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Chapter 10(B):

Lintul-2: water limited crop growth

A simple general crop growth model
for water-limited growing conditions
(example: spring wheat)

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Contents:

LINTUL2 A SIMPLE GENERAL CROP GROWTH MODEL FOR WATER-LIMITED GROWING CONDITIONS (EXAMPLE: SPRING WHEAT)

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Introduction

LINTUL2 describes production (as applied to spring wheat) under water-limited conditions by including a water balance of crop and soil in the LINTUL1 model. Conditions are still optimal with respect to other growth factors, i.e. ample nutrients and a pest-, disease- and weed-free environment. With the LINTUL2 model, options for water conservation can be studied, as well as differences among cultivars in drought tolerance. The simple crop / soil water balances in LINTUL2 are derived from more complex versions documented by Stroosnijder (1982) and Penning de Vries *et al.* (1989).

LINTUL2 can only be understood on the basis of LINTUL1, the crop growth model for potential production. The effect of modified water relations is transmitted through two variables, one acting on total crop growth and the other one acting on root-shoot partitioning.

The soil water balance model, as well as its interaction with the crop, is introduced first in terms of mathematical equations. Subsequently, the LINTUL2 program is explained.

The main model equations and functions of the program

Soil water balance The soil water balance is determined by infiltration into the soil as a result of precipitation, irrigation, run-off or run-on, and percolation to or capillary rise from deeper soil layers, and evapotranspiration of water from the soil surface and the crop. Potential evapotranspiration is often calculated by a Penman-type equation (Penman, 1948), but also other methods are used, depending on the objective, situation and data availability (Van Kraalingen & Stol, 1997). Subsequently, on the basis of *LAI* the incoming energy is partitioned between the vegetation and the bare soil, and potential evaporation and potential transpiration are calculated. Finally, the actual rate of water loss from the soil surface depends on the water content of the top soil compartment and the actual crop transpiration is affected by the water contents in the rooted soil profile layers.

Two main approaches to model the soil water balance may be distinguished: the tipping bucket approach (Van Keulen, 1975), and the Richards approach (Darcy, 1856; Richards, 1931). An extensive comparison between the tipping bucket approach and the Richards approach is reported in Rijneveld (1996).

Tipping bucket approach If the objective is to calculate the amount of water available to the crop over longer periods of time such as a season, the tipping bucket model (sometimes also named the 'cascading model') is appropriate. In the tipping bucket approach, the water infiltrating into the soil fills the compartments to field capacity from the surface downwards. A possible surplus of water is lost by deep drainage below the rooting depth. Water entering the profile is distributed within one time step of integration, usually one day in crop growth models. Thus, field capacity may be reached within one day. Transport of water between soil compartments along developing gradients in matric potentials is not described in such models. Instead, a parameterised method is used, derived from a detailed physically based Richards model, to "mimick" the redistribution process (Van Keulen, 1975): the water loss by evaporation through the soil surface is withdrawn from the various compartments as a function of soil physical properties and the current water distribution in the soil profile. In the straightforward tipping bucket approach, water stress can be considered, but the consequences of waterlogging and related anoxic conditions on root growth to a lesser extent. However, with respect to waterlogging a number of versions have been developed in which waterlogging and capillary rise are mimicked, while maintaining the comfortable, large daily time step.

The tipping bucket water balance in LINTUL2 contains one soil layer, and all of the above mentioned flows, except capillary rise. Instead, the single rooted soil layer increases in thickness with the rate at which these roots grow in downward direction and thus soil, in which the water content equals that belonging to field capacity, is explored for the soil water newly found. Figure 1 summarizes the flows and shows which ones are affected by *LAI*.

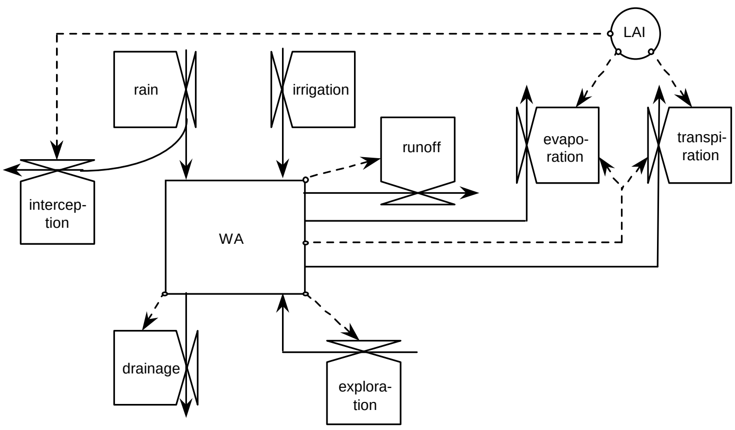


Figure 1. Relational diagram of the tipping bucket water balance in LINTUL2, comprising the amount of water (*WA*) in the single rooted soil layer as state variable and the water flows into and out of this soil layer. The feedback of the crop on the appropriate flows is indicated by dashed lines starting at *LAI*.

Water uptake Uptake of water from the soil by plant roots is driven by crop transpiration and may be modified by the amount of water in the profile. The increase in rooting depth over time is assumed to be constant (derived from experiments) up to an either crop- or soil-specific maximum. Only vertical root distribution is considered, because in dense crop stands, such as for wheat, root density is high enough not to limit water uptake (Van Keulen, 1975). Water uptake is dependent on the average water content in the soil compartment, and gradients developing around individual roots are not considered. If the water content in the tipping bucket approach is less than a lower threshold value (θ_{cr}), crop growth rate decreases and the allocation of biomass is changed: a larger proportion of biomass is allocated to roots as a consequence of growth reduction in the shoot, and, if wilting point is reached, growth completely stops. If the water content exceeds an upper threshold value (θ_{wet}), crop growth rate is reduced similarly to the case of water shortage, but now it is due to a lack of aeration, resulting from water logging.

Interactions between crop and soil water Crop roots react to water tension, rather than to water content. Nevertheless, since transport due to gradients in soil water tension is not included in the tipping bucket approach, soil water contents are directly used to calculate crop reaction and soil water balance. However, the choice of these water contents is based on certain important soil water tension values from the soil water characteristic, that relates matric suction and water content (Figure 2): air dry (*AD*) at pF=5; wilting point (*WP*) at pF=4.2; field capacity (*FC*) at pF=2; and the water content at which the soil lacks oxygen (*WET*), at a pF=0.5. Thus, a specific soil type may be selected via these values.

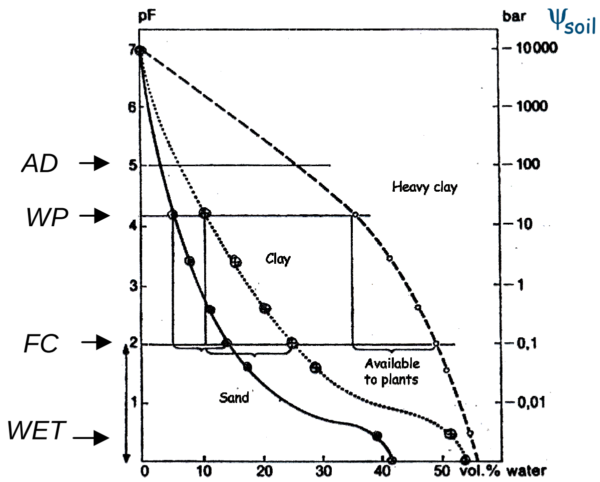


Figure 2. Soil water characteristics for sand, clay and a heavy clay soil and the indication of some important data points used in the tipping bucket model.
(pF = ^{10}log{–(suction in cm hanging water column)/cm}, left y-axis; a bar = 10 m of water pressure is 1000 cm), right y-axis.)

Soil water content is expected to affect emergence, root growth, crop growth rate, and the allocation of biomass over roots and shoot of the crop.

Emergence and root growth take place only if there is enough water in the soil, i.e. if the water content is above wilting point. Emergence takes place only once, of course, but in the course of crop development, root growth could be hampered a number of times due to a water content below wilting point.

Crop growth rate is affected if the transpiration of the crop is hampered due to a low water content in the rooted soil. From experiments of Briggs & Shantz (1914) with maize it appears that such a reduction in growth is proportional to the ratio of the actual transpiration and the potential transpiration, Figure 3. This ratio may be called the transpiration reduction factor.

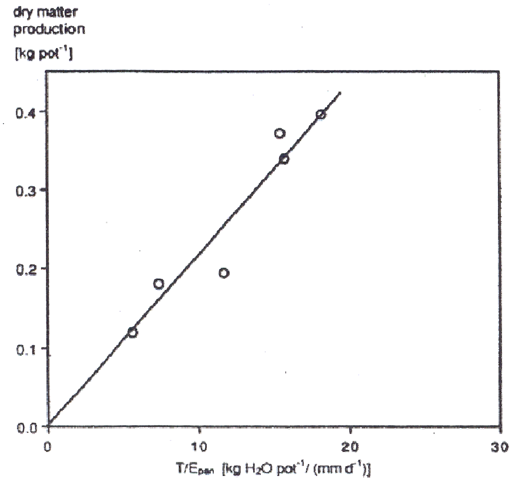


Figure 3. Experimental evidence of a linear reduction in growth with actual transpiration (T, further called T_{act}) relative to pote ntial transpiration (E_{pan})[1], Briggs & Shantz (1914), for maize. The ratio on the x-axis may be called the transpiration reduction factor, $T_{red\text{-}tran}$. The $T_{red\text{-}tran}$ is here given in kg H_2O pot^{-1} / (mm d^{-1}), but in the further text the units are expressed in (mm d^{-1}) / (mm d^{-1}).

Actual crop transpiration is assumed to decline linearly below a critical water content (θ_{cr}) in case of water shortage, and above a critical water content (θ_{wet}, compare the water content at "*WET*" in Figure 2) in case of a surplus of water, at which a shortage of oxygen exists for most plant species, except for aerenchymatic species such as rice and reed, Figure 4.

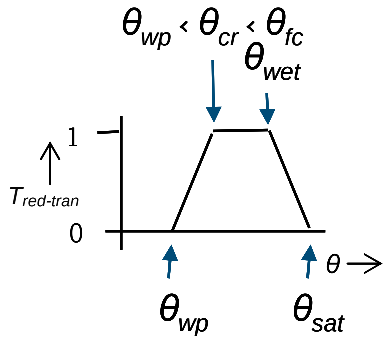


Figure 4. The transpiration reduction factor ($T_{red\text{-}tran}$, y-axis) as a function of water content (θ, x-axis) between wilting point (θ_{wp}) and completely saturated soil (θ_{sat}). Below θ_{cr} and beyond θ_{wet}, transpiration reduction takes place.

The critical water content (θ_{cr}) lies between the water content at field capacity (θ_{fc}) and that at wilting point (θ_{wp}). It is assumed that θ_{cr} is affected by the drought tolerance of the crop: a very drought-tolerant crop will unrestrictedly extract water from the soil to a lower water content as compared to a drought-sensitive crop. The critical water content is calculated by Eq. (1):

$$\theta_{cr} = \theta_{wp} + \frac{ET_{crop}}{ET_{crop} + T_{co}} (\theta_{fc} - \theta_{wp}) \qquad (1)$$

where ET_{crop} is the potential transpiration rate of the crop, the calculation of which will be discussed later, and T_{co} is the transpiration coefficient, which is a measure of the drought tolerance of the crop. The ratio

[1] E_{pan} is the evaporation from an open pan filled with water and is a measure for potential evapotranspiration.

$ET_{crop} / (ET_{crop} + T_{co})$ in Eq. (1) is a fraction between 0 (at an infinite drought tolerance, where $\theta_{cr} = \theta_{wp}$) and 1 (if the crop would be extremely sensitive to drought, resulting in $\theta_{cr} = \theta_{fc}$). By including the dynamic potential transpiration rate in the calculation of θ_{cr} we recognize that on days of high potential transpiration it is more difficult for even a drought-tolerant crop to take up enough water from the soil and to maintain its turgor against the large demand.

The transpiration reduction factor ($T_{red\text{-}tran}$), as calculated from Figure 4, is now used to reduce the leaf expansion rate in the juvenile stage, which is mainly driven by temperature (see Chapter 10A on LINTUL1):

$$\frac{dL}{dt} = \frac{L_t\,(e^{(r_l\ T_{eff}\ \Delta t)} - 1)}{\Delta t}\,T_{red-tran} \tag{2}$$

Moreover, crop growth rate as a whole is reduced:

$$\frac{dW}{dt} = RUE\ I_{int}\ T_{red-tran} \tag{3}$$

Both Eqs. (2) and (3) are extensions of Eqs. (12) and (3) from LINTUL1, respectively.

The use of the transpiration reduction factor as a multiplication factor in Eq. (3) shows that it is not decided whether a water shortage (or surplus) affects the interception of light, for example via leaf rolling, or the radiation use efficiency, for example via closure of stomata, or perhaps both processes.

Allocation of biomass over roots and shoot of the crop is changed if water stress occurs, Figure 5 (Magrin et al., 1991). The crop thus responds to a water shortage by a better exploration of the soil volume.

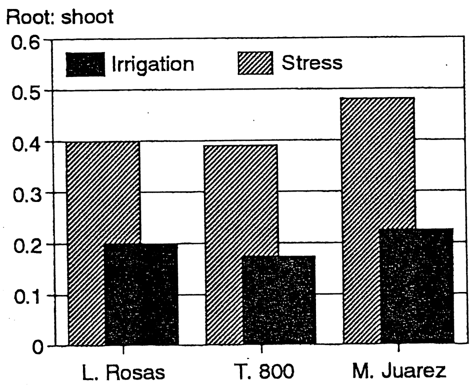


Figure 5. Root : shoot ratios in irrigated and droughted treatments for three wheat cultivars. Values derive from one lysimeter per treatment.

Since allocation of biomass over the different crop parts is not well understood, the process is modelled in a general way, based on two assumptions: (1) upon drought, more roots will be formed to alleviate the water shortage and thus less biomass is left for the shoot, (2) the distribution of dry matter among stem, leaves and storage organs remains unchanged.

The root and shoot modification factors of the dry matter allocation, using *r* to indicate roots, *s* stem, *l* leaves and *so* for storage organs, are now derived. If the soil is too dry, more roots are formed to alleviate the water shortage and thus more newly produced biomass is allocated to the roots. The new amount of biomass allocated to the roots is given by Eq. (4)

$$r_{new} = r_{old}\ rMOD, \quad \text{with } 1 \le rMOD \le f_{max} \tag{4}$$

where *rMOD* is the root modification factor and f_{max} is the maximum modification of the partitioning of dry matter to the roots. The amount that does not go to the shoot, i.e. to (*s* + *l* + *so*), will be ($r_{new} - r_{old}$), but the distribution of biomass over the aboveground crop parts remains the same, namely $s_{old} : l_{old} : so_{old}$.
For instance, the stem, *s*, will get a fraction $\{s_{old} / (s_{old} + l_{old} + so_{old})\}$ less dry matter of the quantity ($r_{new} - r_{old}$):

$$\frac{s_{old}}{s_{old} + l_{old} + so_{old}} (r_{new} - r_{old}) \tag{5}$$

Thus, the new amount of dry matter allocated to the stem will be

$$s_{new} = s_{old} - \{\frac{s_{old}}{s_{old} + l_{old} + so_{old}} (r_{new} - r_{old})\} \tag{6}$$

Since $(s_{old} + l_{old} + so_{old}) = 1 - r_{old}$, Eq. (6) can also be written as:

$$s_{new} = s_{old} - \{\frac{s_{old}}{1 - r_{old}} (r_{new} - r_{old})\} \tag{7}$$

Taking s_{old} on the right hand side of the equation outside brackets, and rearranging a bit, the shoot modification factor *shMOD*, that applies to all individual above ground crop parts, may be defined as:

$$shMOD = 1 - \frac{r_{new} - r_{old}}{1 - r_{old}} = \frac{1 - r_{new}}{1 - r_{old}} = \frac{1 - r_{new}}{1 - {r_{new}}/{rMOD}} \tag{8}$$

where r_{old} is taken as $r_{new} / rMOD$ according to Eq. (4).
What remains to be defined is an equation for the modification factor *rMOD*. Eq. (4) states: $1 \leq rMOD \leq f_{max}$, where the number 1 represents no modification in allocation of dry matter over root and shoot and the variable f_{max} represents the maximum modification in allocation of dry matter to the roots. A numerical value of f_{max} of 2 seems reasonable in view of Figure 5, although we do not know how severe the water stress in the experiments of Magrin et al. (1991) was. Therefore, f_{max} could be set to a different value, if appropriate. The function for *rMOD* is defined by a hyperbola type of equation, Eq. (9):

$$\left\{ \begin{array}{ll} rMOD = \dfrac{1}{T_{red-tran} + {1}/{f_{max}}} & ,\text{if } T_{red-tran} \leq {1}/{f_{max}} \\ rMOD = 1 & ,\text{if } T_{red-tran} > {1}/{f_{max}} \end{array} \right\} \tag{9}$$

Eq. (9) logically comprises the restriction that *rMOD* can not be smaller than 1. Figure 6 shows plots of Eq. (9) for f_{max} = 2 and f_{max} = 4. The function intersects the y-axis at a value f_{max}, and the x-axis at a value (1-1/f_{max}), beyond which $T_{red-tran}$ does not affect the partitioning fractions. The higher f_{max}, the earlier the crop experiences water stress, and the more dry matter is distributed to the roots.
Let r_{old}, s_{old}, l_{old}, and so_{old}, denote the partitioning fractions under non water-limited conditions, and r_{new}, s_{new}, l_{new}, and so_{new}, the partitioning fractions under water-limited conditions. Then, the partitioning fractions under water limited conditions can be calculated by Eqs. (4) and (10):

$$r_{new} = r_{old} \quad rMOD \tag{4}$$

$$\begin{Bmatrix} s_{new} = s_{old} \quad shMOD \\ l_{new} = l_{old} \quad shMOD \\ so_{new} = so_{old} \quad shMOD \end{Bmatrix} \tag{10}$$

where *rMOD* and *shMOD* are given by Eqs. (9) and (8), respectively. The partitioning fractions, F_i, earlier defined for non water-limited conditions, and given in the chapter about LINTUL1 (Chapter 10A, Figure 3), are in fact similar to the symbols r_{old}, s_{old}, l_{old}, and so_{old}. However, the symbol F_i is also used to identify the modified fractions r_{new}, s_{new}, l_{new}, and so_{new}, and the dry matter allocated to the different organs can still be calculated by Eq. (7) from Chapter 10A: $dW_i/dt = RUE \;\; I_{int} \;\; F_i$, where i represents the root (*rt*), stem (*st*), leaves (*lv*) or storage organ (*so*) of the plant, respectively. Obviously, the *new* and the *old* partitioning fractions coincide if *rMOD* = 1 (no water shortage and thus no modification), resulting in *shMOD* = 1.

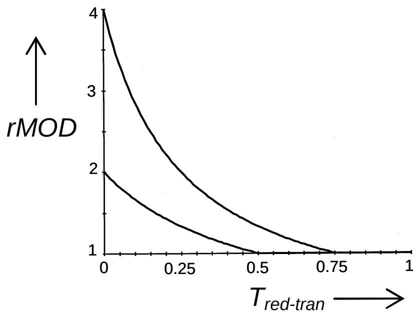


Figure 6. The root modification factor *rMOD* as defined by Eq. (9), as a function of $T_{red\text{-}tran}$ for f_{max} = 2 (lower line) and f_{max} = 4 (upper line). Note that the origin is (0,1) rather than (0,0).

To summarize this section on the interactions between crop and soil water, Figure 7 is given where, in addition to the feedbacks of *LAI* on the water balance as indicated in Figure 1, also the feedbacks of the transpiration reduction factor, $T_{red\text{-}tran}$ (TRANRF), on *dL/dt* (Eq. (2), *GLAI*) and on *dW/dt* (Eq. (3), *GTOTAL*) are indicated (for the definitions of the abbreviations in Figure 7 see the table at the end of this chapter).

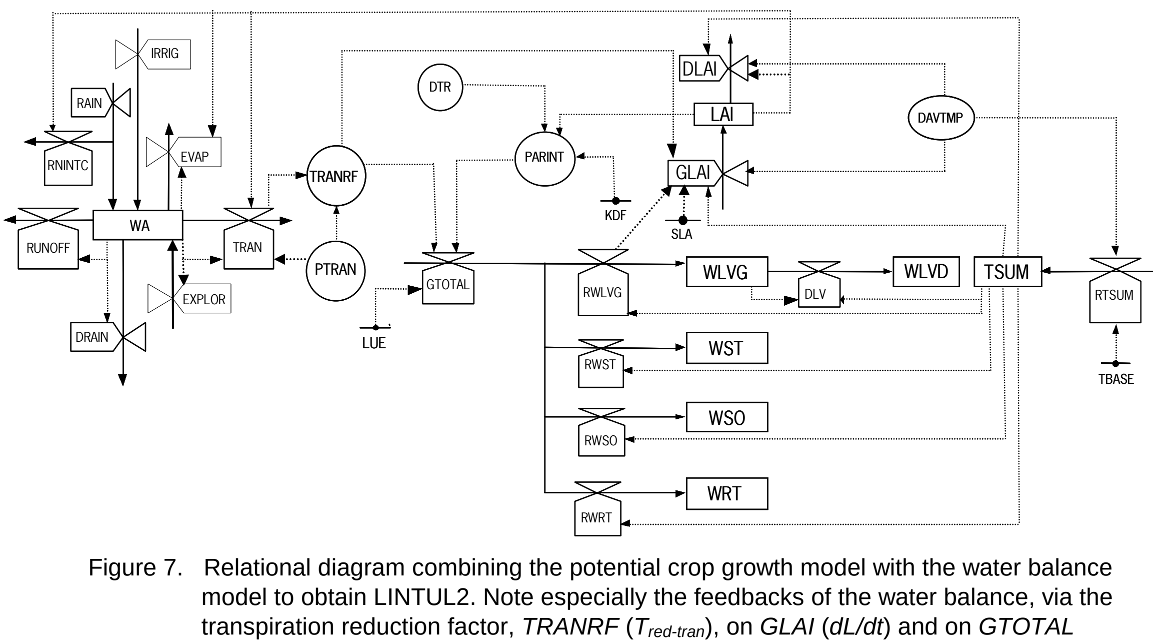


Figure 7. Relational diagram combining the potential crop growth model with the water balance model to obtain LINTUL2. Note especially the feedbacks of the water balance, via the transpiration reduction factor, *TRANRF* ($T_{red\text{-}tran}$), on *GLAI* (*dL/dt*) and on *GTOTAL* (*dW/dt*). Moreover, potential transpiration (*PTRAN*, ET_{crop} in Eq. (1)), needed to calculate the dimensionless *TRANRF* ($T_{red\text{-}tran}$), is indicated.

Water flows in the soil water balance The amount of water in the single rooted soil layer at time t, w_t, is determined by the integral of the flows over time, starting at an initial amount of water, w_0, according to Eq. (11):

$$w_t = w_0 + \{(R + I + dw_{exp}/dt) - (R_{int} + RN + D + T_{act} + E_{act})\}\Delta t \tag{11}$$

where R represents rain (*RAIN* in Figure 7), I, Irrigation (*IRRIG*), dw_{exp}/dt, water explored by the growing roots (*EXPLOR*), R_{int}, intercepted rain (*RNINTC*), RN, run-off (*RUNOFF*), D, drainage rate (*DRAIN*), T_{act}, actual transpiration rate from the canopy and E_{act}, the actual evaporation rate from the soil surface, all expressed in mm d^{-1}. The time step is indicated by Δt and equals one day.

Rain is usually the major source of water for crops. It is read from historical weather records. Many data files with daily weather data are available within the Plant Production Systems Group for a large number of locations in Europe, Asia, Africa and Australia.

Interception of rain is described as a function of leaf area index according to Eq. (12):

$$R_{int} = \min(R\ ,\ R_{intmax}\ LAI) \tag{12}$$

where R_{intmax} is the coefficient of maximum interception of rain per day and per unit leaf area, expressed in mm d^{-1} (liter m^{-2} of leaf d^{-1}), with numerical values reported between 0.03 and 0.6. In LINTUL2 0.25 mm d^{-1} is used. Eq. (12) shows that each day, a maximum interception ($R_{intmax}\ LAI$) may take place, which means that it is assumed that at the start of the day leaves are dry. If there is more precipitation than the maximum that can be retained by the leaves, this maximum value is applied; if there is less precipitation, only the smaller amount, R, will be retained. The minimum function is therefore conveniently used.

Exploration of water by growing roots, dw_{exp}/dt, depends on the rate of vertical extension of the roots, because new soil water, by definition held at the water content belonging to field capacity, is made available for uptake. Thus dw_{exp}/dt is related to the vertical root extension rate, dr_d/dt, Eq. (13):

$$\left\{\begin{array}{lll} \dfrac{dw_{exp}}{dt} = \dfrac{dr_d}{dt}\ \theta_{fc} & & \\ \dfrac{dr_d}{dt} & = \left\{\dfrac{dr_d}{dt}\right\}_{\max} & ,\text{if } \theta \geq \theta_{wp}\ \&\ T_{sum} < T_{sum-ant}\ \&\ r_d < r_{dmax} \\ \dfrac{dr_d}{dt} & = 0 & ,\text{if } \theta < \theta_{wp}\ \text{or}\ T_{sum} \geq T_{sum-ant}\ \text{or}\ r_d \geq r_{dmax} \\ r_{dmax} & = \min(r_{dmax\_crop}, r_{dmax\_soil}) & \end{array}\right\} \tag{13}$$

Eq. (13) shows that there is either a maximum, crop type-specific and fixed, vertical root growth rate $(dr_d/dt)_{max}$ or no growth at all. Root growth only occurs if there is enough water in the profile, the temperature sum at anthesis, $T_{sum\text{-}ant}$, is not yet reached, and the maximum rooting depth, r_{dmax}, is not yet reached (r_d is the actual rooted depth). Maximum rooting depth is determined by the smallest of either a crop-specific physiological maximum, r_{dmax_crop}, or a soil physical maximum, r_{dmax_soil}, for example when the soil is shallow, because its parent material is rocky. By multiplying dr_d/dt by θ_{fc} the water exploration rate is calculated, which, by integration, is added to the soil water in terms of mm of water.

The relationship between the rate of increase of root biomass, dW_{rt}/dt (*RWRT*, g DM m^{-2} d^{-1}), root length and vertical root extension rate, dr_d/dt (*RROOTD*) is complex and not well understood yet. Therefore, the increase in root weight and vertical extension rate are independently dealt with in the model, and dW_{rt}/dt does not appear in the expression to calculate dr_d/dt in Eq. (13).

The relational diagram in Figure 7 shows a feedback from the amount of water, *WA*, to rate *EXPLOR* (dw_{exp}/dt). This feedback is in fact a summary of Eq. (13), which is detailed in the relational diagram in Figure 8. In that figure, the *RRDMAX* (r_{dmax}) could have been given in the form of a auxiliary symbol. This is omitted, however, to only illustrate the most important aspects of the feedback. For the same reason Figure 8 is not included in the relational diagram of the overview of the model as a whole in Figure 7.

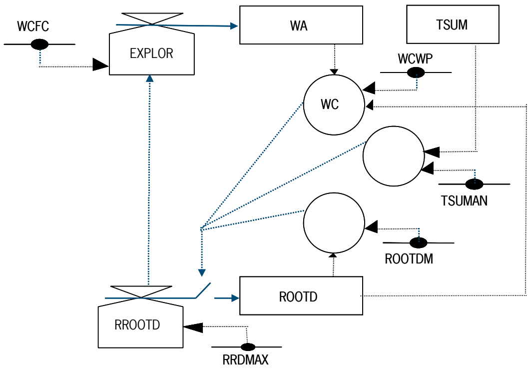


Figure 8. Relational diagram explaining the feedback from the amount of water, *WA*, to rate *EXPLOR* in Figure 7, using Eq. (13).

It was stated earlier that the tipping bucket model does not include capillary rise. Usually, this upward flow of water is slow compared to the downward root growth rate before anthesis[2]. After anthesis, capillary rise could provide a small contribution to the water supply of crops, but this is thus neglected in the model.

Drainage of water, runoff and irrigation are calculated in a preferential sequence in the tipping bucket model. This approach needs some explanation, because in state-determined models the calculations are usually organised such that they simulate the parallel systems processes in a (semi-)parallel way: all rates are calculated on the basis of the states and these rates are subsequently integrated. This implies, however, that the time step of integration should be smaller than the time coefficients of the processes involved, which are often much smaller than a day, whereas in the tipping bucket approach, the time step is fixed at one day. If time steps are taken too large in numerical integration, unrealistic negative water contents may result. Therefore, the tipping bucket model first calculates drainage and, if that is not sufficient to discharge the water to the level of the water content at field capacity, the surplus will (partially) fill the storage capacity of the soil between field capacity and saturation. If the amount of water added to the soil even exceeds the storage capacity between the actual and saturated water content, the excess water does not enter the soil anymore and is assumed to run-off overland. This means that soil at the most can temporarily be saturated, but

[2] For a light clay soil, for example, with a groundwater table at 200 cm below the surface, a rooted zone of 50 cm, and a suction in the rooted zone of 250 cm, it was calculated that capillary rise towards the lower boundary of the rooted zone is 2.3 mm per day, using data from section 3.2 in the book of van Keulen & Wolf, 1986.

ponding does not occur. Rijneveld (1996) compared the tipping bucket approach with the Richards approach to investigate the consequences of the sequential approach and found that, for the appropriate time resolution, i.e. $\geq$ days, the amounts of water were similarly calculated. The tipping bucket model is therefore appropriate to calculate the amount of water available to the crop over longer periods of time such as a season.

Irrigation in the LINTUL2 model may be used to easily compare results obtained under rainfed conditions with results obtained under potential production conditions, because irrigation is used to remove water stress.

Drainage of water occurs when the balance of incoming and outgoing water of the soil { $R - (R_{int} + T_{act} + E_{act})$ } exceeds the amount of water needed to replenish the soil water from the actual amount, w_t, to the field capacity value, w_{fc}. This is the principal definition of the tipping bucket model. However, the LINTUL2 tipping bucket is made more realistic by a restriction on the maximum drainage rate, D_{max}, Eq. (14) 3rd part.

$$\left\{ \begin{array}{ll} D=\frac{(w_t-w_{fc})}{\Delta t}+(R-R_{int}-T_{act}-E_{act}) \ , & 0\leq\frac{(w_t-w_{fc})}{\Delta t}+(R-R_{int}-T_{act}-E_{act})\leq D_{max} \\ D=0 & , \ \frac{(w_t-w_{fc})}{\Delta t}+(R-R_{int}-T_{act}-E_{act})<0 \\ D=D_{max} & , \ \frac{(w_t-w_{fc})}{\Delta t}+(R-R_{int}-T_{act}-E_{act})>D_{max} \end{array} \right\} \quad (14)$$

The amount of water present in the rooted zone at field capacity is calculated by $w_{fc} = \theta_{fc}\, r_d$. The amounts, w, are expressed in mm H_2O [3]. Since the terms R, R_{int}, T_{act}, E_{act} and D_{max} are expressed in mm d^{-1} the result should be added to a rate as well. Therefore, the difference in amounts of water ($w_t - w_{fc}$) is converted into a rate by dividing it by Δt.

Typical maximum drainage rates under saturated conditions are for sand, clay and heavy clay, 250-500, 10-35 and 2-3 mm d^{-1}, respectively (van Keulen & Wolf, 1986)[4]. In case { $(w_t - w_{fc})/\Delta t + R - R_{int} - T_{act} - E_{act}$ } is negative, the 2nd part in Eq. (14) prevents that there is a negative drainage.

Runoff of water may occur when the drainage capacity of the soil is not sufficient to discharge the rain water with the result that the soil becomes saturated, Eq. (15):

$$RN=\max\left\{ 0 \ , \ \frac{(w_t-w_{sat})}{\Delta t}+(R-R_{int}-D-T_{act}-E_{act}) \right\} \quad (15)$$

where w_{sat} is the amount of water that can be stored in the soil if it is saturated ($w_{sat} = \theta_{sat}\, r_d$, see Footnote 3 for an explanation of the units). Eq. (15) calculates the sum of the maximum rate of water addition, $(w_t - w_{sat})/\Delta t$, needed to attain saturation, plus the balance of the rates of water entering and leaving the soil on that day: { $R - (R_{int} + D + T_{act} + E_{act})$ }. If the result of the calculation is positive, there is a surplus of water and runoff takes place. The max-function prevents an erroneous negative run-off.

[3] In $w_{fc} = \theta_{fc}\, r_d$ usually θ_{fc} is expressed in cm^3 H_2O cm^{-3} soil and r_d in cm^3 soil column, which would give cm^3 H_2O for w_{fc}. Since it is reasonable to consider the soil as an isotropic medium, cm^3 can be replaced by cm or by mm.

[4] Wösten *et al.* (2001) reports for sand, clay and heavy clay values of 290-530, 7-45 and 53 mm d^{-1}, respectively. The value for the heavy clay is surprisingly high compared to the one of van Keulen & Wolf (1986). This perhaps may be due to small cracks and worm holes (macropores), or to the small number (9) of representative soil samples used to assess this value. Furthermore, the standard deviation around the saturated hydraulic conductivity is large, possibly due to macropores (Wösten, pers. comm.). Obviously, it is not a trivial task to correctly parameterize a model.

Irrigation may be applied in case of water shortage, for example using sprinkler irrigation or overland flow (furrow irrigation). In case of overland flow, there will be no interception of water by the canopy. In the relational diagrams in Figures 1 and 7 this is apparently the case.

In the LINTUL2 model, however, irrigation is not modelled as an additional input of water from intermittent applications, after a certain low soil water content is reached (usually the water content belonging to a pF ≈ 3), but rather as the volume of irrigation water needed to keep the actual water content, θ, at field capacity, θ_{fc}. In this way, water-limited or rainfed crop production can easily be compared with potential production. The amount of water that matches the difference between the water content at field capacity and the actual water content is calculated by Eq. (16):

$$\begin{Bmatrix} I = \max\left\{0 \ , \ \dfrac{(w_{fc} - w_t)}{\Delta t} - (R - R_{int} - RN - D - T_{act} - E_{act})\right\}, \text{if } SW_{pot} = 1 \\ I = 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if } SW_{pot} = 0 \end{Bmatrix} \tag{16}$$

where SW_{pot} is a dimensionless switch by which we choose between potential (SW_{pot} = 1) and water-limited production. The max-function prevents an erroneous negative irrigation. The combination { R – (R_{int} + RN + D + T_{act} + E_{act}) } is the balance of incoming (R) and outgoing (R_{int} + RN + D + T_{act} + E_{act}) rates of water with respect to the root zone present at the start of the day; the exploration of new soil during that day need not be considered in the calculation of irrigation water. The result of the balance gives a surplus or a shortage of water. In case of a surplus, the rooted soil layer is partially replenished by rain (the gap between w_{fc} and w_t is thus partially filled) and less irrigation water is needed; in case of a shortage the reverse applies and more water is needed by irrigation.

Actual transpiration The transpiration reduction factor, $T_{red\text{-}tran}$, is the ratio between actual transpiration, T_{act} (*TRAN* in Figure 7), and potential transpiration, ET_{crop} (*PTRAN* in Figure 7), of the crop, Figure 3. $T_{red\text{-}tran}$ is calculated in Figure 4 depending on the water content in the soil profile. To calculate the actual transpiration, we thus need an estimate of potential transpiration, ET_{crop}, since $T_{act} = T_{red\text{-}tran}\, ET_{crop}$.

Potential (evapo) transpiration[5] The equations for the water fluxes in the tipping bucket model were descriptive up to now, and based on logical reasoning and a minimum of soil physical data. To calculate potential evapotranspiration, comprising both ET_{soil} (potential soil evaporation) and ET_{crop} (potential crop transpiration), however, we need to consider the energy balance at the earth's surface and the processes related to the removal of the water vapour from the canopy surface. Penman (1948) was the first to describe evapotranspiration in physical-mathematical terms. He derived equations that describe evaporation and transpiration from free-water surfaces, bare soil and short grass swards for 10-day periods. There is ongoing discussion in the literature whether his formulae are also applicable if daily values are used. If used with daily values, 24-hour average values should be used, as is done in the LINTUL2 model. Penman defined potential evapotranspiration in 1956 as the evapotranspiration[6] from "*a fresh green crop, of about the same colour as*

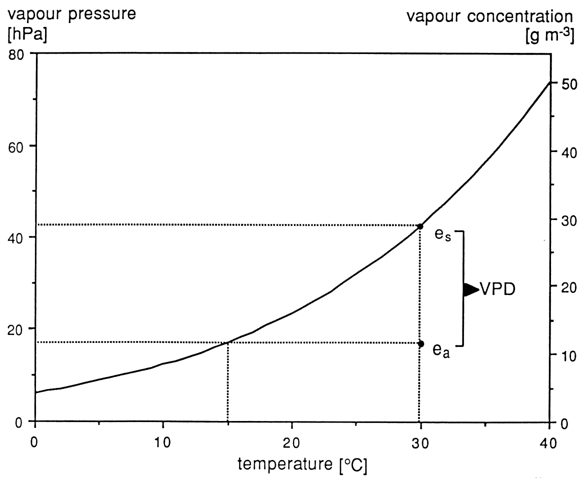
[5] The following text is partially based on Goudriaan and van Laar, 1994, Modelling potential crop growth processes, and on Lövenstein *et al.*, 1995, Principles of Production Ecology.

[6] Penman spoke of potential evaporation, but today the term evapotranspiration is commonly used.

grass, completely shading the ground, of fairly uniform height, and never short of water" (cf. Howell & Evett, 2004), and derived Eq. (17):

$$ET = \frac{\Delta}{\Delta+\gamma}\,\frac{R_{net}}{\lambda} + \frac{\gamma}{\Delta+\gamma}\,\frac{E_{air}}{\lambda} \tag{17}$$

where the potential evapotranspiration of water, ET (kg H_2O m^{-2} d^{-1} or mm d^{-1}) from both crop and soil, is the result of a weighted sum of a net radiation term (R_{net}, MJ m^{-2} d^{-1}) and an aerodynamic term (E_{air}), that both are converted into water evaporation by dividing them by the heat of vaporization, λ, expressed in MJ kg^{-1} H_2O (the value of which is 2.45 around 20˚C). The adiabatic psychrometer coefficient, γ, is a measure of the increase in water vapour pressure in air in exchange for a 1 ˚C decrease of air temperature. Its value is 0.67 hPa ˚C^{-1} at about 20 ˚C (footnote[7]). The slope of the saturated vapour pressure curve, Δ, has the same units as the psychrometer coefficient. Figure 9 shows the empirical saturated vapour pressure (e_s) curve. The fitted equation for e_s and its derivative ($de_s/dT_s = \Delta$) are given too.



$$e_s = 6.11\, e^{\{(17.47 T_S)/(239+T_S)\}}$$

fitted equation to the empirically determined saturated vapour pressure curve in hPa.

$$\Delta = \frac{4175.3\left(6.11\, e^{\{(17.47 T_S)/(239+T_S)\}}\right)}{(239+T_s)^2}$$

$$= e_s \frac{4175.3}{(239+T_s)^2}$$

first derivative of the saturated vapour pressure curve, i.e. the slope $de_s/dT_s = \Delta$ in hPa ˚C^{-1}.

Figure 9. Empirical relationship between temperature, T (T_s: temperature for water vapour saturated air), and saturated vapour pressure, e_s, (left y-axis, hPa) and saturated vapour concentration (right y-axis, g m^{-3}). The ratio between the actual vapour pressure in air, e_a, and the value at saturation, e_s, at a certain temperature, reflects the relative air humidity, RH. The difference between e_s and e_a is the vapour pressure deficit (VPD).
Example: at 15˚C: $RH = e_a/e_s$=1, VPD = 0; at 30˚C: $RH = e_a/e_s$=18/42=0.43, VPD = 24 hPa.

Eq. (17) shows that to evaporate water, energy is needed, the term with R_{net}, and removal of the produced vapour is needed, the term E_{air} or the drying power term.

Drying power term Transpiration of water from a leaf and evaporation of water from a soil surface are diffusion processes that can, in principle, be described by: diffusion flux = (gradient in vapour concentration) / (resistance), or formally, for leaves,

[7] Approximately 2450 J is needed to vaporize 1 g of water (λ), while the volumetric heat capacity of air is 1200 J m^{-3}˚C^{-1}. This means that about 0.5 g of water can be added to the air as vapour in exchange for a temperature decrease of 1 ˚C of that same air. According to the gas law, 0.5 g water per m^3 of air corresponds to a pressure of 67 Pa at a temperature of 20 ˚C ($P = c\,R\,T\,/\,M_{H2O}$, with P: Pa; c: g m^{-3}; R: 8.3142 Pa m^3 mol^{-1} K^{-1} (universal gas constant); T temperature in K; M_{H2O} molecular weight of water, g mol^{-1}).

$$E_{air-leaves} = \frac{[\mathrm{H_2O}]_{int} - [\mathrm{H_2O}]_{ext}}{r_s + r_b} \tag{18}$$

where $E_{air\text{-}leaves}$ is the actual transpiration rate in g H_2O m^{-2} leaf s^{-1}; $[H_2O]_{int}$ vapour concentration inside the stomatal cavity in g H_2O m^{-3} air; $[H_2O]_{ext}$ vapour concentration in the open air in g H_2O m^{-3} air; r_s stomatal resistance to water vapour in s m^{-1}; and r_b the boundary layer resistance to water vapour in s m^{-1}, Figure 10.

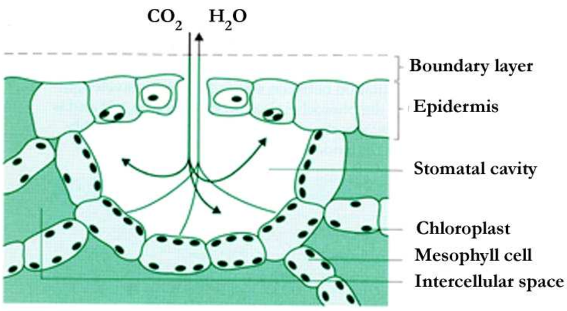


Figure 10. A portion of a leaf showing a stomatal cavity, the exchange processes of CO_2 and H_2O and the boundary layer above the leaf surface.

Equation (18) shows that the transpiration rate is proportional to the vapour concentration difference between the stomatal cavity and the open air, ($[H_2O]_{int}$ – $[H_2O]_{ext}$), and a conductivity, which is the inverse of the sum of the resistances (r_s + r_b). Since the air inside the stomatal cavity is practically saturated with water vapour (relative humidity near 100%), it is the drying power of the air, through its lower water vapour concentration, that determines the gradient. The difference ($e_s – e_a$) is a measure for this gradient in the Penman equation, whereas the boundary layer resistance is determined by an empirical wind function: a stronger wind will diminish the boundary layer and the resistance r_b will decrease (or: the conductivity will increase). The stomatal resistance is actively regulated, whereas the boundary layer thickness depends on the mixing of air around the leaves. Therefore, wind speed affects the boundary layer thickness and will also remove the water vapour that has evaporated, thus affecting the gradient. The aerodynamic component in Eq. (17), E_{air}, may now be defined as

$$E_{air} = (e_s - e_a)\ 0.643\ (1 + 0.54\ wn) \tag{19}$$

The term 0.643 (1 + 0.54 *wn*) is the wind function, f(u), with wind speed *wn* in m s^{-1} measured at a standard height of 2 meter, that originates from Penman (cf. Valiantzas, 2006)[8] and applies to short, closed grass crops. The unit of f(u) is MJ m^{-2} d^{-1} hPa^{-1}.

Radiation power term The energy to evaporate water is supplied by incident global short wave radiation, R_s. About 98% of the radiation emitted by the sun is in the waveband from 300-3000 nm (short-wave radiation). All incident radiation, composed of ultra-violet radiation (UV; 300-400 nm), photosynthetically active radiation (PAR; 400-700 nm) and near-infrared radiation (NIR; 700-3000 nm), is an energy source for

[8] We will see that the value 2.63 is used in the wind function of LINTUL2, rather than the value 0.643. Dividing 0.643 by the heat of vaporization, λ, however, yields 0.263, so λ is incorporated in the wind function of LINTUL2. In Eq. (19), e_s and e_a are expressed in hPa, whereas in LINTUL2 these variables are expressed in kPa, hence the factor 10 to convert f(u) in MJ m^{-2} d^{-1} hPa^{-1} to MJ m^{-2} d^{-1} kPa^{-1}.

evaporation. For crop growth modelling purposes, it is generally assumed that both PAR and NIR have equal shares of about 50% in the total spectrum, thus ignoring the small amount of UV (about 4%). In the near-infrared region of the spectrum most of the radiation is scattered by leaves. Reflection and transmission share their portion rather equally, Table 1. The reflection of NIR reduces the heat load from wavelengths that

Table 1. Absorbed, reflected and transmitted radiation (in %) by a leaf as a function of wave length.

Spectral range	Absorbed	Reflected	Transmitted
PAR	80	10	10
NIR	20	40	40
50% PAR + 50% NIR	50	25	25

are not used for CO_2-assimilation. As a result, only about 50% of the incident global radiation is absorbed by a single green leaf. The extinction coefficient for total global radiation is 0.5 (compare with k=0.7 for PAR alone). We will need this figure when we have to calculate the partitioning of radiation over soil evaporation and canopy transpiration (next section).

A part of the incoming global radiation is reflected by soil and canopy, usually denoted as albedo (α) in the literature. Table 2 lists some albedo values for different surfaces.

Table 2. Approximate albedo values (in %) for different surfaces.

Grass (a cut lawn)	forest	soil	desert soil (sand, no organic matter)	water surface
25	10	10	30	5

The amount of radiation that will be left from the incoming global radiation after reflection is $(1 - \alpha)\, R_s$. The albedo could be calculated from a soil part and a canopy part, depending on the *LAI*. This has been done in the SUCROS2 model (van Laar *et al.*, 1997). In LINTUL2, a simpler approach of fixed values for soil and canopy reflection was chosen, however [9].

In the far-infrared region of the spectrum (between 3000 and 30.000 nm) surfaces behave like black bodies that not only absorb all incident long-wave radiation, but also emit radiation. This emitted so-called thermal long-wave radiation is higher than the amount received which means that less energy is left for evapotranspiration, Eq. (20):

$$R_{net} = (1 - \alpha)\, R_s - R_{netl} \tag{20}$$

where R_{netl} is the net outgoing long wave radiation in MJ m^{-2} d^{-1}. Any surface above the absolute minimum temperature (–273.15 ˚C or 0 K) emits thermal radiation, proportional to the fourth power of the absolute temperature according to the law of Stefan-Boltzmann, Eq. (21):

$$R_{netl} = \sigma\, (273.15 + T)^4 \tag{21}$$

where σ is the Stefan-Boltzmann constant 5.668 10^{-8} W m^{-2} K^{-4} or 4.897 10^{-9} MJ d^{-1} m^{-2} K^{-4}. Since the earth with its vegetation at terrestrial temperatures is warmer than the sky outside the troposphere, there is a net

[9] A comparison of both methods to calculate the effect of the albedo reveals a small numerical difference only.

upward flux of long-wave radiation. This flux is larger under clear than under overcast skies, as clouds with temperatures approaching those at earth, are (downward) radiating surfaces too (Chang, 1968, p.166). This effect is not taken into account here, because, besides the global radiation, also the number of sunshine hours would have to be known. The outgoing long wave radiation is, however, corrected for the relative air humidity by a modified Brunt (1932) formula: max{ 0. , 0.55 (1 – e_a / e_s) }. Combining Eqs. (20) and (21) with the modified Brunt formula gives the expression for the net radiation:

$$R_{net} = (1-\alpha)\, R_s - \sigma\, (273.15 + T)^4 \max\{ 0.\, ,\, 0.55\, (1 - e_a / e_s) \} \tag{22}$$

Potential evapotranspiration can now be calculated by combining Eqs. (19) and (22) with Eq. (17).

Use of the equations for the drying power term (Eq. 19) and the radiation power term (Eq. 22) in LINTUL2. The drying and radiation power terms of the Penman equation are expressed per unit ground area, and do not take account of the size of the canopy. We thus still need to quantify the weighing factors that partition total evaporative demand between soil and crop. This partitioning depends on the leaf area index of the crop. Radiation not intercepted by a small-sized canopy will reach the soil and contribute to potential soil evaporation. As stated already, the average extinction coefficient for visible and near-infrared radiation is about 0.5, so soil evaporation is weighed by a factor $e^{-0.5\,L}$ and crop transpiration by $(1 - e^{-0.5\,L})$. Equation (22) for the net radiation energy is first used to calculate the potential evaporation of bare soil and the potential transpiration for a fully closed canopy, because of their different albedo's:

$$R_{net\_soil} = (1 - 0.15)\, R_s - \sigma\, (273.15 + T)^4 \max\{ 0.\, ,\, 0.55\, (1 - e_a / e_s) \} \tag{22a}$$

$$R_{net\_canopy} = (1 - 0.25)\, R_s - \sigma\, (273.15 + T)^4 \max\{ 0.\, ,\, 0.55\, (1 - e_a / e_s) \} \tag{22b}$$

where α = 0.15 and α = 0.25 are albedo values for soil and canopy, respectively.

Equation (19) for the drying power term is applied to both soil and canopy, because both surfaces may be considered as having a relative humidity of one (*RH* = 1) in their pores: stomata under normal conditions contain water with a saturated vapour pressure; soil pores at a suction of even pF=4 have still a relative humidity of 99.3 % (Koorevaar *et al.*, 1983). Clearly, possible effects of mulching or soil crust formation on evaporation are not considered here. Equation (17) can now be used to calculate *ET* for soil (Eq. 17a) and crop (Eq. 17b), while using the weighing factors according to the leaf area index, *L*:

$$ET_{\mathrm{soil}} = \mathrm{e}^{(-0.5\,L)} \left\{ \frac{\Delta}{\Delta+\gamma} \frac{R_{net\_soil}}{\lambda} + \frac{\gamma}{\Delta+\gamma} \frac{E_{air}}{\lambda} \right\} \tag{17a}$$

When leaves are wet, transpiration of water from the stomata is delayed. Therefore, potential transpiration rate is reduced by half the amount of intercepted rain (as the average of values 0.3 - 1.0 reported by Singh & Sceicz (1979)).

$$ET_{\mathrm{crop}} = \max\left[0\, ,\, \mathrm{e}^{(1-0.5\,L)} \left\{ \frac{\Delta}{\Delta+\gamma} \frac{R_{net\_canopy}}{\lambda} + \frac{\gamma}{\Delta+\gamma} \frac{E_{air}}{\lambda} \right\} - 0.5\, R_{\mathrm{int}} \right] \tag{17b}$$

Actual evaporation The actual transpiration was seen to be calculated from $T_{act} = T_{red\text{-}tran}\, ET_{crop}$, where $T_{red\text{-}tran}$ is read from Figure 4. Transpiration completely ceases at the water content at wilting point, θ_{wp}.

Actual evaporation, E_{act}, however, can continue till the air-dry water content in the soil, θ_{ad}, according to Figure 11.

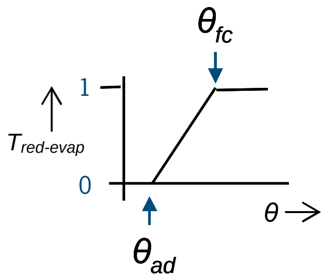


Figure 11. The evaporation reduction factor ($T_{red\text{-}evap}$, y-axis) as a function of water content (θ, x-axis) between the water contents at field capacity (θ_{fc}) and at air dry (θ_{ad}). Below θ_{fc} evaporation reduction takes place.

The evaporation reduction factor, $T_{red\text{-}evap}$ is defined as E_{act} / ET_{soil}, from which E_{act} is calculated for use in e.g. Eq. (11).

This model description is concluded with a summary of some important corresponding abbreviations used in the mathematical description on the one hand and in the program description on the other hand: Table 3.

Table 3. Some important corresponding abbreviations in the mathematical description and in the program description.

Mathematical abbreviation	*Description*	*Unit*	*Program abbreviation*
ET	Potential evapotranspiration of the crop–soil system as a whole	kg H_2O m^{-2} d^{-1} or mm H_2O d^{-1}	No separate variable
ET_{crop}	Potential transpiration crop	kg H_2O m^{-2} d^{-1}	*PTRAN*
ET_{soil}	Potential evaporation soil	kg H_2O m^{-2} d^{-1}	*PEVAP*
T_{act}	Actual transpiration crop	kg H_2O m^{-2} d^{-1}	*TRAN*
E_{act}	Actual evaporation soil	kg H_2O m^{-2} d^{-1}	*EVAP*
$T_{red\text{-}tran}$	Transpiration reduction factor	–	*TRANRF* Also FR in subroutine EVAPTR.
$T_{red\text{-}evap}$	Evaporation reduction factor	–	No separate variable, but calculated by LIMIT(0. , 1. , (*WC–WCAD*) / (*WCFC–WCAD*)) in subroutine EVAPTR)

Explanation of the simulation program

Computer code that is specific for LINTUL2 is typed in **boldface**.

```
DEFINE_CALL GLA(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,   ...
                INPUT,INPUT,INPUT,INPUT,INPUT,                   OUTPUT)
DEFINE_CALL PENMAN(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,   OUTPUT,OUTPUT)
DEFINE_CALL EVAPTR(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,INPUT,                     OUTPUT,OUTPUT)
DEFINE_CALL DRUNIR(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,INPUT,              OUTPUT,OUTPUT,OUTPUT)

TITLE LINTUL2
```

1. INITIAL CONDITIONS AND RUN CONTROL

```
INITIAL

*     Initial conditions
INCON ZERO = 0.; ROOTDI = 0.1
      WLVI = LAII / SLA
      WAI  = 1000. * ROOTDI * WCI
```

In addition to the statements explained in LINTUL1, some extra initial conditions are specified. ROOTDI (m) is rooting depth at the time of crop emergence. The initial soil water level in the root zone (WAI, kg water m^{-2} ground area, also expressed more briefly as 'mm') is calculated by multiplying the rooted volume (1000. * ROOTDI) with the initial soil water content (WCI, m^3 water m^{-3} soil).

```
*     Run control
FINISH TSUM > 2080.
TIMER STTIME = 1.; FINTIM = 200.; DELT = 1.; PRDEL = 5.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT LAI, WSOTHA, WSO, WST, WLV, WRT, TSUM, DAVTMP, DTR, ...
      ROOTD, TRAN, EVAP, TRANRF, WA, WC
```

2. ENVIRONMENTAL DATA AND TEMPERATURE SUM

```
DYNAMIC

WEATHER WTRDIR='C:\SYS\WEATHER\'; CNTR='IT'; ISTN=3; IYEAR=1985
*     Reading weather data from weather file:
*     RDD     Daily global radiation      J/(m2*d)
*     TMMN    Daily minimum temperature   degree C
*     TMMX    Daily maximum temperature   degree C
*     VP      Vapour pressure             kPa
*     WN      Wind speed                  m/s
*     RAIN    Precipitation               mm

DTR    = RDD/1.E+6
DAVTMP = 0.5 * (TMMN + TMMX)
DTEFF  = MAX ( 0., DAVTMP-TBASE )
EMERG = MAX ( REAAND(TIME-DOYEM+1.,WC-WCWP), INSW(-LAI,1.,0.) )
TSUM   = INTGRL(ZERO, RTSUM)
RTSUM  = DTEFF*EMERG
```

From the weather file additional data are required for modelling the water balance of crop and soil: daily values of vapour pressure (VP, kPa), wind speed (WN, m s^{-1}) and precipitation (RAIN, mm d^{-1}). Emergence of the crop takes place when the emergence date is reached (TIME=DOYEM) and enough water is available in the soil (WC>WCWP). The variable EMERG equals one from the day of emergence, this variable is used here to start the calculation of temperature sum accumulation (RTSUM).

3. LEAF GROWTH AND SENESCENCE

```
CALL GLA( TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,...
```

```
          TRANRF,WC,WCWP,...
          GLAI)
GLV   = FLV * GTOTAL

DLAI  = LAI * RDR
RDR   = MAX(RDRDV, RDRSH)
RDRDV = INSW(TSUM-TSUMAN, 0., AFGEN(RDRT, DAVTMP))
RDRSH = LIMIT(0., RDRSHM, RDRSHM * (LAI-LAICR) / LAICR)
DLV   = WLVG * RDR

RLAI  = GLAI - DLAI
LAI   = INTGRL(ZERO, RLAI)
```

In the Subroutine GLA two changes are made compared to the LINTUL1-version. First, crop emergence is delayed when the soil water content (WC, $m^3 m^{-3}$) is below the level at which - in this soil type - wilting occurs (WCWP, $m^3 m^{-3}$). Second, leaf area growth is slowed down when the crop suffers from drought. The severity of the drought is measured by the 'transpiration reduction factor' (TRANRF, -), i.e. the ratio of actual and potential transpiration calculated in Section 6.

4. LIGHT INTERCEPTION AND TOTAL CROP GROWTH RATE

```
PARINT = 0.5 * DTR    * (1. - EXP(-K*LAI))
GTOTAL = LUE * PARINT * TRANRF
```

Total crop growth rate (GTOTAL g $m^{-2} d^{-1}$) is decreased by drought in the same way as leaf area growth: directly proportional to the ratio of actual and potential transpiration (TRANRF, -: see Section 6).

5. GROWTH RATES AND DRY MATTER PRODUCTION OF PLANT ORGANS

```
FRTWET = AFGEN( FRTTB, TSUM )
FRTMOD = MAX( 1., 1./(TRANRF+0.5) )
FRT    = FRTWET * FRTMOD
FSHMOD = (1.-FRT) / (1.-FRT/FRTMOD)
FLV    = AFGEN( FLVTB, TSUM ) * FSHMOD
FST    = AFGEN( FSTTB, TSUM ) * FSHMOD
FSO    = AFGEN( FSOTB, TSUM ) * FSHMOD

WLVG   = INTGRL( WLVI, RWLVG)
WLVD   = INTGRL( ZERO, DLV  )
WST    = INTGRL( ZERO, RWST )
WSO    = INTGRL( ZERO, RWSO )
WRT    = INTGRL( ZERO, RWRT )
WLV    = WLVG + WLVD
RWLVG  = GTOTAL * FLV - DLV
RWST   = GTOTAL * FST
RWSO   = GTOTAL * FSO
RWRT   = GTOTAL * FRT
```

Allocation of biomass to the various organs (FRT, FLV, FST, FSO) depends, as in LINTUL1, on the temperature sum, but severe water stress (TRANRF < 0.5) leads to increased investment in roots (FRTMOD becomes greater than 1) and reduced allocation to the shoot organs (FSHMOD < 1).

```
RROOTD = RRDMAX * INSW( WC-WCWP, 0., 1. )    * ...
         REAAND( ROOTDM-ROOTD, TSUMAN-TSUM ) * EMERG
ROOTD  = INTGRL( ROOTDI, RROOTD)
```

The length of fibrous roots can vary strongly without much dependence on root weight. Hence, rooted depth is calculated independently of the growth of root mass. The rate at which the rooted depth increases varies between 10 and 30 mm d^{-1} depending on soil and crop characteristics. For spring wheat a value of 12 mm d^{-1} is common (RROOTD = 0.012 m d^{-1}; van Keulen & Seligman, 1987). Root growth generally stops around flowering (TSUM = TSUMAN), but earlier if the soil becomes too dry (WC < WCWP) or if the simulated cultivar has reached its maximum depth for the particular soil type (ROOTDM, m).

6. SOIL WATER BALANCE

```
EXPLOR = 1000. * RROOTD * WCFC
RNINTC = MIN( RAIN, 0.25*LAI )
CALL PENMAN( DAVTMP,VP,DTR,LAI,WN,RNINTC, ...
              PEVAP,PTRAN)
CALL EVAPTR( PEVAP,PTRAN,ROOTD,WA,WCAD,WCWP,WCFC,WCWET,WCST,...
             TRANCO,DELT,...
             EVAP,TRAN)
TRANRF = TRAN / NOTNUL(PTRAN)
CALL DRUNIR( RAIN,RNINTC,EVAP,TRAN,IRRIGF,...
             DRATE,DELT,WA,ROOTD,WCFC,WCST,...
             DRAIN,RUNOFF,IRRIG)
RWA = (RAIN+EXPLOR+IRRIG) - (RNINTC+RUNOFF+TRAN+EVAP+DRAIN)
WA  = INTGRL( WAI,RWA)
WC  = 0.001 * WA/ROOTD
```

The amount of water in the soil root-zone (WA, mm) varies continuously because of several processes that add or remove water. Water can be added by rain (RAIN, mm d^{-1}), part of which may be prevented from reaching the soil due to interception by the canopy (RNINTC, mm d^{-1}). Water may be added by irrigation (IRRIG, mm d^{-1}), and the crop can gain access to additional water by exploring new soil layers by root depth growth (EXPLOR, mm d^{-1}), assuming that deeper soil layers are at field capacity. Water can be removed by runoff from the soil surface or by drainage below the root-zone if more water is added than the soil can keep (RUNOFF, DRAIN, mm d^{-1}). Finally, water is lost by evaporation from the soil surface and by transpiration from the canopy (EVAP, TRAN, mm d^{-1}). Below we will discuss most of these processes in more detail.

6.1. Rain and interception of rain

The amount of rainfall intercepted by the canopy (RNINTC, mm d^{-1}) equals the interception capacity of leaves (0.25 mm d^{-1}) times the leaf area index (LAI). Obviously, this maximum amount can only be intercepted if rainfall intensity (`RAIN`, mm d^{-1}) is higher, hence the use of the `MIN` function. It is assumed that each new day with rain, this interception may take place, or, differently stated, that at the start of a new day the leaves are dry again.

6.2. Drainage, runoff and irrigation

Rates of water drainage, runoff and irrigation (`DRAIN`, `RUNOFF` and `IRRIG`, mm d^{-1}) are calculated in the Subroutine `DRUNIR`.

Not all the water that reaches the surface infiltrates permanently into the soil, especially not during heavy rain. If more water enters the soil than can be retained at field capacity (`WC = WCFC`), the excess is drained below the root zone (`DRAIN`, mm d^{-1}). Drainage is limited by the maximum drainage rate of the subsoil (`DRATE`, mm d^{-1}). A high value implies complete drainage. A low value implies restricted drainage and waterlogged conditions may occur during wet periods. A zero value means no drainage at all (impermeable layer).

Runoff (`RUNOFF`, mm d^{-1}) occurs when drainage is insufficient to keep the soil water content below full saturation (`WC < WCST`).

LINTUL2 contains a facility for easy comparison of crop growth under drought with growth under optimal water supply. When the 'irrigation-factor' is set at unity (`IRRIGF = 1`), the model will simulate daily rates of irrigation (`IRRIG`, mm d^{-1}) that exactly keep the soil at field capacity (`WC = WCFC`). The default setting of the irrigation-factor is zero, implying rain-fed conditions.

6.3. Potential rates of evaporation and transpiration: the Penman equations

Transpiration is the loss of water from plants, and evaporation is the loss of water from the soil or from a free-water surface. Evapotranspiration is the term for the sum of transpiration and evaporation from a crop-soil system. Penman (1948) was the first to describe evapo-transpiration in physical-mathematical terms. He derived equations that describe evaporation and transpiration from free-water surfaces, bare soil and low grass swards for 10-day periods. There is ongoing discussion in the literature whether his formulae are also applicable if daily values are used. If used with daily values, 24 hour average values should be used, as is done in the present model.

The values calculated according to the Penman equations are *potential* rates, i.e. without limitations with respect to the supply of liquid water to the evaporating surface. These 'Penman'-values for potential evaporation from the soil (`PEVAP`, mm d^{-1} or kg m^{-2} d^{-1}) and for potential transpiration from the crop (`PTRAN`, mm d^{-1}) are used as reference values, to which actual water demand is related.

The Penman equations are embodied in Subroutine `PENMAN`. The equations can most easily be understood if we consider evapotranspiration to be governed by two factors: radiation to supply the energy to vapourize water and air drying power to remove the vapour. The Penman-equations thus are written as the weighted sum of two terms, a radiation term (`PENMRS` and `PENMRC` for soil and crop, respectively, J m^{-2} d^{-1}) and a drying power term (`PENMD`, J m^{-2} d^{-1}).

The radiation term depends on net radiation (NRAD, J m^{-2} d^{-1}), the latent heat of evaporation (LHVAP equal to 2.4×10^6 J kg^{-1} at 30 °C with only a small temperature dependence) and a weighting factor (SLOPE/(SLOPE+PSYCH)) in which SLOPE (kPa $°C^{-1}$) is the tangent of the relation between saturated vapour pressure (kPa) and temperature (°C) and PSYCH (0.067 kPa $°C^{-1}$ at sea level) the psychrometer constant (Monteith, 1965). Net radiation is calculated as the balance between incoming short-wave radiation from the sun, (measured DTRJM2, J m^{-2} d^{-1}, minus 15 - 25% reflection) and net outgoing long-wave radiation (RLWN, J m^{-2} d^{-1}). RLWN increases with the temperature of the evaporating surface according to the Brunt (1932) formula, and decreases with vapour pressure in the atmosphere (VP, kPa).

The 'drying power' of the air decreases with air humidity (VP) and increases with wind speed (WN). The numerical values applied here refer to WN in m s^{-1}, measured at a standard height of 2 meter, and VP expressed in kPa. The wind function (WDF, kg m^{-2} d^{-1} kPa^{-1}) estimates the conductance for transfer of latent and sensible[10] heat from the surface to the standard height and depends on roughness of the surface and atmospheric stability. In this model, the wind function for short, closed grass crops is used (Penman, 1956).

The radiation and drying power terms of the Penman equations are expressed per unit ground area, and do not take the size of the canopy into account. We thus still need to quantify the weighing factors that partition evaporative demand between soil and crop. This depends on the leaf area index of the crop. Radiation not intercepted by a small-sized canopy will reach the soil and contribute to potential soil evaporation. The average extinction coefficient for visible and near infrared radiation is about 0.5, so soil evaporation is weighed by a factor $e^{-0.5\ LAI}$ and crop transpiration by $(1 - e^{-0.5\ LAI})$. Possible effects of mulching or soil crust formation on evaporation are not considered here.

When leaves are wet, transpiration of water taken up by the crop from the soil is delayed. Therefore, potential transpiration rate is reduced by half the amount of rain interception (as the average of values 0.3 - 1.0 reported by Singh & Sceicz (1979)).

6.4. Actual rates of evaporation and transpiration

The *actual* rates of evaporation and transpiration (EVAP and TRAN, respectively, mm d^{-1}) are calculated in Subroutine EVAPTR.

Both rates depend on their potential values (explained in the previous section), but also on soil water content (WC, m^3 m^{-3}) and soil characteristics. Four specific points of the soil water content - water potential relation (soil water characteristic or pF-curve) are needed: the volumetric water contents (m^3 H_2O m^{-3} soil) at saturation (WCST), at field capacity (WCFC), at wilting point (WCWP) and when air dry (WCAD).

Evaporation (EVAP) is important under incomplete soil cover, but is much lower than transpiration under a well developed crop canopy. Evaporation decreases when soil water content becomes lower than field capacity (WC < WCFC), but continues, albeit at a decreasing rate, until the soil is airdry (WC = WCAD).

[10] The term *latent* heat loss is reserved for the hidden loss of energy resulting from transpiration (or evaporation) of water from a surface. The term *sensible* heat loss refers to the warming up of leaves by absorbing radiation (Lövenstein, *et al.*, 1995).

Water in the crop provides only a small buffer between daily uptake and daily transpiration loss and their daily totals can be considered equal. Under ample water supply, the rate of water uptake by the crop follows the potential transpiration rate very closely. However, if the available water in the soil decreases below a critical level (`WC < WCCR`), uptake cannot meet the demand, and actual transpiration (`TRAN`, mm d^{-1}) becomes less than the potential rate and closing of stomata is observed. The critical soil water level (`WCCR`, m^3 m^{-3}) lies between the wilting point and field capacity (`WCWP < WCCR < WCFC`). The critical point is reached earlier, i.e. at higher water levels, when much water is needed by a high potential transpiration rate. `WCCR` also depends on crop characteristics expressed in the so-called ‘transpirational constant’ (`TRANCO`, mm d^{-1}). Too much water in the soil is also possible: when soil water content becomes too high (`WC > WCWET`), crop functioning including transpiration becomes hampered by waterlogging.

The degree to which actual transpiration falls below the potential rate is an indicator for the degree of water stress under which the crop grows. This is expressed in the transpiration reduction factor `TRANRF` `(=TRAN/PTRAN).`

7. FUNCTIONS AND PARAMETERS FOR SPRING WHEAT

```
*      Section 1
PARAM LAII = 0.012; SLA = 0.022; WCI = 0.23
*      Section 2
PARAM TBASE = 0.
*      Section 3
PARAM DOYEM = 32.
PARAM RGRL  = 0.009; LAICR = 4.
FUNCTION RDRT = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09, 50.,0.09
*      Section 4
PARAM LUE = 3.0; K = 0.6
*      Section 5
PARAM ROOTDM = 1.2
*      Partitioning tables for leaves (LV), stems (ST),
*      storage organs (SO) and roots (RT):
FUNCTION FRTTB =     0.,0.50,   110.,0.50,   275.,0.34,   555.,0.12, ...
      780.,0.07,  1055.,0.03,  1160.,0.02,  1305.,0.  ,  2500.,0.
FUNCTION FLVTB =     0.,0.33,   110.,0.33,   275.,0.46,   555.,0.44, ...
      780.,0.14,  1055.,0.  ,                            2500.,0.
FUNCTION FSTTB =     0.,0.17,   110.,0.17,   275.,0.20,   555.,0.44, ...
      780.,0.79,  1055.,0.97,  1160.,0.  ,               2500.,0.
FUNCTION FSOTB =     0.,0.  ,                                        ...
                  1055.,0.  ,  1160.,0.98,  1305.,1.  ,  2500.,1.

*      Section 6
PARAM WCAD   = 0.025; WCWP  = 0.075; WCFC   = 0.23
PARAM WCWET  = 0.35 ; WCST  = 0.40
PARAM TRANCO = 8.   ; DRATE = 50.  ; IRRIGF = 1.
END

* Start of rerun section
```

```
PARAM IRRIGF = 0.
END
PARAM IRRIGF = 1.; DOYEM = 60.
END
PARAM IRRIGF = 0.
END

STOP


* Start of Subroutines (see Sections 3 and 6)
* ---------------------------------------------------------------------*
*  SUBROUTINE GLA                                                      *
*  Purpose: This subroutine computes daily increase of leaf area index *
*           (m2 leaf/ m2 ground/ d)                                    *
* ---------------------------------------------------------------------*
      SUBROUTINE GLA(TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,
     $               TRANRF,WC,WCWP,
     $               GLAI)
      IMPLICIT REAL (A-Z)
*---- Growth during maturation stage:
      GLAI = SLA * GLV
*---- Growth during juvenile stage:
      IF ((TSUM.LT.330.).AND.(LAI.LT.0.75))
     $   GLAI = LAI * (EXP(RGRL * DTEFF * DELT) - 1.) / DELT * TRANRF
*---- Growth at day of seedling emergence:
      IF ((TIME.GE.DOYEM).AND.(LAI.EQ.0.).AND.(WC.GT.WCWP))
     $   GLAI = LAII / DELT
*---- Growth before seedling emergence:
      IF (TIME.LT.DOYEM) GLAI = 0.
      RETURN
      END
```

```
* ---------------------------------------------------------------*
*  SUBROUTINE PENMAN                                              *
*  Purpose: Computation of the PENMAN EQUATION                    *
* ---------------------------------------------------------------*
      SUBROUTINE PENMAN(DAVTMP,VP,DTR,LAI,WN,RNINTC,
     $                  PEVAP,PTRAN)
      IMPLICIT REAL (A-Z)
      DTRJM2  =  DTR * 1.E6
      BOLTZM  =  5.668E-8
      LHVAP   =  2.4E6
      PSYCH   =  0.067
      BBRAD   =  BOLTZM * (DAVTMP+273.)**4 * 86400.
      SVP     =  0.611  * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
      SLOPE   =  4158.6 * SVP / (DAVTMP + 239.)**2
      RLWN    =  BBRAD  * MAX(0.,0.55*(1.-VP/SVP))
      NRADS   =  DTRJM2 * (1.-0.15) - RLWN
      NRADC   =  DTRJM2 * (1.-0.25) - RLWN
      PENMRS  =  NRADS  * SLOPE/(SLOPE+PSYCH)
      PENMRC  =  NRADC  * SLOPE/(SLOPE+PSYCH)
      WDF     =  2.63  * (1.0 + 0.54 * WN)
      PENMD   =  LHVAP  * WDF * (SVP-VP) * PSYCH/(SLOPE+PSYCH)
      PEVAP   =  EXP(-0.5*LAI) * (PENMRS + PENMD) / LHVAP
      PTRAN   =  (1.-EXP(-0.5*LAI)) * (PENMRC + PENMD) / LHVAP
      PTRAN   =  MAX( 0., PTRAN-0.5*RNINTC )
      RETURN
      END
* -------------------------------------------------------------------*
*  SUBROUTINE EVAPTR                                                  *
*  Purpose: To compute actual rates of evaporation and transpiration *
* -------------------------------------------------------------------*
      SUBROUTINE EVAPTR(PEVAP,PTRAN,ROOTD,WA,WCAD,WCWP,WCFC,WCWET,WCST,
     $                  TRANCO,DELT,
     $                  EVAP,TRAN)
      IMPLICIT REAL (A-Z)
      WC      =  0.001 * WA   / ROOTD
      WAAD    =  1000. * WCAD * ROOTD
      WAFC    =  1000. * WCFC * ROOTD
      EVAP    =  PEVAP * LIMIT( 0., 1., (WC-WCAD)/(WCFC-WCAD) )
      WCCR    =  WCWP + MAX( 0.01, PTRAN/(PTRAN+TRANCO) * (WCFC-WCWP) )
              IF (WC.GT.WCCR) THEN
                 FR = LIMIT( 0., 1., (WCST-WC)/(WCST-WCWET) )
              ELSE
                 FR = LIMIT( 0., 1., (WC-WCWP)/(WCCR-WCWP)  )
              ENDIF
      TRAN    =  PTRAN * FR
      AVAILF  =  MIN( 1., ((WA-WAAD)/DELT)/NOTNUL(EVAP+TRAN) )
      EVAP    =  EVAP * AVAILF
      TRAN    =  TRAN * AVAILF
      RETURN
      END
```

```
* ---------------------------------------------------------------*
*  SUBROUTINE DRUNIR                                             *
*  Purpose: To compute rates of drainage, runoff and irrigation *
* ---------------------------------------------------------------*

      SUBROUTINE DRUNIR(RAIN,RNINTC,EVAP,TRAN,IRRIGF,
     $                  DRATE,DELT,WA,ROOTD,WCFC,WCST,
     $                  DRAIN,RUNOFF,IRRIG)
      IMPLICIT REAL (A-Z)

      WC   = 0.001 * WA   / ROOTD
      WAFC = 1000. * WCFC * ROOTD
      WAST = 1000. * WCST * ROOTD

      DRAIN  = LIMIT( 0., DRATE, (WA-WAFC)/DELT +
     $               (RAIN - RNINTC - EVAP - TRAN)                  )
      RUNOFF = MAX( 0., (WA-WAST)/DELT +
     $               (RAIN - RNINTC - EVAP - TRAN - DRAIN)          )
      IRRIG  = IRRIGF * MAX( 0., (WAFC-WA)/DELT -
     $               (RAIN - RNINTC - EVAP - TRAN - DRAIN - RUNOFF) )

      RETURN
      END
```

REFERENCES

Briggs, L. J. & H. L. Shantz, 1914. Relative water requirements of plants. Journ. of Agr. Res. 3, 1-65.

Brunt, D., 1932. Notes on radiation in the atmosphere. I. Quarterly Journal of the Royal Meteorological Society 58: 349-420.

Chang, Jen-Hu, 1968. Climate and agriculture. An Ecological Survey. Aldine Publishing Company / Chicago, pp. 304.

Darcy, H., 1856. Les fontaines publique de la ville de Dijon. Dalmont, Paris, 647 pp. et 28 planches.

Gallagher, J.N. & P.V. Biscoe, 1978. Radiation absorption, growth and yield of cereals. Journal of Agricultural Science, Cambridge 91: 47-60.

Goudriaan, J. & H.H. van Laar, 1994. Modelling potential crop growth processes. Kluwer Academic Publishers, Dordrecht / Boston / London. pp. 238.

Howell, T.A., Evett, S.R. 2004. The Penman-Monteith method. Section 3 in Evapotranspiration: Determination of Consumptive Use in Water Rights Proceedings. Continuing Legal Education in Colorado, Inc. Denver, CO.

Van Keulen, H., 1975. Simulation of water use and herbage growth in arid regions. PhD dissertation, Simulation monographs, Pudoc Wageningen, pp.176.

Keulen, H. van & N.G. Seligman, 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation Monographs, Pudoc, Wageningen, pp. 310.

Keulen, H. van & J. Wolf, 1986. Modelling of agricultural production: weather, soils and crops. Pudoc, Wageningen. pp. 479. ISBN 90-220-0858-4.

Koorevaar, P., G. Menelik & C. Dirksen, 1983. Elements of Soil physics. Developments in soil Science 13. Elsevier – Amsterdam – Oxford. pp. 228.

Kraalingen, D.W.G. van, C. Rappoldt & H.H. van Laar, 1994. Appendix 5: The FORTRAN Simulation Translator (FST), a simulation language. In: J. Goudriaan & H.H. van Laar, Modelling potential crop growth processes. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 219-232.

Kraalingen, D.W.G. van & W. Stol, 1997. Evapotranspiration modules for crop growth simulation: Implementation of the algorithms from Penman, Makkink and Priestly-Taylor. The C.T. de Wit Graduate School for Production Ecology and the DLO Research Institute for Agrobiology and Soil Fertility. No.11, pp. 29 + 4 Appendixes.

Laar, H.H. van, J. Goudriaan & H. van Keulen, 1997. SUCROS97: Simulation of crop growth for potential and water-limited production situations, as applied to spring wheat. Quantitative Approches in Systems Analysis. The C.T. de Wit Graduate School for Production Ecology and the DLO Research Institute for Agrobiology and Soil Fertility. No.14, pp. 52 + 3 Appendixes.

Lövenstein, H., E.A. Lantinga, R. Rabbinge & H. van Keulen, 1995. Principles of production Ecology. Department of Theoretical Production Ecology and Centre for Agrobiological Research. pp. 121.

Magrin, G.O., A.J. Hall, S. Castellano & S.G. Meira, 1991. Rooting depth, growth cycle duration, and timing of the jointing stage in wheat: Traits that can contribute to early drought tolerance. In: 'Wheat for the Nontraditional, Warm Areas', by D.A. Saunders (Ed.), Mexico, D.F.: CIMMYT, p.509-515.

Monteith, J.L., 1965. Evaporation and environment. Proc. Symp. Society of Experimental Biology 19: 205-234.

Monteith, J.L., 1977. Cimate and the efficiency of crop production in Britain. Phil. Trans. R. Soc. Lond. B. 281: 277-294.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society A193: 120-145.

Penman, H.L., 1956. Evaporation: an introductory survey. Netherlands Journal of Agricultural Science 4: 9-29.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989. Simulation of ecophysiological processes of growth of several annual crops. Simulation Monographs 29, Pudoc, Wageningen, pp. 271.

Richards, L.A. 1931. Capillary conduction of liquids in porous mediums. Physics 1: 318-333.

Rijneveld, W, 1996. On Water Flow: Simulation of unsaturated flow with the tipping bucket model with special regard to the simulation of hysteresis and preferential flow. MSc thesis Theoretical Production Ecology, pp. 172.

Singh, B. & G. Sceicz, 1979. The effect of intercepted rainfall on the water balance of a hardwood forest. Water Resources Research 15: 131-138.

Sinclair, T.R. & Muchow, R.C., 1999. Radiation use efficiency. Adv. Agron. 65, 215-265.

Stroosnijder, L., 1982. Simulation of the soil water balance. In: Eds F.W.T. Penning de Vries & H.H. van Laar, Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen, pp. 175-193.

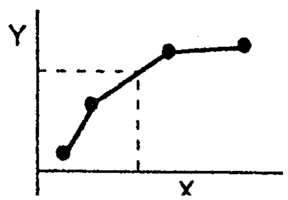
Valiantzas, J.D., 2006. Simplified versions for the Penman evaporation equation using routine weather data. Journal of Hydrology, Vol 331, issues 3-4: 690-702.

Wösten, J.H.M., G.J. Veerman, W.J.M. de Groot & J. Stolte, 2001. Waterretentie- en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: de Staringreeks. Alterra-rapport 153, ISSN 1566-7197, pp. 86.

SOME MAJOR SPECIFICS OF THE FST SIMULATION LANGUAGE.

For further details see FST lecture on https://portal.wur.nl/Courses/HPC21306_2007_3/default.aspx

Mathematical notation or graph	FST function
$y(t)=y(0)+\int_{0}^{t}\frac{dy(t)}{dt}dt$	`Y = INTGRL(YI , RY)` Integration command in the form of a function call. The algorithm of the numerical integration depends on the selected translation mode (Euler or Runge-Kutta). `Y` state variable `YI` initial value of Y `RY` rate of change of Y

	`Y = AFGEN(F , X)`
	Linear interpolation between (`x,y`) function points.
	`Y` result of interpolation, estimated `F(X)`
	`F` Table of `(X,Y)` values specified with a `FUNCTION` statement
	`X` value of independent variable
	
	In the `FUNCTION` statement, the `X` in the `(X,Y)` pairs must continuously increase, so in the definition
	`FUNCTION F = (X1,Y1),(X2,Y2),(X3,Y3),...`
	`(X4,Y4), (X5,Y5)`
	`X1 < X2 < X3 < X4 < X5`.

$\begin{Bmatrix} y=y_1, x<0 \\ y=y_2, x\geq 0 \end{Bmatrix}$	`Y = INSW(X, Y1, Y2)`
	Input switch. `Y` is set equal to `Y1` or `Y2` depending on the value of `X`.
	`Y` returned either as `Y1` or `Y2`
	`X` control variable
	`Y1` returned value of `Y`, if `X`<0
	`Y2` returned value of `Y`, if `X`≥0

$\begin{Bmatrix} y=x\ ,\ x_l \leq x \leq x_h \\ y=x_l,\ x<x_l \\ y=x_h,\ x>x_h \end{Bmatrix}$	`Y = LIMIT(Xl, Xh, X)`
	Limit function. `Y` is equal to `X`, but limited between `Xl` and `Xh`.
	`Y` returned as `X` bounded on [`Xl , Xh`]
	`Xl` lower bound of `X`
	`Xh` upper bound of `X`

y = max(*X1*, *X2*, *X3*, *X4*, . . . *Xn*)	`Y = MAX(X1, X2, X3, X4, . . . Xn)` Maximum function `Y` returned as the maximum value among the real arguments `X1, X2, . . . Xn`.
$y = e^x$	`Y = EXP(x)` Exponential function `Y` returned as e to the power of `x`.
Stop if TSUM > 2080	`FINISH TSUM > 2080` The program will stop if the `TSUM` reaches 2080 ˚Cd, even if the timer condition of FINishing TIMe (`FINTIM`) is not reached yet.

–	SUBROUTINE. SUBROUTINES contain calculations or decisions that may be executed from the computer program a number of times, by calling it via CALL SUBNAM, where SUBNAM is a specific name of the subroutine. Subroutines may output a number of calculated variables, but also just one. The GLA subroutine in LINTUL1 is an example of a subroutine with only one output, GLAI, calculated on the basis of a number of inputs.

–	WEATHER. The WEATHER statement is defined for example as
	`WEATHER WTRDIR='C:\WEATHER\'; . . .`
	`CNTR='NLD';ISTN=1; IYEAR=2007`
	where WTRDIR='C:\WEATHER\' defines the folder where the weather data file(s) are placed on the computer;
	CNTR is the country from which the weather originates, here the Netherlands (NLD);
	ISTN is the weather station, here 1 refers to Wageningen;
	IYEAR is the year in which the weather is recorded, here 2007.
	The data contained in the weather system comprises total daily global shortwave radiation (RDD, kJ m^{-2} d^{-1}); minimum and the maximum air temperature (TMMN; TMMX, ˚C); vapour pressure (VP, kPa) at 9 a.m.; average wind speed (WN, m s^{-1}); total daily rainfall (RAIN, mm d^{-1}); latitude of the site (LAT, degrees); longitude of the site (LONG, degrees); elevation of the site above sea level (ELEV, m); day number of the year (the time, DOY, d); and the year number (IYEAR; y).
	
	Note: the RDD values in the weather data files must be given in the units kJ m^{-2} d^{-1}. If these numbers are read by the weather system via the WEATHER line explained above, they are converted into the units J m^{-2} d^{-1}. This is done because J is the basic unit, rather than kJ.
	Because the LINTUL programs use MJ, e.g. LUE is expressed in g (DM) MJ^{-1}, the value of RDD is divided by 10^6 with the units J MJ^{-1}.

DEFINITIONS OF THE ABBREVIATIONS USED IN THE MODELS LINTUL1 AND LINTUL2

Name	Description	Units*
AVAILF	Effect of soil water status on evapotranspiration	-
BBRAD	Black body radiation	J m^{-2} d^{-1}
BOLTZM	Stefan-Boltzmann constant	J m^{-2} s^{-1} K^{-4}
CNTR	Country code for weather file	-
DAVTMP	Daily average temperature	°C
DELT	Time step of integration	d
DLAI	Death rate of leaf area index	m^2 m^{-2} d^{-1}
DLV	Death rate of leaves	g m^{-2} d^{-1}
DOYEM	Daynumber at crop emergence	d
DRAIN	Drainage rate below the root zone	mm d^{-1}
DRATE	Maximum drainage rate (soil characteristic)	mm d^{-1}
DRUNIR	FORTRAN subroutine to calculate DRAIN, RUNOFF and IRRIG	-
DTEFF	Daily effective temperature	°C
DTR	Daily global radiation	MJ m^{-2} d^{-1}
DTRJM2	Daily global radiation	J m^{-2} d^{-1}
EMERG	Auxiliary variable indicating crop emergence	-
EVAP	Rate of evaporation from the soil	mm d^{-1}
EVAPTR	FORTRAN subroutine to calculate EVAP and TRAN	-
EXPLOR	Exploration rate of new soil water layers by root depth growth	mm d^{-1}
FINTIM	Finish time of simulation run	d
FLV	Fraction of dry matter allocated to the leaves	-
FLVTB	Table of FLV as a function of TSUM	-
FR	Auxiliary variable in Subroutine EVAPTR	-
FRT	Fraction of dry matter allocated to the roots	-
FRTMOD	Relative modification of FRT by drought	-
FRTTB	Table of FRT as a function of TSUM	-
FRTWET	FRT at optimal water supply	-
FSHMOD	Relative modification of allocation to shoot by drought	-
FSO	Fraction of dry matter allocated to the storage organs	-
FSOTB	Table of FSO as a function of TSUM	-
FST	Fraction of dry matter allocated to the stems	-
FSTTB	Table of FST as a function of TSUM	-
GLA	FORTRAN subroutine to calculate GLAI	-
GLAI	Growth rate of leaf area index	m^2 m^{-2} d^{-1}
GLV	Growth rate of leaf dry matter	g m^{-2} d^{-1}
GTOTAL	Growth rate of total crop dry matter	g m^{-2} d^{-1}
IRRIG	Irrigation rate	mm d^{-1}
IRRIGF	Irrigation rate relative to the rate needed to keep the soil water status at field capacity (WC=WCFC)	-
ISTN	Weather station number	-
IYEAR	Year	-

K	Extinction coefficient for photosynthetically active radiation	-
LAI	Leaf area index	$m^2\ m^{-2}$
LAICR	Critical LAI beyond which leaves die due to self-shading	$m^2\ m^{-2}$
LAII	Initial leaf area index (at crop emergence)	$m^2\ m^{-2}$
LHVAP	Latent heat of vaporization	$J\ kg^{-1}$
LUE	Light use efficiency (dry matter produced per unit of intercepted photosynthetically active radiation)	$g\ MJ^{-1}$
NRADC	Net radiation absorption rate by the crop	$J\ m^{-2}\ d^{-1}$
NRADS	Net radiation absorption rate by the soil	$J\ m^{-2}\ d^{-1}$
PARINT	Intercepted photosynthetically active radiation	$MJ\ m^{-2}\ d^{-1}$
PENMAN	FORTRAN subroutine to calculate PEVAP and PTRAN	-
PENMD	Drying power term of the Penman equation	$J\ m^{-2}\ d^{-1}$
PENMRC	Radiation term of the Penman equation for transpiration from the canopy	$J\ m^{-2}\ d^{-1}$
PENMRS	Radiation term of the Penman equation for evaporation from the soil	$J\ m^{-2}\ d^{-1}$
PEVAP	Potential rate of evaporation from the soil	$mm\ d^{-1}$
PRDEL	Time interval for printing	d
PSYCH	Psychrometric constant	kPa $°C^{-1}$
PTRAN	Potential transpiration rate	$mm\ d^{-1}$
RAIN	Water input through rainfall	$mm\ d^{-1}$
RDD	Daily global radiation (weather file)	$J\ m^{-2}\ d^{-1}$
RDR	Relative death rate of leaves	d^{-1}
RDRDV	Relative death rate of leaves due to ageing	d^{-1}
RDRSH	Relative death rate of leaves due to shading	d^{-1}
RDRSHM	Maximum relative death rate of leaves due to shading	d^{-1}
RDRT	Table of RDR as a function of temperature	-
RGRL	Relative growth rate of LAI during exponential growth	$(°C\ d)^{-1}$
RLAI	Growth rate of LAI	$m^2\ m^{-2}\ d^{-1}$
RLWN	Net outgoing long-wave radiation	$J\ m^{-2}\ d^{-1}$
RNINTC	Interception of rain by the canopy	$mm\ d^{-1}$
ROOTD	Rooting depth	m
ROOTDI	Initial rooting depth (at crop emergence)	m
ROOTDM	Maximum rooting depth	m
RRDMAX	Maximum rate of increase in rooting depth	$m\ d^{-1}$
RROOTD	Rate of increase in rooting depth	$m\ d^{-1}$
RTSUM	Rate of increase of the temperature sum	°C
RUNOFF	Loss of water by runoff	$mm\ d^{-1}$
RWA	Overall rate of change of soil water amount	$mm\ d^{-1}$
RWLVG	Net rate of increase weight of green leaves	$g\ m^{-2}\ d^{-1}$
RWRT	Rate of increase weight of roots	$g\ m^{-2}\ d^{-1}$
RWSO	Rate of increase weight of storage organs	$g\ m^{-2}\ d^{-1}$
RWST	Rate of increase weight of stems	$g\ m^{-2}\ d^{-1}$
SLA	Specific leaf area	$m^2\ g^{-1}$
SLOPE	Change of saturation vapour pressure per °C	kPa $°C^{-1}$
STTIME	Start time of the simulation run	d
SVP	Saturation vapour pressure	kPa
TBASE	Base temperature	°C
TIME	Time from 1 January	d
TMMN	Daily minimum temperature (weather file)	°C

TMMX	Daily maximum temperature (weather file)	°C
TRAN	Rate of transpiration by the crop	mm d^{-1}
TRANCO	Transpiration constant (crop characteristic indicating the level of drought tolerance)	mm d^{-1}
TRANRF	Ratio of actual and potential transpiration (factor that accounts for reduced LUE because of water stress)	-
TSUM	Temperature sum	°C d
TSUMAN	Temperature sum at anthesis	°C d
VP	Vapour pressure of the air	kPa
WA	Actual amount of water in the soil	mm
WAAD	Water amount of the soil at air dryness	mm
WAFC	Water amount of the soil at field capacity	mm
WAI	Initial soil water amount (at start of the simulation run)	mm
WAST	Water amount in the soil at full saturation	mm
WCAD	Soil water content at air dryness	m^3 m^{-3}
WCCR	Critical soil water content for transpiration reduction due to drought	m^3 m^{-3}
WCFC	Soil water content at field capacity	m^3 m^{-3}
WCI	Initial soil water content (at start of the simulation run)	m^3 m^{-3}
WC	Actual soil water content	m^3 m^{-3}
WCST	Soil water content at full saturation	m^3 m^{-3}
WCWET	Critical soil water content for transpiration reduction due to waterlogging	m^3 m^{-3}
WCWP	Soil water content at wilting point	m^3 m^{-3}
WDF	Wind function in the Penman equation	kg m^{-2} d^{-1} kPa^{-1}
WLV	Dry weight of leaves	g m^{-2}
WLVD	Dry weight of dead leaves	g m^{-2}
WLVG	Dry weight of green leaves	g m^{-2}
WLVI	Initial dry weight of green leaves (at crop emergence)	g m^{-2}
WN	Wind speed	m s^{-1}
WRT	Dry weight of roots	g m^{-2}
WSO	Dry weight of storage organs	g m^{-2}
WSOTHA	Dry weight of storage organs	t ha^{-1}
WST	Dry weight of stems	g m^{-2}
WTRDIR	Weather directory	-
ZERO	Initial value used in integral statements	*same unit as state variable*

* mm water is equivalent to kg water m^{-2} ground area

PROGRAM LISTING LINTUL1

```
DEFINE_CALL GLA(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                INPUT,INPUT,                                     OUTPUT)

TITLE LINTUL1
*----------------------------------------------------------------------*
*  LINTUL, Light INTerception and UtiLization simulator               *
*          A simple general crop growth model, which simulates dry     *
*          matter production as the result of light interception and   *
*          utilization with a constant light use efficiency.           *
*  LINTUL1 is the version of LINTUL for optimal growing conditions.    *
*                                                                      *
*          Example for spring wheat                                    *
*                                                                      *
*  DLO-Research Institute for Agrobiology and Soil Fertility (AB-DLO)  *
*  Dept of Theor. Prod. Ecology, Wageningen Agric. Univ. (TPE-WAU)     *
*                                                                      *
*  Reference: Spitters, C.J.T. & A.H.C.M. Schapendonk, 1990.           *
*  Evaluation of breeding strategies for drought tolerance in potato   *
*  by means of crop growth simulation. Plant and Soil 123: 193-203.    *
*----------------------------------------------------------------------*

***   1. Initial conditions and run control

INITIAL

*     Initial conditions
INCON ZERO = 0.
      WLVI = LAII / SLA

*     Run control
FINISH TSUM > 2080.
TIMER STTIME = 1.; FINTIM = 601.; DELT = 1.; PRDEL = 10.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT LAI, WSOTHA, WSO, WST, WLV, WRT, TSUM, DAVTMP, DTR

***   2. Environmental data and temperature sum

DYNAMIC

WEATHER WTRDIR='C:\SYS\WEATHER\'; CNTR='IT'; ISTN=3; IYEAR=1985
*     Reading weather data from weather file:
*     RDD    Daily global radiation        J/(m2*d)
*     TMMN   Daily minimum temperature     degree C
*     TMMX   Daily maximum temperature     degree C

      DTR    = RDD/1.E+6
      DAVTMP = 0.5 * (TMMN + TMMX)
      DTEFF  = MAX(0., DAVTMP-TBASE )
      EMERG  = INSW(TIME-DOYEM, 0., 1.)
      TSUM   = INTGRL(ZERO, RTSUM)
      RTSUM  = DTEFF*EMERG

***   3. Leaf growth and senescence
```

```
      CALL GLA(TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,...
               GLAI)
      GLV   = FLV * GTOTAL

      DLAI  = LAI * RDR
      RDR   = MAX(RDRDV, RDRSH)
      RDRDV = INSW(TSUM-TSUMAN, 0., AFGEN(RDRT, DAVTMP))
      RDRSH = LIMIT(0., RDRSHM, RDRSHM * (LAI-LAICR) / LAICR)
      DLV   = WLVG * RDR

      RLAI  = GLAI - DLAI
      LAI   = INTGRL(ZERO, RLAI)

***   4. Light interception and total crop growth rate

      PARINT = 0.5 * DTR    * (1. - EXP(-K*LAI))
      GTOTAL = LUE * PARINT

***   5. Growth rates and dry matter production of plant organs

      FRT    = AFGEN( FRTTB, TSUM )
      FLV    = AFGEN( FLVTB, TSUM )
      FST    = AFGEN( FSTTB, TSUM )
      FSO    = AFGEN( FSOTB, TSUM )

      WLVG   = INTGRL( WLVI, RWLVG)
      WLVD   = INTGRL( ZERO, DLV  )
      WST    = INTGRL( ZERO, RWST )
      WSO    = INTGRL( ZERO, RWSO )
      WSOTHA = WSO / 100.
      WRT    = INTGRL( ZERO, RWRT )
      WLV    = WLVG + WLVD
      RWLVG  = GTOTAL * FLV - DLV
      RWST   = GTOTAL * FST
      RWSO   = GTOTAL * FSO
      RWRT   = GTOTAL * FRT

***   6. Functions and parameters for spring wheat

*     Section 1
PARAM LAII  = 0.012; SLA = 0.022

*     Section 2
PARAM TBASE = 0.

*     Section 3
PARAM DOYEM = 32.
PARAM RGRL  = 0.009; TSUMAN = 1110.; LAICR = 4.; RDRSHM = 0.03
FUNCTION RDRT = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09, 50.,0.09

*     Section 4
PARAM LUE = 3.0; K = 0.6

*     Section 5
*     Partitioning tables for leaves (LV), stems (ST),
*     storage organs (SO) and roots (RT):
```

```
FUNCTION FRTTB =     0.,0.50,   110.,0.50,   275.,0.34,   555.,0.12, ...
      780.,0.07,  1055.,0.03,  1160.,0.02,  1305.,0.  ,  2500.,0.
FUNCTION FLVTB =     0.,0.33,   110.,0.33,   275.,0.46,   555.,0.44, ...
      780.,0.14,  1055.,0.  ,                            2500.,0.
FUNCTION FSTTB =     0.,0.17,   110.,0.17,   275.,0.20,   555.,0.44, ...
      780.,0.79,  1055.,0.97,  1160.,0.  ,               2500.,0.
FUNCTION FSOTB =     0.,0.  ,                                        ...
                  1055.,0.  ,  1160.,0.98,  1305.,1.  ,  2500.,1.

***********************************************************************

END
PARAM DOYEM = 360.
END
PARAM DOYEM = 400.
END

STOP

* ----------------------------------------------------------------------*
*  SUBROUTINE GLA                                                        *
*  Purpose: This subroutine computes daily increase of leaf area index *
*           (ha leaf/ ha ground/ d)                                      *
* ----------------------------------------------------------------------*

      SUBROUTINE GLA(TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,
     $               GLAI)
      IMPLICIT REAL (A-Z)

*---- Growth during maturation stage:
      GLAI = SLA * GLV

*---- Growth during juvenile stage:
      IF ((TSUM.LT.330.).AND.(LAI.LT.0.75))
     $   GLAI = LAI * (EXP(RGRL * DTEFF * DELT) - 1.) / DELT

*---- Growth at day of seedling emergence:
      IF ((TIME.GE.DOYEM).AND.(LAI.EQ.0.))
     $   GLAI = LAII / DELT

*---- Growth before seedling emergence:
      IF (TIME.LT.DOYEM) GLAI = 0.

      RETURN
      END
```

PROGRAM LISTING LINTUL2

```
DEFINE_CALL GLA(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                INPUT,INPUT,INPUT,INPUT,INPUT,                  OUTPUT)
DEFINE_CALL PENMAN(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,   OUTPUT,OUTPUT)
DEFINE_CALL EVAPTR(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,INPUT,                     OUTPUT,OUTPUT)
DEFINE_CALL DRUNIR(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                   INPUT,INPUT,INPUT,              OUTPUT,OUTPUT,OUTPUT)

TITLE LINTUL2
*----------------------------------------------------------------------*
*  LINTUL, Light INTerception and UtiLization simulator                *
*          A simple general crop growth model, which simulates dry     *
*          matter production as the result of light interception and   *
*          utilization with a constant light use efficiency.           *
*  LINTUL2 is an extended version of LINTUL1 (the version of LINTUL    *
*          for optimal growing conditions). LINTUL2 includes a simple  *
*          water balance for studying effects of drought. The water    *
*          balance can be found in section 6 of the program, and the   *
*          effect of drought on light use efficiency in section 4.     *
*                                                                      *
*          Example for spring wheat                                    *
*                                                                      *
*  DLO-Research Institute for Agrobiology and Soil Fertility (AB-DLO)  *
*  Dept of Theor. Prod. Ecology, Wageningen Agric. Univ. (TPE-WAU)     *
*                                                                      *
*  Reference: Spitters, C.J.T. & A.H.C.M. Schapendonk, 1990.           *
*  Evaluation of breeding strategies for drought tolerance in potato   *
*  by means of crop growth simulation. Plant and Soil 123: 193-203.    *
*----------------------------------------------------------------------*

***   1. Initial conditions and run control
INITIAL

*     Initial conditions
INCON ZERO = 0.; ROOTDI = 0.1
      WLVI = LAII / SLA
      WAI  = 1000. * ROOTDI * WCI

*     Run control
FINISH TSUM > 2080.
TIMER STTIME = 1.; FINTIM = 601.; DELT = 1.; PRDEL = 10.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT LAI, WSOTHA, WSO, WST, WLV, WRT, TSUM, DAVTMP, DTR, ...
      ROOTD, TRAN, EVAP, TRANRF, WA, WC, ...
      PEVAP, PTRAN

***   2. Environmental data and temperature sum

DYNAMIC

WEATHER WTRDIR='C:\SYS\WEATHER\'; CNTR='IT'; ISTN=3; IYEAR=1985
*     Reading weather data from weather file:
*     RDD    Daily global radiation        J/(m2*d)
```

```
*      TMMN   Daily minimum temperature     degree C
*      TMMX   Daily maximum temperature     degree C
*      VP     Vapour pressure               kPa
*      WN     Wind speed                    m/s
*      RAIN   Precipitation                 mm
       DTR    = RDD/1.E+6
       DAVTMP = 0.5 * (TMMN + TMMX)
       DTEFF  = MAX ( 0., DAVTMP-TBASE )
       EMERG  = MAX ( REAAND(TIME-DOYEM+1.,WC-WCWP), INSW(-LAI,1.,0.) )
       TSUM   = INTGRL(ZERO, RTSUM)
       RTSUM  = DTEFF*EMERG

***    3. Leaf growth and senescence
       CALL GLA( TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,...
                 TRANRF,WC,WCWP,...
                 GLAI)
       GLV   = FLV * GTOTAL

       DLAI  = LAI * RDR
       RDR   = MAX(RDRDV, RDRSH)
       RDRDV = INSW(TSUM-TSUMAN, 0., AFGEN(RDRT, DAVTMP))
       RDRSH = LIMIT(0., RDRSHM, RDRSHM * (LAI-LAICR) / LAICR)
       DLV   = WLVG * RDR

       RLAI  = GLAI - DLAI
       LAI   = INTGRL(ZERO, RLAI)

***    4. Light interception and total crop growth rate
       PARINT = 0.5 * DTR    * (1. - EXP(-K*LAI))
       GTOTAL = LUE * PARINT * TRANRF

***    5. Growth rates and dry matter production of plant organs
       FRTWET = AFGEN( FRTTB, TSUM )
       FRTMOD = MAX( 1., 1./(TRANRF+0.5) )
       FRT    = FRTWET * FRTMOD
       FSHMOD = (1.-FRT) / (1.-FRT/FRTMOD)
       FLV    = AFGEN( FLVTB, TSUM ) * FSHMOD
       FST    = AFGEN( FSTTB, TSUM ) * FSHMOD
       FSO    = AFGEN( FSOTB, TSUM ) * FSHMOD

       WLVG   = INTGRL( WLVI, RWLVG)
       WLVD   = INTGRL( ZERO, DLV  )
       WST    = INTGRL( ZERO, RWST )
       WSO    = INTGRL( ZERO, RWSO )
       WSOTHA = WSO / 100.
       WRT    = INTGRL( ZERO, RWRT )
       WLV    = WLVG + WLVD
       RWLVG  = GTOTAL * FLV - DLV
       RWST   = GTOTAL * FST
       RWSO   = GTOTAL * FSO
       RWRT   = GTOTAL * FRT

       RROOTD = RRDMAX * INSW( WC-WCWP, 0., 1. ) * ...
                REAAND( ROOTDM-ROOTD, TSUMAN-TSUM ) * EMERG
       ROOTD  = INTGRL( ROOTDI, RROOTD)
```

```
***   6. Soil moisture balance
      EXPLOR = 1000. * RROOTD * WCFC
      RNINTC = MIN( RAIN, 0.25*LAI )
      CALL PENMAN( DAVTMP,VP,DTR,LAI,WN,RNINTC, ...
                   PEVAP,PTRAN)
      CALL EVAPTR( PEVAP,PTRAN,ROOTD,WA,WCAD,WCWP,WCFC,WCWET,WCST,...
                   TRANCO,DELT,...
                   EVAP,TRAN)
      TRANRF = TRAN / NOTNUL(PTRAN)
      CALL DRUNIR( RAIN,RNINTC,EVAP,TRAN,IRRIGF,...
                   DRATE,DELT,WA,ROOTD,WCFC,WCST,...
                   DRAIN,RUNOFF,IRRIG)
      RWA = (RAIN+EXPLOR+IRRIG) - (RNINTC+RUNOFF+TRAN+EVAP+DRAIN)
      WA  = INTGRL( WAI,RWA)
      WC  = 0.001 * WA/ROOTD

***   7. Functions and parameters for spring wheat

*     Section 1
PARAM WCI   = 0.23
PARAM LAII  = 0.012; SLA = 0.022
*     Section 2
PARAM TBASE = 0.
*     Section 3
PARAM DOYEM = 32.
PARAM RGRL  = 0.009; TSUMAN = 1110.; LAICR = 4.; RDRSHM = 0.03
FUNCTION RDRT = -10.,0.03, 10.,0.03, 15.,0.04, 30.,0.09, 50.,0.09
*     Section 4
PARAM LUE = 3.0; K = 0.6
*     Section 5
PARAM ROOTDM = 1.2; RRDMAX = 0.012
*     Partitioning tables for leaves (LV), stems (ST),
*     storage organs (SO) and roots (RT):
FUNCTION FRTTB =     0.,0.50,   110.,0.50,   275.,0.34,   555.,0.12, ...
      780.,0.07,  1055.,0.03,  1160.,0.02,  1305.,0.  ,  2500.,0.
FUNCTION FLVTB =     0.,0.33,   110.,0.33,   275.,0.46,   555.,0.44, ...
      780.,0.14,  1055.,0.  ,                            2500.,0.
FUNCTION FSTTB =     0.,0.17,   110.,0.17,   275.,0.20,   555.,0.44, ...
      780.,0.79,  1055.,0.97,  1160.,0.  ,               2500.,0.
FUNCTION FSOTB =     0.,0.  ,                                        ...
                  1055.,0.  ,  1160.,0.98,  1305.,1.  ,  2500.,1.
*     Section 6
PARAM WCAD = 0.025; WCWP = 0.075; WCFC = 0.23; WCWET = 0.35; WCST = 0.40
PARAM TRANCO = 8.; DRATE = 50.; IRRIGF = 1.

END
PARAM IRRIGF = 0.
END
PARAM IRRIGF = 1.; DOYEM = 360.
END
PARAM IRRIGF = 0.
END
PARAM IRRIGF = 1.; DOYEM = 400.
END
PARAM IRRIGF = 0.
END
STOP
```

```
* -------------------------------------------------------------------*
*  SUBROUTINE GLA                                                     *
*  Purpose: This subroutine computes daily increase of leaf area index *
*           (ha leaf/ ha ground/ d)                                   *
* -------------------------------------------------------------------*

      SUBROUTINE GLA(TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,
     $               TRANRF,WC,WCWP,
     $               GLAI)
      IMPLICIT REAL (A-Z)

*---- Growth during maturation stage:
      GLAI = SLA * GLV

*---- Growth during juvenile stage:
      IF ((TSUM.LT.330.).AND.(LAI.LT.0.75))
     $   GLAI = LAI * (EXP(RGRL * DTEFF * DELT) - 1.) / DELT * TRANRF

*---- Growth at day of seedling emergence:
      IF ((TIME.GE.DOYEM).AND.(LAI.EQ.0.).AND.(WC.GT.WCWP))
     $   GLAI = LAII / DELT

*---- Growth before seedling emergence:
      IF (TIME.LT.DOYEM) GLAI = 0.

      RETURN
      END

* -------------------------------------------------------------------*
*  SUBROUTINE PENMAN                                                  *
*  Purpose: Computation of the PENMAN EQUATION                        *
* -------------------------------------------------------------------*
      SUBROUTINE PENMAN(DAVTMP,VP,DTR,LAI,WN,RNINTC,
     $                  PEVAP,PTRAN)
      IMPLICIT REAL (A-Z)

      DTRJM2 = DTR * 1.E6
      BOLTZM = 5.668E-8
      LHVAP  = 2.4E6
      PSYCH  = 0.067

      BBRAD  = BOLTZM * (DAVTMP+273.)**4 * 86400.
      SVP    = 0.611 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
      SLOPE  = 4158.6 * SVP / (DAVTMP + 239.)**2
      RLWN   = BBRAD * MAX(0.,0.55*(1.-VP/SVP))
      NRADS  = DTRJM2 * (1.-0.15) - RLWN
      NRADC  = DTRJM2 * (1.-0.25) - RLWN
      PENMRS = NRADS * SLOPE/(SLOPE+PSYCH)
      PENMRC = NRADC * SLOPE/(SLOPE+PSYCH)

      WDF    = 2.63 * (1.0 + 0.54 * WN)
      PENMD  = LHVAP * WDF * (SVP-VP) * PSYCH/(SLOPE+PSYCH)

      PEVAP  =     EXP(-0.5*LAI)  * (PENMRS + PENMD) / LHVAP
      PTRAN  = (1.-EXP(-0.5*LAI)) * (PENMRC + PENMD) / LHVAP
      PTRAN  = MAX( 0., PTRAN-0.5*RNINTC )
```

```
      RETURN
      END

* -------------------------------------------------------------------*
*  SUBROUTINE EVAPTR                                                 *
*  Purpose: To compute actual rates of evaporation and transpiration *
* -------------------------------------------------------------------*
      SUBROUTINE EVAPTR(PEVAP,PTRAN,ROOTD,WA,WCAD,WCWP,WCFC,WCWET,WCST,
     $                  TRANCO,DELT,
     $                  EVAP,TRAN)
      IMPLICIT REAL (A-Z)

      WC   = 0.001 * WA   / ROOTD
      WAAD = 1000. * WCAD * ROOTD
      WAFC = 1000. * WCFC * ROOTD

      EVAP  = PEVAP * LIMIT( 0., 1., (WC-WCAD)/(WCFC-WCAD) )

         WCCR = WCWP + MAX( 0.01, PTRAN/(PTRAN+TRANCO) * (WCFC-WCWP) )
         IF (WC.GT.WCCR) THEN
             FR = LIMIT( 0., 1., (WCST-WC)/(WCST-WCWET) )
         ELSE
             FR = LIMIT( 0., 1., (WC-WCWP)/(WCCR-WCWP)  )
         ENDIF
      TRAN = PTRAN * FR

         AVAILF = MIN( 1., ((WA-WAAD)/DELT)/NOTNUL(EVAP+TRAN) )
      EVAP = EVAP * AVAILF
      TRAN = TRAN * AVAILF

      RETURN
      END

* -------------------------------------------------------------------*
*  SUBROUTINE DRUNIR                                                 *
*  Purpose: To compute rates of drainage, runoff and irrigation      *
* -------------------------------------------------------------------*
      SUBROUTINE DRUNIR(RAIN,RNINTC,EVAP,TRAN,IRRIGF,
     $                  DRATE,DELT,WA,ROOTD,WCFC,WCST,
     $                  DRAIN,RUNOFF,IRRIG)
      IMPLICIT REAL (A-Z)

      WC   = 0.001 * WA   / ROOTD
      WAFC = 1000. * WCFC * ROOTD
      WAST = 1000. * WCST * ROOTD

      DRAIN  = LIMIT( 0., DRATE, (WA-WAFC)/DELT +
     $               (RAIN - RNINTC - EVAP - TRAN)                 )

      RUNOFF =          MAX( 0., (WA-WAST)/DELT +
     $               (RAIN - RNINTC - EVAP - TRAN - DRAIN)         )

      IRRIG  = IRRIGF * MAX( 0., (WAFC-WA)/DELT -
     $               (RAIN - RNINTC - EVAP - TRAN - DRAIN - RUNOFF) )

      RETURN
      END
```

EXERCISES ON POTENTIAL AND WATER LIMITED CROP GROWTH AS CALCULATED BY LINTUL 1 & 2

to be inserted directly from the updated file Lintul-2exercises5Feb2009.pdf (5 pages)

HANDOUTS LECTURE:
EVAPOTRANSPIRATION & LINTUL2: WATER LIMITED CROP GROWTH