major differences among methods to simulate phenology in maize. This calls for caution when interpreting the results of model intercomparisons. While multi-model averaging seems to produce robust estimates of grain yield for wheat (Asseng et al., 2013) and maize (Bassu et al., 2014) at a given location, when projecting new scenarios it is relevant to consider the different mechanisms and trajectories by which each model arrives to a given estimated yield. This is critically important when projecting yield in climate or management scenarios that operate well beyond the calibration domain.

5. Conclusions

The methods to simulate water uptake in the models APSIM, CropSyst, DSSAT, EPIC, SWAP and WOFOST differ. Each method responded differently to variations in soil texture, layering, and moisture distribution with depth. Specifically, these three variables affected the

onset of water stress, the cumulative water uptake, the shape of the drying front under a constant transpiration demand, and the response to high transpiration demand. The temporal pattern of water use in EPIC differed from all other methods, showing a convex instead of a concave progression of the actual to potential transpiration ratio as the soil dried. Both EPIC and DSSAT were sensitive to changes in the thickness of the soil layers with depth.

While CropSyst, EPIC, DSSAT and SWAP developed similar soil drying fronts, both CropSyst and SWAP tended to be more conservative in the use of subsoil water. It is expected that these differences translate to different timings of water stress development in simulated crops, as well as to a number of cascading effects on other components of the simulation controlled by soil moisture (e.g. soil respiration and landscape level hydrology).

It seems that the framework used in CropSyst (Campbell et al., 1974; Campbell, 1985) has the properties required in a simulation model while maintaining simplicity: economy of parameters and a mechanistic basis. Improvements in simulating water uptake will more likely result from refining this framework than from expanding further the empiric approaches used in other models.

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Appendix

Source code used in publication is available at:

<https://github.com/gcamargo1/WaterUptakeModels>