TWO APPROACHES TO THE DESCRIPTION OF DISTRIBUTION KEYS IN CROP SIMULATION MODELS

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A b s t r a c t. Distribution keys are used in crop models for the description of assimilates partitioning between several plant organs. Standard approach is to use table data for discrete points as functions of a physiological age and to interpolate these relations between the given points. A universal function can be proposed for the construction of continuous relations for a majority of the known distribution keys. This possibility is discussed in the paper. Another approach concerning the description of a shoot/ root relation in the model is also presented. The main idea is to take into account N:C interaction in plant for the determination of a fraction of assimilates which must be allocated in roots or remains in leaves. Indeed, this fraction is changed during vegetation as influenced by environmental conditions. The last approach can be called "adaptive distribution key".

K e y w o r d s: dynamic model, plant development, physiological age, dry matter, distribution keys

PHYSIOLOGICAL AGE

Plant development is determined by a genetic code and is modified according to environmental conditions. Air temperature is the leading factor influencing the rate of plant development: the higher the temperature, the higher the rate of development. But it is not the only factor controlling this process. A very high temperature causes deceleration of plant development. Besides, water stress modifies it in a following manner: it decelerates the development from sowing to emergence and from flowering to full ripeness. On the other hand, water stress accelerates development between emergence and flowering. In [3] the following method was proposed for the description of this process. Let T_0 denote temperature threshold (biological zero). The following variable can be determined:

$$\gamma(k) = \left(T_{av}(k) - T_0\right) \, sign\left(T_{av}(k) - T_0\right) \quad (1)$$

where k is the day number of the Julian calendar, $T_{av}(k)$ average air temperature on the day k, $sign(\bullet)$ Kroneker function. For estimating the overheating effect we include a squared term in the increment of the physiological age:

$$\Delta\tau(k) = \gamma(k)\left(1 - \gamma(k)/c_0\right) \quad (2)$$

where c_0 is the empirical coefficient. Finally, the physiological age (or the development stage, DVS) is determined as a sum of these terms multiplied by the water stress function, $Str(\psi(k))$:

$$DVS(k) = \sum_{j=k_0}^{k} \Delta\tau(j) \, Str\left(\psi(j)\right) \quad (3)$$

where $\psi(j)$ is an average soil water potential of a rooting zone, k_0 is sowing day number and the stress function is determined according to Eq. (4):

$$Str(\psi) = \begin{cases} 1 & if \ \psi \geq \psi_0 \\ 1 + \left(S_0 - 1\right)\dfrac{\psi - \psi_0}{\psi_w - \psi_0} & if \ \psi \geq \psi_0 \end{cases}$$

$$(4)$$

where ψ_w is hydraulic water potential at wilting point, ψ_0 and S_0 are empirical constants. The last equation means that the rate of development increases or decreases when ψ is less than ψ_0: it increases when $S_0 > 1$ and decreases in the case of $S_0 < 1$. The accumulated value of $DVS(k)$ is compared with a threshold, $Tr(IPhase)$, depending on the phase number $IPhase$. All the parameters included in the Eqs. (1)-(4), i.e., T_0, c_0, S_0, and ψ_0 depend on the development stage $IPhase$.

The model parameters characterising the rate of maize development cultivated in Krasnodar region (Russia) are presented in the Table 1. In the Table 2 there are parameters concerning alfalfa cultivated in Saratov region (Middle Volga). Figure 1 shows a comparison of the experimental dates of plant development with the simulated ones, which are obtained with the help of AGROTOOL model developed in the Agrophysical Research Institute [6].

DETERMINISTIC DISTRIBUTION KEYS

As it was pointed out, plant development is controlled by the value of physiological age. On the other hand, plant growth is determined by the photosynthesis rate and the so-called distribution keys. More precisely, if ΔW denotes dry matter growth rate of a total crop (difference between photosynthesis and respiration), the partitioning coefficients (distribution keys) are used for the calculation of rates of biomass increase in various plant organs [1,6]. Dry matter is first partitioned between shoots and roots (determination of shoot/root relation):

$$\Delta W_r = c_{rs}\Delta W$$
$$\Delta W_s = \left(1 - c_{rs}\right)\Delta W \qquad (5)$$

where: ΔW - dry matter growth rate of total crop (kg ha^{-1} d^{-1}), ΔW_r - dry matter growth rate in roots (kg ha^{-1} d^{-1}), ΔW_s - dry matter growth rate in shoots (kg ha^{-1} d^{-1}), c_{rs} - distribution key for roots (kg kg^{-1}).

The growth rate of other organs, i.e., leaves, stems and ears (tubers) is the product of dry matter growth in shoots and the fraction allocated to these organs:

$$\Delta W_i = c_i \Delta W_s \qquad (6)$$

where: ΔW_i - dry matter growth rate of organ i (kg ha^{-1} d^{-1}), c_i - distribution key of organ i (kg ha^{-1} d^{-1}), i - leaves (l), stems (s), ears (e) (kg kg^{-1}).

T a b l e 1. Parameters characterising the rate of development for maize

Phase name	T_0	c_0	ψ_0	S_0	DVS	Tr (IPhase)
Emergence	5.0	70.0	-3000	0.5	75.1	0.00
7-8 leaf	7.0	70.0	-3000	2.0	295.3	0.35
Silking	10.0	70.0	-4000	2.0	667.2	-0.95
Flowering	10.0	70.0	-4000	2.0	694.1	1.00
Milk ripening	4.0	70.0	-3000	0.5	980.1	1.42
Wax ripening	2.0	40.0	-7000	0.7	1296.2	1.89
Full ripening	0.0	40.0	-4000	0.7	1365.7	2.00

T a b l e 2. Parameters characterising the rate of development for alfalfa

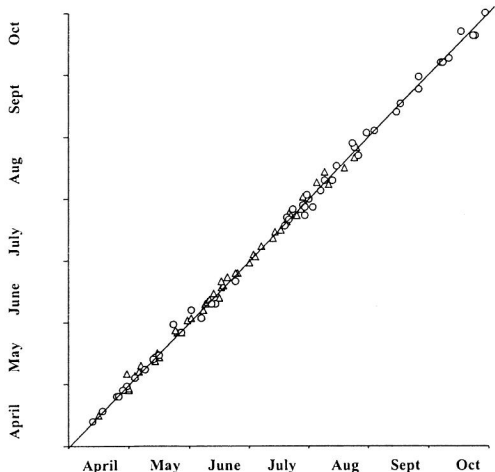| Phase name	T_0	c_0	ψ_0	S_0	DVS	Tr (IPhase)
Renewal of vegetation	5.0	60.0	-3000	0.5	0.0	0.00
Growing	5.0	60.0	-3000	2.0	40.3	0.12
Branching of first order	7.0	40.0	-3000	2.0	118.6	0.36
Branching of second order	7.0	40.0	-3000	2.0	140.7	0.43
Bud formation	4.0	40.0	-3000	2.0	220.3	0.68
Flowering	7.0	70.0	-3000	2.0	281.0	0.87
Cut harvest	7.0	70.0	-3000	2.0	324.2	1.00

Fig. 1. Comparison of the experimental and simulation results of development stages in alfalfa ($\triangle$) and maize (o).

In the deterministic case all the distribution keys c_{rs}, c_i are functions of physiological age DVS and are crop specific. In any case they are non-negative and satisfy a normalisation condition:

$$p_i \geq 0, \quad p_l + p_s + p_e = 1.$$

In the well known models, for example WOFOST, distribution keys (or partitioning factors) are described using AFGEN tables with the development stage as independent variable [1]. We use another approach in our models. Our aim was to determine distribution keys as continuous functions determined in an analytical way. Let us consider this new approach.

First of all, let us define a new scale for the physiological age, DVS, which starts at the emergence and finishes at the full ripeness. This new scale can be obtained by dividing the temperature sum determined in Eq. (2) by the temperature sum required to complete a given stage: since emergence to flowering first, and then since flowering to full ripeness. In this case the new value of physiological age is equal to 0 at the emergence, increases up to 1 at the flowering time and reaches 2 at the full ripeness. Note that this scale is used practically in all the western models [1,2,7]. The last column in Tables 1 and 2 shows the DVS values characterising

the physiological age in this new scale. For alfalfa, the DVS value is changed in the limits $0 \leq DVS \leq 1$ because the cut harvest is often produced at the flowering stage.

We will determine a deterministic distribution key, DDK, as a function of DVS. Note, first of all, that the distribution keys are monotonous functions of the physiological age - monotonously increasing or monotonously decreasing. So the following function can be chosen as a base function for the DDK description:

$$y(x) = \frac{x}{x + \exp(a_1 - a_2 x)} \qquad (7)$$

where an independent variable x coincides with the physiological age, DVS. This function is widely used in the EPIC model [6] for the description of various processes taking place in crops. Two kinds of functions based on the Eq. (6) will be used in our model. They are depicted in Fig. 2. The first of them can be used for the
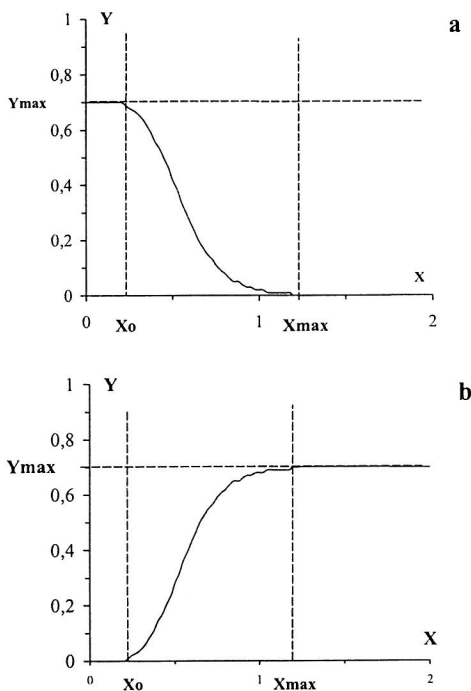

Fig. 2. A monotonously decreasing (a) and increasing (b) functions for a DDK description.

Table 3. Parameters of deterministic distribution keys (DDK) for several crops

Para-meter	Maize			Winter wheat			Barley			Potatoes		
	roots	leaves	corncob	roots	leaves	ear	roots	leaves	ear	roots	leaves	tuber
Curve type	1	1	2	1	1	2	1	1	2	1	1	2
X_0	0.0	0.0	1.05	0.1	0.1	0.95	0.1	0.1	0.95	1.0	1.0	1.0
X_{max}	1.0	1.0	0.95	1.2	0.95	1.05	1.2	0.95	1.05	1.36	1.27	1.36
Y_{max}	0.5	0.65	1.0	0.5	0.65	1.0	0.5	0.65	1.0	0.2	0.75	1.0
A_1	0.69	6.98	4.36	-0.87	1.55	4.87	-0.96	1.62	4.87	-1.08	-1.02	1.23
A_2	2.46	9.55	75.4	2.65	4.47	122.5	2.65	4.96	122.5	8.68	7.7	13.48

simulation of dry matter partitioning between shoots and roots, and between leaves and stems. The second one can be used for the growth rate of reproductive or storage organs. The function has six parameters: function type (1 or 2), x_0, x_{max}, y_{max}, a_1 and a_2. These parameters are to be determined in the process of model calibration.

For the estimation of the parameters put in the Eq. (6) the WOFOST model data were used [1]. This procedure was made with the help of nonlinear mean square method. The results of the calculation for several cultures are presented in Table 3. Figure 3 shows examples of *DDK* as functions of the physiological age for spring barley. Note that the method proposed can be used for the simulation of plant growth and development in many dynamic crop models with a daily time step.
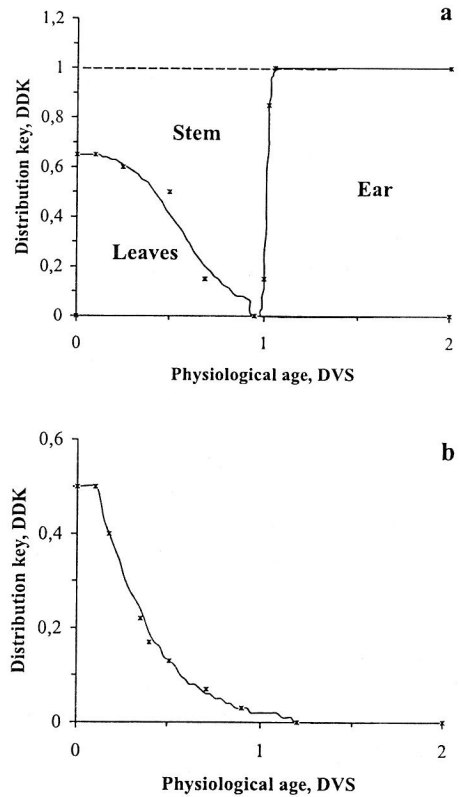

Fig. 3. *DDK* describing shoot dry matter partitioning (a) and shoot/root relation (b) for spring barley (market points denote Table data for the WOFOST model).

ADAPTIVE DESTRIBUTION KEY

Deterministic distribution keys are proposed for the description of dry matter allocation for many annual crops such as wheat, maize, potatoes, rice and others. But it is not evident how to apply this approach to such cultures as Lucerne, clover and other perennial forage crops. Actually, after any harvest a sufficient root dry matter remains in the soil, and the accumulated amount of new assimilates limits new plant growth. Root dry matter can even decrease due to respiration while the above-ground biomass rises. After some time when leaf+stem biomass has increased and daily photosynthesis exceeds plant demand, an extra amount of carbohydrates must be transported into roots causing their growth renewal. So, the whole situation could be under control of C and N content in the plant organs, CO_2 assimilation by the green plant parts, and N uptake by the roots. Our aim was to describe an alternative mechanism of dry matter partitioning which reflects adaptive crop reactions to ambient conditions and especially on the assimilation of carbon dioxide by the leaves and nitrogen uptake by the roots. In fact, during renewal of vegetation in spring or after recurrent cutting, there is a large amount of roots and a small amount of above ground dry matter. High availability of nitrogen leads to the primary growth of green plan organs so that the accumulated carbohydrates limit further plant growth. Root dry matter decreases due to respiration. When sufficient shoot dry matter is reached and excess of carbohydrates is produced, a fraction of them is allocated into roots and their dry matter rises again.

Let us describe this situation formally. We suppose that soil nitrogen does not limit plant productivity. In such a case the rate of N absorption is proportional to the integral root surface and the absorption rate of root unit is constant and equal to the saturation value V_{max}. The amount of assimilates accumulated in a day k, ΔW, must be distributed in root and shoot according to Eq. (4). Let Ω $(k-1)$ denote the root area for a previous day, k-1. An increase of this value on the day k can be calculated by the formula:

$$\Delta\Omega(k) = s_r \Delta W_r(k) \qquad (8)$$

where s_r is a specific root area, m^2 kg^{-1}. The equation of nitrogen balance can be written as:

$$\int_{(k-1)T}^{kT} N_L(t)w_L(t)dt + \int_{(k-1)T}^{kT} N_R(t)w_R(t)dt =$$

$$= V_{max} \int_{(k-1)T}^{kT} (\Omega(k-1)+\omega(t))\, dt$$

where w_L and w_R are the rates of biomass growth, N_L and N_R nitrogen concentration in shoot and root, $\omega(t)$ current increase of the root area, T=24 h. It is assumed that all the nitrogen is utilised completely and no reserve is stored. For $N_L(t)$ and $N_R(t)$ that change slowly during vegetation, the last equation can be rewritten in the form:

$$N_L\Delta W_L(k)+N_R\Delta W_R(k) =$$
$$V_{max}(\Omega(k-1)+\xi\Delta\Omega(k)) \qquad (9)$$

where:

$$\xi\Delta\Omega(k) = \int_{(k-1)T}^{kT} \omega(t)dt \qquad (10)$$

It is clear that the coefficient ξ ranges in the following limits $0<\xi<1$. It can assumed to be approximately equal to 0.5.

Assimilate distribution which is controlled by the partitioning coefficient c_{rs} in Eq. (5) is determined first by the relationship between available forms of carbon and nitrogen, and secondly, by the demand of plant organs in these nutrient elements. If nitrogen absorbed by the roots (kg ha^{-1} day^{-1}):

$$\Delta N_R = V_{max}\, \Omega(k) \qquad (11)$$

exceeds a demand of the above ground crop part, $N_L\Delta W$ all the assimilates remain in the leaves, and c_{rs} equals zero. In the reverse case, when:

$$V_{max}\, \Omega(k) \leq N_L\Delta W$$

all the assimilates are allocated in the roots and c_{rs}=1. Any intermediate case leads to a formula, which follows from Eqs (9)-(11):

$$c_{rs} = \frac{N_L \Delta W(k) - V_{max}\Omega}{\Delta W(k)(\xi s_r V_{max} + N_L - N_r)}. \qquad (12)$$

Actually, a small part of assimilates is always transported into the roots or remains in the leaves. So c_{rs} is greater than 0 and less than 1. We can assume that $\alpha \le c_{rs} \le (1-\alpha)$, where α is a small positive value.

The whole situation is clarified in Fig. 4. It demonstrates a saw-shape time course of the above-ground biomass and oscillating character of the root biomass dynamics. Since daily amount of assimilates produced by photosynthetic organs depends on current weather conditions, the last distribution key reflects adaptive plant reaction to the environment. It was the reason to call it "adaptive distribution key" - *ADK*.
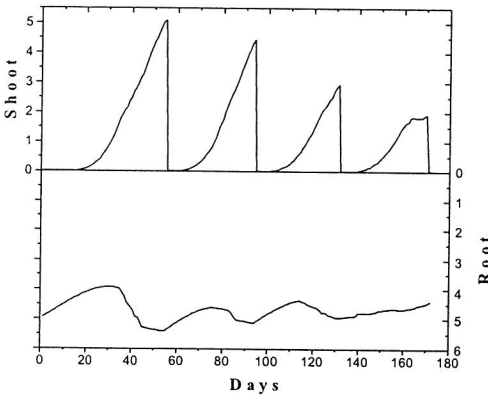

Fig. 4. Dynamics of shoot and root formation of alfalfa during vegetation. Numbers along the X-axes denote days since vegetation renewal.

CONCLUSIONS

Units describing plant development and dry matter distribution are integral parts of any crop production model. However, various types of approach to description of these processes can be found. The majority of processes taking place in soil or atmosphere such as water movement in an unsaturated soil or turbulent gas exchange in a near-soil layer have a strong theoretical base. Some physical or biophysical processes in plant canopy like photosynthesis or transpiration are also well investigated and have rather strong quantitative foundation [3-5]. Processes of the ontogenetic development or growth of plant organs are different from those mentioned above. There is no scientific ground for their description to give it a strong theoretical base. It is the reason to use some approximate formulae to represent these processes in models. So success is only possible if the functions chosen reflect appropriate phenomena with a small number of unknown parameters for identification. On the other hand, progress in the use of more physiological ideas for this end seems to be attractive. The present paper illustrates these points of view. Deterministic distribution keys, *DDK*, are simple enough and allow easy calibration for a family of crops. Adaptive distribution key, *ADK*, reflects some physiological processes in plants and can be considered as an example of a more realistic approach to quantitative plant physiology. Note, that *ADK* is a single key for the description of the dynamics of shoo/root relation for a perennial crop.

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