System description of the WOFOST 7.2 cropping systems model

Wageningen Environmental Research

May 2020

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History of modifications

Revision	Date	Author(s)	Description
1.0	2019-12-12	Allard de Wit	Initial release of WOFOST 7.2 documentation.
1.1	2020-05-14	Allard de Wit	Comments from Maurits van den Berg taken into account.

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Chapter 1

Introduction

1.1 About WOFOST

WOFOST is the acronym for WOrld FOod STudies and its purpose is to serve as a simulation model for cropping systems. The model thus simulates the growth of crops in interaction with their environment including weather, soil and agromanagement. The output of the WOFOST model includes the simulated total crop biomass and crop yield as well as variables like leaf area and crop water use.

WOFOST has been developed by Wageningen University and Research (and its predecessors) already since the 1980s. Currently, the model is maintained and improved by Wageningen University and Research in cooperation with the Joint Research Centre of the European Commission. Several implementations of the model are available which have been developed for both research and operational applications.

for a general introduction to the WOFOST model and an overview of the processes included in the model, see:

Wit, Allard de, Hendrik Boogaard, Davide Fumagalli, Sander Janssen, Rob Knapen, Daniel van Kraalingen, Iwan Supit, Raymond van der Wijngaart, and Kees van Diepen. *25 Years of the WOFOST Cropping Systems Model.* Agricultural Systems 168 (January 1, 2019): 154–67. [1]

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[1]https://doi.org/10.1016/j.agsy.2018.06.018

1.2   Levels of crop production

To be able to deal with the ecological diversity of agriculture, three hierarchical levels of crop growth can be distinguished: potential growth, limited growth and reduced growth. Each of these growth levels corresponds to a level of crop production: potential, attainable and reduced production

Potential production level
Potential production represents the production ceiling for a given crop when grown in a given area under specific weather conditions. It is determined by the crop's photosynthesis response to CO_2 and the temperature and solar radiation regimes during the growing season. In practice, this ceiling can only be reached with a high input of fertilizers, irrigation and thorough pest and weed control. In addition, crop establishment should be perfect, there should be no losses caused by traffic or grazing, and there should be no damage to the crop by wind, hail, frosts. Because potential yield is also determined by crop properties, yield potential varies over crop varieties and can be increased by breeding. In the computer model, potential yield depends on the choice of crop variety, sowing date and weather data set. Near-potential yield levels are realized on some arable and grassland farms in Western Europe, and sometimes in (glasshouse) horticulture. In these cases, the weather conditions and crop characteristics exclusively determine the potential growth rate. When the canopy fully covers the soil, the increase in biomass, expressed in dry matter, is typically between 150 and 350 kg ha^{-1} day^{-1}.

Attainable production level
At this production level the yield of the crop is limited by the availability of water and/or nutrients during a part or the complete growing season. In this scenario, the water-limited yield represents the maximum yield that can be obtained under rain-fed conditions but with optimal nutrient supply. The yield limiting effect of drought depends on the soil moisture availability as determined by the amounts of rainfall and evapotranspiration, and their distribution over the growing season, by soil type, soil depth and groundwater influence. The difference between potential and water-limited production indicates the production increase that could be achieved by irrigation. A special case of water-limited conditions is related to an excess of soil moisture, causing oxygen shortage for the plant roots. So oxygen limited production would be a more appropriate term. Its effect depends on soil properties and drainage measures and is difficult to quantify by modelling.

The nutrient limited production corresponds to a situation that water is not limiting but when nutrient availability is insufficient to cover the crop's de-

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mands, which is actually very common with N (also in cases when part of the fertiliser applied is lost through leaching, volatilisation or denitrification). Usually in (sub)-humid climates, the water-limited yield is higher than the nutrient-limited yield, so that yields can be increased by nutrient application without irrigation, but in cases of severe droughts the nutrient-limited yield may exceed the water-limited yield, and then water should be applied to increase yield.

Reduced production level
In this scenario the crop yield can be further reduced by factors such as pest, disease, competition with weeds and pollutants (ozone, salt or heavy metals). This yield level reflects what farmers actual harvest from their fields. The gaps between the different yield levels (yield gap) vary widely across the globe and finding approaches to close the yield gap is an area of ongoing research, see http://yieldgap.org

Reality rarely corresponds exactly to one of these growth/production levels, but it is useful to reduce specific cases to one of them, because this enables you to focus on the principal environmental constraints to crop production, such as light, temperature, water and the macro nutrients nitrogen (N), phosphorus (P) and potassium (K). Other factors can often be neglected because they do not influence the crop's growth rate (De Wit, 1986; Rabbinge and De Wit, 1989; Penning de Vries et al., 1989).

Note that the WOFOST 7.2 crop simulation model can be applied in the domain of potential crop production and production with a water shortage (potential and water-limited yield levels). To estimate nutrient limited production the output from WOFOST has often been coupled to the QUEFTS model (Jansen et al., 1990) which can estimate nutrient requirements and nutrient-limited yields. However, QUEFTS is not a dynamic simulation model but uses seasonal nutrient supply to estimate nutrient-limited yield. Therefore it is not regarded to be part of WOFOST.

1.3   Guide to this manual

This manual covers a detailed description of the processes of crop growth and water movement as they are implemented in WOFOST Version 7.2. First of all, ancillary calculations will be described including:

- derived meteorological variables

- reference evapotranspiration

- day length and solar elevation

- extraterrestrial radiation

Next, the different components of the crop simulation itself will be described in detail:

- Phenology

- Transpiration

- Assimilation:

  Gross photosynthesis rate

  Correction for suboptimal temperature

  Correction for water stress

- Maintenance respiration

- Growth of the crop:

  Net photosynthesis rate

  Growth respiration

  Partitioning

  Leaf growth and senescence

  Stems

  Roots

  Storage organs

Finally, the soil components are described. Currently, several water balance implementations are available for simulating the interaction between the soil and the crop.

1.4 Acronyms used

Throughout the document, important parameters and variables are described using mathematical symbols as well as the acronyms that are used in the WOFOST software code. For example the crop development stage $D_{s,t}$ is also denoted as **DVS**.

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Chapter 2

Ancillary calculations

2.1 Preparatory (weather) variables

The daily average temperature is calculated as the average of the daily minimum and the maximum temperature. This average temperature $\bar{T}$ is equal to the so called air temperature (T) used in the model calculations. The maximum and minimum temperatures are measured daily values or derived from other sources such as a weather forecasting model.

$$T = \frac{T_{\max} + T_{\min}}{2} \tag{2.1}$$

Where:

T	:	Average daily air temperature	[°C]
$T_{\max}$	:	Maximum temperature	[°C]
$T_{\min}$	:	Minimum temperature	[°C]

Similarly, the daytime average temperature can be estimated as:

$$T_{day} = \frac{T_{\max} + T}{2} \quad where \quad T = \frac{T_{\max} + T_{\min}}{2} \tag{2.2}$$

The difference between maximum and minimum temperature is used to calculate the empiric constant of the wind function in the Penman equation.

$$\Delta T = T_{\max} - T_{\min} \tag{2.3}$$

Where:

ΔT	:	Temperature difference	[°C]
T_{max}	:	Maximum temperature	[°C]
T_{min}	:	Minimum temperature	[°C]

As will be explained later in §2.3.1, the evaporative demand, EA, depends on the windspeed and the difference between saturated and actual vapor pressure. The windspeed dependency is incorporated in the evaporative demand as the windspeed measured at a height of two meters, and multiplied by an empirical coefficient (see also eq. 2.19). This coefficient is temperature dependent and can be calculated as (Frère, 1979):

$$BU = 0.54 + 0.35 \frac{\Delta T - 12}{4} \qquad for \quad \Delta T \geq 12°C \qquad (2.4)$$

$$BU = 0.54 \qquad for \quad \Delta T < 12°C$$

Where:

| BU | : | Empirical coefficient in the wind function | [-] |
| ΔT | : | Temperature difference | [°C] |

The air temperature can be used to calculate the latent heat of vaporization:

$$\lambda = 2.501 - (2.361 \cdot 10^{-3}) T \qquad (2.5)$$

Where:

| λ | : | Latent heat of vaporization | [MJ kg^{-1}] |
| T | : | Average daily temperature | [°C] |

As the value of the latent heat varies only slightly over normal temperature ranges a single value for λ may be taken. In the model for λ a value of 2.45 MJ kg^{-1} is assumed (T=20 °C). The barometric pressure at sea level is used to calculate the psychrometric constant at sea level (Brunt, 1932).

$$\gamma_o = \frac{C_p P_o}{\epsilon \lambda} 10^{-3} = 0.00163 P_{\frac{o}{\lambda}} \qquad (2.6)$$

Where:

γ_o	:	Psychrometric constant at sea level	$[\text{kPa } ^\circ\text{C}^{-1}]$
C_p	:	Specific heat of moist air = 1.013 10^{-3}	$[\text{MJ kg}^{-1} \, ^\circ\text{C}^{-1}]$
P_o	:	Atmospheric pressure at sea level	$[\text{kPa}]$
ϵ	:	Ratio molecule weight water vapor / dry air = 0.622	$[\,]$
λ	:	Latent Heat of vaporization	$[\text{MJ kg}^{-1}]$

In the model however, a fixed value of $\gamma_o = 0.67$ is assumed. This value can be obtained by using for P the atmospheric pressure at sea level, which is assumed to be 101.3 kPa and $\lambda = 2.45$ MJ kg^{-1}. It should be mentioned, that the barometric pressure changes with altitude, so does also the psychrometer constant. Therefore, the two following equations are used to correct for altitude difference.

$$P \;=\; P_o \, e^{\frac{-0.034\,z}{T+273}} \tag{2.7}$$

Where:

P	:	Atmospheric pressure at elevation z	$[\text{kPa}]$
P_o	:	Atmospheric pressure at sea level	$[\text{kPa}]$
T	:	Daily temperature	$[^\circ\text{C}]$
z	:	Elevation	$[\text{m}]$

$$\gamma \;=\; \gamma_o \, \frac{P}{P_o} \tag{2.8}$$

Where:

γ	:	Psychrometric constant at elevation z	$[\text{kPa } ^\circ\text{C}]$
γ_o	:	Psychrometric constant at sea level	$[\text{kPa } ^\circ\text{C}]$
P	:	Atmospheric pressure at elevation z	$[\text{kPa}]$
P_o	:	Atmospheric pressure at sea level	$[\text{kPa}]$

The saturated vapor pressure is related to the mean daily air temperature and may be approximated with the equation of Goudriaan (1977).

$$e_s \;=\; 0.610588 \cdot e^{\frac{17.32491\,T}{T+238.102}} \tag{2.9}$$

Where:

e_s	:	Saturated vapor pressure	$[\text{kPa}]$
T	:	Air temperature	$[^\circ\text{C}]$

From this equation the derivate, i.e. the slope of the saturated vapor pressure-temperature curve is established.

$$\Delta = \frac{238.102 \cdot 17.32491 \cdot e_s}{(T + 238.102)^2} \tag{2.10}$$

Where:

Δ	:	Slope of the saturation vapor pressure curve	$[\text{kPa} \, °\text{C}^{-1}]$
e_s	:	Saturated vapor pressure	$[\text{kPa}]$
T	:	Air temperature	$[°\text{C}]$

The measured vapor pressure is not allowed to exceed the calculated saturated vapor pressure.

2.2 Methods to estimate global radiation

In case no observations for the incoming solar radiation are available, the formula postulated by Ångström (1924) can be used to estimate this parameter using sunshine duration observations.

$$S_{g,d} = S_{o,d} \left(A + B \frac{n}{D} \right) \tag{2.11}$$

Where:

$S_{g,d}$	:	Incoming daily global solar radiation	$[\text{J m}^{-2} \, \text{d}^{-1}]$
$S_{o,d}$	:	Daily extra-terrestrial radiation (see eq. 2.27)	$[\text{J m}^{-2} \, \text{d}^{-1}]$
A	:	Empirical constant	[-]
B	:	Empirical constant	[-]
n	:	Bright sunshine hours per day	$[\text{hr}]$
D	:	Astronomical day length (see e.q. 2.30)	$[\text{hr}]$

It should be mentioned that the empirical constants A and B of the Ångström formula can be found with linear regression by comparing the incoming global radiation with the relative sunshine duration n/D, taking into consideration the daily extra-terrestrial radiation. A is the intercept and B the slope of the regression. It should also be mentioned that the regression constants A and B have a physical meaning. A can be considered as the fraction of extra terrestrial radiation on overcast days. The sum of A and B can be considered as the fraction of radiation received on clear days. For several regions in Europe the Ångström constants have been established by Supit (1994). Indicative values for empirical constants in the Ångström formula are depicted in Table 2.1.

It should be clear that the constants **A** and **B** should be provided by the user. As an alternative, the method developed by Supit (1994) can be applied. This

Table 2.1: Indicative values for empirical constants in the Ångström formula in relation to latitude and climate used by the FAO (Frère & Popov, 1979)

Zone	A	B
Cold and temperate zones	0.18	0.55
Dry tropical zones	0.25	0.45
Humid tropical zones	0.29	0.42

method calculates the incoming global radiation as a function of cloud cover and sunshine duration. It can be considered as an extension of the formula developed by Hargreaves (1985). Using this method, the accuracy of the results is slightly less in comparison to the results obtained with the Ångström formula.

$$S_{g,d} = c_a S_{o,d} \left(\sqrt{(T_{\max} - T_{\min})} + c_b \sqrt{(1 - Cloud/8)} \right) + c_c \qquad (2.12)$$

Where:

$S_{g,d}$	:	Incoming daily global solar radiation	[J m^{-2} d^{-1}]
$S_{o,d}$	:	Daily extra-terrestrial radiation (see eq. 2.27)	[J m^{-2} d^{-1}]
Cloud	:	Mean total cloud cover during daytime	[octas]
$T_{\max}$	:	Maximum temperature	[°C]
$T_{\min}$	:	Minimum temperature	[°C]
c_a, c_b, c_c	:	Empirical regression constants	[-]

For five regions in Europe the constants c_a, c_b and c_c have been established (Supit, 1994).

Finally, in case no observations of either incoming radiation, sunshine duration and cloudcover are available, this formula, will be used. The accuracy of this method is less then the accuracy of the two earlier mentioned methods.

$$S_{g,d} = c_d S_{o,d} \sqrt{(T_{\max} - T_{\min})} + c_e \qquad (2.13)$$

Where:

$S_{g,d}$	:	Incoming daily global solar radiation	[J m^{-2} d^{-1}]
$S_{o,d}$	:	Daily extra-terrestrial radiation (see eq. 2.27)	[J m^{-2} d^{-1}]
$T_{\max}$	:	Maximum temperature	[°C]
$T_{\min}$	:	Minimum temperature	[°C]
c_d, c_e	:	Empirical regression constants	[-]

For six regions in Europe the constants c_d and c_e have been established (Supit, 1994). In section 2.4 it is explained how the daily extra-terrestrial radiation,

$S_{o,d}$, can be calculated.

2.3   Reference evapotranspiration

Transpiration is the loss of water from the plants and evaporation is the loss of water from the soil or from a free-water surface. Evapotranspiration covers both transpiration and evaporation. The principal driving force for evaporation is the gradient of vapour pressure between the evaporating surface and the surrounding air. The vapour pressure at the evaporating surface is equal to the saturated vapour pressure at the prevailing temperature of that surface. The vapour pressure of the air is a function of the ambient temperature and its relative humidity. The rate of evaporation depends on the diffusion resistance between the evaporating surface and the air. The magnitude of the resistance is strongly related to wind speed. The two environmental variables, air humidity and wind speed combined determine the 'evaporative demand' of the air.

The problem in the approach above is that the temperature of the evaporating surface is usually not known from standard meteorological observations. Evaporation of 1 mm layer of water requires 2.45 MJ m^{-2} of energy and can therefore be described through quantification of an energy balance. The energy dissipation, required for evaporation, leads to cooling of the evaporating surface which reduces the vapour gradient. Hence, a driving force is required to maintain the corresponding surface temperature, and thus, maintain the vapour pressure gradient. The energy for this driving force is supplied by the net solar radiation received by the canopy and or soil. Net radiation is the balance between incoming (short-wave) radiation from the sun and radiation losses due to reflection and outgoing (long-wave) radiation.

Heat supplied by moving air is another source of energy, but this is usually negligible, except in situations where the vegetation is surrounded by extensive bare areas (oasis). Only 5-8% of incoming radiation is dissipated in photosynthesis, which is, therefore, disregarded here. Respiration yields an insignificant amount of energy. To simplify the treatment of evapotranspiration, it is considered to be governed by two factors: radiation and evaporative demand.

Penman (1948) was the first to describe evapotranspiration in physical mathematical terms. He calculated evaporation from free-water surfaces, wet bare soil and low grass swards for 10-day periods. The original Penman reference evapotranspiration has now been superseded by the Penman-Monteith reference evapotranspiration. The latter has a better physical basis and is standardized and promoted by the Food and Agriculture Organization. WOFOST

uses the Penman-Monteith equation to compute the crop reference evapotranspiration but still applies the older Penman approach as reference evapotranspiration for open water and bare soil. Moreover, the option to use the older Penman approach as reference evapotranspiration is still available in order to compare with historical studies.

The value calculated according to the Penmn and Penman-Monteith equations is the potential evapotranspiration $ET0$, i.e. without limitations with respect to the supply of liquid water to the evaporating surface. This $ET0$ value is often used as a reference value, to which actual crop water demand is related. To translate $ET0$ into crop water requirements, so called crop factors can be used (e.g. Doorenbos & Pruitt, 1977; Feddes *et al.*, 1978). See also §3.5.

Note that the equations used to compute $ET0$ provide the value in mm/day while internally this is converted into cm/day.

2.3.1 Terms in the Penman formula

The Penman formula (equation 2.14) consists of two segments. The first part, the radiative term, calculates the net absorbed radiation. The second part, the aerodynamic term, calculates the evaporative demand of the atmosphere (Choisnel *et al.*, 1992; Frère and Popov, 1979; Penman, 1956, 1948). The resulting equations are used to calculate the potential evaporation rates from a water surface, from bare soil surfaces and the potential evapotranspiration rate from a crop canopy.

$$ET0 \ = \ W \ R_{na} \ + \ (1 - W) \ E_a \qquad (2.14)$$

Where:

ET0	:	Evapo(transpi)ration	[mm d^{-1}]
W	:	Temperature related weighing factor	[-]
R$_{na}$	:	Net absorbed radiation in equivalent evaporation	[mm d^{-1}]
EA	:	Evaporative demand in equivalent evaporation	[mm d^{-1}]

The temperature related weighing factor W in equation 2.14 is defined as (Frère and Popov, 1979; Penman, 1948, 1956).

$$W \ = \ \frac{\Delta}{(\Delta + \gamma)} \qquad (2.15)$$

Where:

Δ : Slope of the saturation vapor pressure curve (see eq. $\quad$ [kPa $°C^{-1}$] 2.10)

γ : Psychrometric constant (see eq. 2.8) $\qquad$ [kPa C^{-1}]

To calculate net outgoing long wave radiation Penman (1956) used an equation which is derived from the formula postulated by Brunt (1932). The net outgoing long wave radiation increases with increasing values for the mean air temperature and the relative sunshine duration and decreases with increasing vapor pressure.

$$R_{nl} \uparrow = \sigma \, (T + 273)^4 \, (0.56 - 0.079 \, \sqrt{e_a}) \, (0.1 + 0.9 \, \frac{n}{D}) \qquad (2.16)$$

Where:

$R_{nl}\uparrow$: Net outgoing long-wave radiation $\qquad$ [J m^{-2} d^{-1}]
σ : Stefan Boltzmann constant $= 4.90$ x 10^{-9} $\qquad$ [J m^{-2} K^{-4} s^{-1}]
T : Air temperature $\qquad$ [°C]
e_a : Actual vapor pressure $\qquad$ [kPa]
n/D : Relative sunshine duration $\qquad$ [-]

The relative sunshine duration, n/D, is established in the model using:

$$\frac{n}{D} = \frac{T_{atm} - A}{B} \qquad (2.17)$$

Where:

n/D : Relative sunshine duration $\qquad$ [-]
T_{atm} : Atmospheric transmission (see eq. 2.29) $\qquad$ [-]
A : Empirical constant in the Ångström equation $\qquad$ [-]
B : Empirical constant in the Ångström equation $\qquad$ [-]

The calculation of the atmospheric transmission, T_{atm}, will be explained in §2.4.

Part of the actual received radiation is reflected by the surface. The fraction reflected (albedo) is different for a water surface, a soil surface and a crop canopy. The absorbed fraction of radiation actually received minus the net outgoing radiation equals the net absorbed radiation, which is divided by the latent heat of vaporization of water to express the amount of radiation in depth of evaporative water layer (mm d^{-1}).

$$R_{na} = \frac{(1 - \alpha) \, R_{av} - R_{nl} \uparrow}{\lambda} \qquad (2.18)$$

Where:

Table 2.2: Albedo values for wet and dry soils (ten Berge, 1986)

soil type	wet	dry
Dune sand	0.24	0.37
Sandy loam	0.10-0.19	0.17-0.23
Clay loam	0.10-0.14	0.20-0.23
Clay	0.08	0.14

R_{na}	:	Net absorbed radiation	[mm d^{-1}]
α	:	Albedo or reflection coefficient of regarded surface	[-]
R_{av}	:	Average radiation	[J m^{-2} d^{-1}]
$R_{nl}\uparrow$	:	Net outgoing long-wave radiation	[J m^{-2} d^{-1}]
λ	:	Latent heat	[J kg^{-1}]

The soil's albedo depends on the surface color and on the moisture content. Albedo values for dry soil vary from 0.14 (clay) to 0.37 (dune sand). Ten Berge (1986) described the dependence of the albedo value on soil moisture in relation to the average water content of the top soil layer. See Table 2.2. In WOFOST 7.2 the following values for the albedo are assumed: for bare soil 0.15, for a canopy 0.25 and for a water surface a value of 0.05.

The evaporative demand of the atmosphere depends on the difference between saturated and actual vapor pressure and on the wind function. For crop canopies the evaporative demand is somewhat higher than for soil or water surfaces due to a higher surface roughness. This is reflected in a higher value for *factor* in the wind function.

$$EA = 0.26 \, (e_s - e_a) \, (factor + BU \, u(2)) \qquad (2.19)$$

Where:

EA	:	Evaporative demand	[mm d^{-1}]
e_s	:	Saturated vapor pressure (see eq. 2.9)	[kPa]
e_a	:	Actual vapor pressure	[kPa]
factor	:	Empirical constant	[-]
BU	:	Coefficient in wind function (see eq. 2.4)	[-]
u(2)	:	Mean windspeed at 2 m height	[m s^{-1}]

The following values for *factor* are assumed (Frère, 1979). For crop canopies *factor* = 1.0 and for a free water a surface *factor* = 0.5.

Substituting equations 2.19 and 2.18 in equation 2.14 yields

$$ET0 \; = \; \frac{(\Delta R_{na} \; + \; \gamma EA)}{\Delta \; + \; \gamma} \qquad\qquad (2.20)$$

Where:

ET0	:	Evapo(transpiration)	$[\text{mm d}^{-1}]$
R_{na}	:	Net absorbed radiation	$[\text{mm d}^{-1}]$
EA	:	Evaporative demand	$[\text{mm d}^{-1}]$
Δ	:	Slope of the saturation vapor pressure curve	$[\text{kPa C}^{-1}]$
γ	:	Psychrometric constant	$[\text{kPa C}^{-1}]$

With the equations 2.18, 2.19, 2.20 and the different values for factor and albedo, the evapo(transpi)ration from a wet bare soil surface $E0_s$, a water surface, $E0_w$, and a crop canopy, ET0, can be easily calculated.

2.3.2   Terms in the Penman-Monteith formula

The Penman-Monteith equation implemented in WOFOST closely follows the algorithm laid down in FAO Irrigation and drainage paper 56 ("Crop evapotranspiration - Guidelines for computing crop water requirements") by Allen et al. (1998) which is available online [1] and will not be repeated here.

Standard values for the reference canopy reflection and canopy resistance of 0.23 and 70 sm^{-1} are used and the soil heat flux is explicitly set to zero. Moreover, some of the terms in the FAO PM equation have been rearranged for clarity. For example the magic number "0.408" in the FAO equation can be more easily understood as one divided by the latent heat for vaporisation.

2.4   Day length and solar elevation

The ASTRO module calculates day length, some intermediate variables for the calculation of the solar elevation, the integral of the solar elevation over a day and the fraction of diffuse radiation.

Day length is a function of the angle of the sun above the horizon (solar elevation). Solar elevation is the angle between the sun rays and the earth's surface. Solar elevation is determined by latitude, the day and the hour on a certain day. The dependency on the hour of a certain day is simple to explain. The sun rises and the sun sets every day. Just before sun rise and just after sun

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[1]http://www.fao.org/3/X0490E/x0490e00.htm

set the solar elevation is zero. At the equator on days that the sun is in zenith (the point in the sky directly overhead) at 12 o'clock solar time it holds that:

$$\sin\beta = \cos(15(t_h - 12)) \tag{2.21}$$

Where:

β	:	Solar elevation	[degrees]
t_h	:	Hour of the day	[h]

The angle of the sun changes during the day because the earth rotates once around its axis every 24 hours at a speed of 15per hour (= 360/24).

To explain the dependency of solar elevation on latitude and day number first the situation is regarded when the sun is in zenith. This is at 12 o'clock solar time (not to be mixed up with noon). The solar declination, the place were the sun is in zenith at 12 o'clock solar time, changes every day. On the 21st of June the sun stands perpendicular above the northern tropic of Cancer (+23.45N) and on the 22nd of December the stands perpendicular above the tropic of Capricorn (-23.45S). In figure 2.1 the situation is depicted for 22nd of December when the sun reaches its highest point at the tropic of Capricorn at the southern hemisphere. On the northern hemisphere this results in the shortest day of the year.

The solar declination during the year can be approached by a cosine function. (Note a shift of ten days). The distance of the sun to the earth is considered to be infinite, therefore declination can be considered equal for all places on earth.

$$\delta = -23.45\cos(2\pi\frac{t_d + 10}{365}) \tag{2.22}$$

Where:

δ	:	Solar declination	[degrees]
t_d	:	Number of the day since 1 January	[-]

The orbit of the earth around the sun is a non concentric ellipse (see figure 2.2), therefore the solar radiation received at the top of the atmosphere during the year is not constant. At the first of January the earth is closest to the sun, radiation at the top of the atmosphere will then be higher as during other days.

The average solar radiation at the top of the atmosphere is estimated at 1370 W m^{-2}. A daily solar radiation constant can than be calculated as a cosine times the average solar radiation at the top of the atmosphere multiplied by
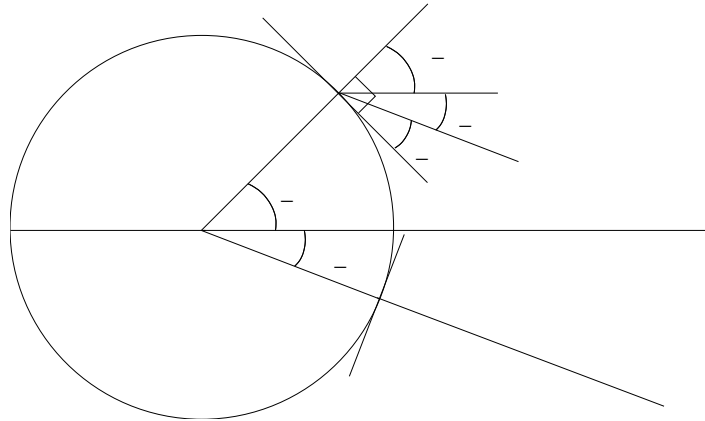
Figure 2.1: Solar declination

p]
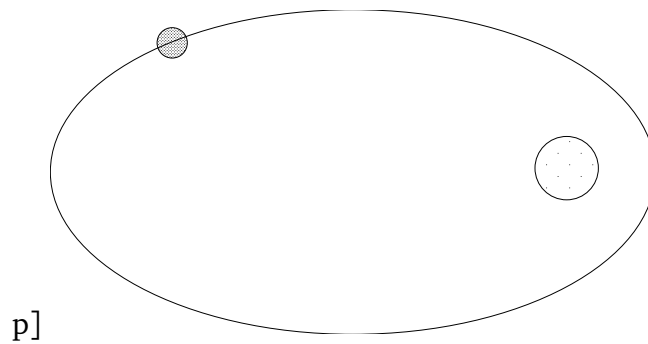
Figure 2.2: Orbit of the earth around the sun

correction factor to correct for the elliptical orbit of the earth around the sun. This correction factor is estimated to be 0.033.

$$S_{c,d} = S_c(1 + 0.033\cos(2\pi\frac{t_d}{365}))$$ (2.23)

Where:

$S_{c,d}$	:	Solar constant at the top of the atmosphere for a certain day	[J m^{-2} s^{-1}]
S_c	:	Average solar radiation at the top of atmosphere (1370 J m^{-2} s^{-1}; I.E.A., 1978)	[J m^{-2} s^{-1}]
t_d	:	Number of day since 1 January	[-]

Note that during the winter in Europe the solar radiation at the top of the atmosphere is at its maximum! The height of the sun at any moment throughout the day and at any place and date can be calculated using:

$$\sin\beta = \sin\lambda\sin\delta + \cos\lambda\cos\delta\cos(2\pi\frac{(t_h + 12)}{24})$$ (2.24)

Where:

β	:	Solar elevation	[degrees]
λ	:	Latitude	[degrees]
δ	:	Solar declination	[degrees]
t_h	:	Hour of the day (solar time)	[h]

To compute day length for photoperiod-sensitive species, it must be realized that, even when the sun is still below the horizon the light level is high enough to trigger the photoperiodicity mechanism. Photoperiodic day length is 0.5 h longer than the astronomical day length at the equator and about 0.8 h in temperate zones, depending on the date of the year. The light level to which photoperiodism is sensitive is quite low and not well quantified. Vergara & Chang (1985) determined it to be 1.5-15 mW m^{-2} for rice crops; Salisbury (1981) determined the level to be higher. As a compromise a value of 50 mW m^{-2} is used in the model, which corresponds with a sun angle of -4 degrees. The photosynthetic active period and the astronomical day length can be calculated as:

$$D = 12 + \frac{24}{180}\arcsin(\frac{-\sin\frac{p}{180} + sinLD}{cosLD})$$ (2.25)

Where:

D   :   Day length   [h]
sinLD   :   Seasonal offset of sine of solar height $= \sin\delta\sin\lambda$ [-]
cosLD   :   Amplitude of sine of solar height $= \cos\delta\cos\lambda$ [-]
p   :   correction constant   [degrees]

The correction constant for the photosynthetic day length is -4 degrees. For the astronomical day length the correction constant is -0.833 degrees (i.e. solar height for which the upper edge of the solar disk appears on the horizon). However, in the model for the calculation of the astronomical day length, a correction constant of 0 degrees is used.

For locations below -66.5 and above 66.5 degrees of latitude, situations of no daylight (polar night) and 24h day light (e.g. polar day) occur. In such cases the calculated daylenght will be set to zero daylength (polar night) or 24 hour day length (polar day).

The integral of the solar height over the day can be obtained as twice the integral from sunrise (β=0) to 12 o'clock solar time ($\beta = 90+ \delta - \lambda$):

$$\int \sin\beta \, dt_h \;=\; 3600\left(D\sin\lambda\sin\delta + \frac{24}{\pi}\cos\lambda\cos\delta\sqrt{1-\tan^2\lambda\tan^2\delta}\right) \quad (2.26)$$

Where:

$\int \sin\beta$:   Integral solar height   [s]
D   :   Day length   [h]
β :   Solar elevation   [degrees]
t_h :   Hour of the day   [h]

Multiplication of equation 2.23 with 2.26 yields the daily extra-terrestrial radiation which is also known as the Angot radiation. Note that the dimension of the daily extra-terrestrial is radiation $J\,m^{-2}\,d^{-1}$.

$$S_{o,d} = S_{c,d} \int \sin\beta \, dt_h \quad (2.27)$$

Where:

$S_{o,d}$:   Daily extra-terrestrial radiation $[J\,m^{-2}\,d^{-1}]$
$S_{c,d}$:   Solar constant at the top of the atmosphere for a cer- $[J\,m^{-2}\,s^{-1}]$
            tain day (see eq. 2.23)
t_d :   Number of day since 1 January   [-]

In the model the integral of the effective solar height, a modification of equation 2.27 is also calculated. This modified integral takes the effect of the daily

course in atmospheric transmission into account. Transmission is lower near the margins of the day because of haze in the morning and clouds in the afternoon. Besides that, path length of solar radiation in the atmosphere is longer (Spitters *et al.*, 1986). This modified integral can be calculated as:

$$\int \sin \beta_m = \int \sin \beta (1 + c sin\beta) dt_h \tag{2.28}$$

$$= 3600 \cdot \left\{ \begin{array}{l} D(\sin \lambda \sin \delta + 0.4((\sin \lambda \sin \delta)^2 + 0.5(\cos \lambda \cos \delta)^2)) + \\[2mm] \frac{12}{\pi} \cos \lambda \cos \delta (2 + 3 \cdot 0.4 \sin \lambda \sin \delta) \sqrt{1 - \tan^2 \lambda \tan^2 \delta} \end{array} \right\}$$

Where:

$\int \sin \beta_m$	:	Integral of effective solar height	[s]
D	:	Day length	[h]
c	:	Coefficient of regression on transmission on solar angle = 0.4	[-]
β	:	Solar elevation	[degrees]
λ	:	Latitude	[degrees]
δ	:	Solar declination	[degrees]
t_h	:	Hour of the day f	[h]

A distinction is made between diffuse sky light, with incidence under various angles and direct sunlight with an angle of incidence equal to the solar declination. It is important to distinguish these fluxes because of the large difference in illumination intensity between shaded leaves and sunlit leaves and therefore the difference in the CO_2 assimilation light response of single leaves, which is non-linear. Shaded leaves receive only diffuse radiation. Sunlit leaves receive both direct and diffuse radiation. The diffuse flux is the result of the scattering of sun rays by clouds, aerosols and gases in the atmosphere. The proportion of diffuse light in the total incident light flux depends on the status of the atmosphere, i.e. cloudiness, concentration of aerosols. This fraction is calculated from the atmospheric transmission using an empirical function. This relationship is based on data from different meteorological stations from a wide range of latitudes and longitudes (Spitters *et al.*, 1986).

The atmospheric transmission is the ratio between actual radiation and the quantity that would have reached the earth's surface in the absence of an atmosphere (i.e. Angot radiation). This ratio can be calculated as:

$$T_{atm} = s \frac{}{\frac{g,d}{S_{c,d} \int \sin \beta}} \tag{2.29}$$

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Where:

T_{atm}	:	Atmospheric transmission	[-]
$S_{g,d}$	:	Daily global radiation	[J m^{-2} d^{-1}]
$S_{c,d}$	:	Solar constant at the top of the atmosphere for a certain day (see eq. 2.23 and 2.27)	[J m^{-2} s^{-1}]
$\int \sin\beta$	:	Integral of solar height	[s]

Relationships between the share of the diffuse flux in the global irradiance (S_{df}/S_g) and the atmospheric transmission (S_g/S_o) are found in several research reports concerning the use of solar energy in solar collectors. The relation is characterized by an approximately linear trend for transmissions ranging between 0.35 and 0.75. At low transmissions, nearly all of the incoming radiation is diffuse so that the curve bends off. There is some variation among published relations, arising from differences in atmospheric conditions, especially relative sunshine duration, water content of the atmosphere, and cloud type, but also lack of fit of the presented regression equation from the data and differences in the method of measuring the diffuse radiation.

The relation used in WOFOST Version 7.2 has been derived by de Jong (1980) and has been recommended by Spitters *et al.* (1986).

$$\frac{S_{df,d}}{S_{g,d}} = 1 \qquad\qquad for \ \frac{S_{g,d}}{S_{o,d}} \le 0.07$$

$$\frac{S_{df,d}}{S_{g,d}} = 1 - 2.3(\frac{S_{g,d}}{S_{o,d}} - 0.07)^2 \qquad for \ 0.07 < \frac{S_{g,d}}{S_{o,d}} \le 0.35$$

$$\frac{S_{df,d}}{S_{g,d}} = 1.33 - 1.46\frac{S_{g,d}}{S_{o,d}} \qquad for \ 0.35 < \frac{S_{g,d}}{S_{o,d}} \le 0.75$$

$$\frac{S_{df,d}}{S_{g,d}} = 0.23 \qquad\qquad for \ \frac{S_{g,d}}{S_{o,d}} > 0.75$$

$$(2.30)$$

Where:

$S_{df,d}$	:	Daily diffuse radiation	[J m^{-2} d^{-1}]
$S_{g,d}$	:	Daily global radiation	[J m^{-2} d^{-1}]
$S_{o,d}$	:	Daily extra-terrestrial radiation (see eq. 2.27)	[J m^{-2} d^{-1}]

The relationships are remarkably constant over climates and latitudes so that the presented equations will be valid for a wide range of conditions (Spitters *et al.*, 1986).

Measured or estimated daily total solar irradiation (wavelength 300-3000 nm)

is input for the model. Only half of this incoming radiation is photosynthetical active (PAR, Photosynthetically active radiation, wavelength 400 - 700 nm). The photosynthetically active diffuse radiation, perpendicular to the direction of the solar rays can be calculated as:

$$D_p = S_{\frac{df,d}{S_{g,d}}} \; T_{atm} \; 0.5 S_{c,d} \tag{2.31}$$

Where:

D_p	:	Diffuse irradiation perpendicular to the direction of light	$[\text{J m}^{-2}\,\text{s}^{-1}]$
T_{atm}	:	Atmospheric transmission (see eq. 2.29)	$[\text{-}]$
$S_{c,d}$	:	Solar constant at the top of the atmosphere for a certain day	$[\text{J m}^{-2}\,\text{s}^{-1}]$
$S_{g,d}$	:	Daily global radiation	$[\text{J m}^{-2}\,\text{d}^{-1}]$
$S_{df,d}$	:	Daily diffuse radiation (see eq. 2.30)	$[\text{J m}^{-2}\,\text{d}^{-1}]$

Chapter 3

Crop development and growth

3.1 Overview of the crop growth model

The WOFOST model describes phenological development, growth and yield formation of a crop from emergence untill maturity on the basis of crop genetic traits and environmental conditions. The model simulates dry matter accumulation of a crop as a function of irradiation, temperature and crop characteristics in time steps of one day. The basis for calculating dry matter production, is the rate of gross CO_2 assimilation of the canopy. This rate is dependent on the radiation energy absorbed by the canopy, which is a function of incoming radiation and the optical characteristics of the leaf canopy. From the absorbed radiation and the photosynthetic characteristics of single leaves, the daily rate of CO_2 assimilation of the crop is calculated. Part of the carbohydrates produced (CH_2O) are used to provide energy for the maintenance of the existing live biomass (maintenance respiration). The remaining carbohydrates are converted into structural matter. In this conversion, some of the weight is lost as growth respiration. The growth rate is thus obtained as:

$$\Delta W = C_e \left(A - R_m \right) \tag{3.1}$$

Where:

ΔW	:	Growth rate	[kg Dry Matter ha^{-1} d^{-1}]
A	:	Gross assimilation rate	[kg CH_2O ha^{-1} d^{-1}]
R_m	:	Maintenance respiration rate	[kg CH_2O ha^{-1} d^{-1}]
C_e	:	Conversion efficiency off assimilates total crop	[kg Dry Matter kg^{-1} CH_2O]

The dry matter produced is partitioned amongst the various plant organs such as roots, leaves, stems and storage organs, using partitioning factors that are a function of the phenological development stage of the crop (Spitters et al., 1989). The fraction partitioned to the leaves, determines leaf area development and hence the dynamics of light interception. The dry weights of the plant organs are obtained by integrating their growth rates over time.

Leaf mass is subdivided into age classes. During the development of the crop a part of living biomass dies due to senescence. Some simulated crop growth processes are influenced by temperature, such as the maximum rate of photosynthesis and the maintenance respiration. Other processes like the partitioning of assimilates or senescence of crop tissue are steered by the phenological stage. The phenological development stage is calculated as a function of ambient temperature and possibly modified by the effect of day length and vernalization. An overview of all these processes is given in figure 3.1.

3.2 Phenological development of a crop

The physiological age of a plant is defined by the development stage (acronym: **DVS**), which on its turn is characterized by the formation of the various organs and their appearance. For cereal crops, the most important phenological change is the one from vegetative to the reproductive stage, which determines the most important change in the dry matter allocation over organs. Other crops like sugar beet, potatoes or legumes have a more gradual change in the appearance of different crop organs.

As many physiological and morphological processes change with DVS, accurate quantification of phenological development is essential in any simulation model for crop growth. In WOFOST, the development stage is expressed as a dimensionless variable, having the value -0.1 at sowing, 0 at seedling emergence, 1 at flowering and 2 at maturity.

This approach for phenological development is typical for a cereal crop and all other crops are forced into this pattern. This also implies that DVS = 1 not necessarily corresponds to a flowering phase, but rather indicates the start of the formation of the storage or reproductive organs. For example, for the simulation of potato or root crops the DVS = 1 represents the moment of tuber or root initiation rather than flowering.

In recent years the BBCH scale (https://en.wikipedia.org/wiki/BBCH-scale) was developed to provide a framework for defining phenological scales for a

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Figure 3.1: Schematic overview of the major processes implemented in WOFOST and their linkages.

variety of crops. The phenological stages used by WOFOST roughly correspond to BBCH scales 0 (sowing), 1 (leaf development), 6 (flowering) and 9 (senescence). Converting the internal algorithms of WOFOST to use the BBCH scale for phenology is not trivial because many WOFOST parameters are defined as a function of DVS. Nevertheless, in calibration studies it was demonstrated that specific DVS values can be linked consistently to specific BBCH stages. Although the exact DVS values for a crop to reach a specific BBCH stages can be variety specific.

3.2.1   Crop emergence

As start of the growing season the date of sowing or of emergence can be chosen. For a photosynthesis-driven model like WOFOST, the simulation of crop growth starts at emergence. If the sowing date is chosen by the model user, the day of emergence is determined by the model. The crop emergence can be defined as a function of the effective daily temperature sum since sowing date. Emergence takes place when the effective daily temperature sum reaches the threshold temperature for emergence (acronym: **TSUMEM**). This threshold temperature is crop specific and should be given by the user. The daily effective temperature depends on the base temperature **TBASEM**, below which no germination processes take place, and the maximum daily temperature, beyond which the germination activity does not increase anymore **TEFFMX**. Both are crop specific. An example of this effective daily temperature as a function of daily average temperature is shown in figure 3.2.

The following relationship can be defined for the effective temperature sum:

$$
\begin{aligned}
T_e &= 0 & T &\leq T_b \\
T_e &= T - T_b & T_b &< T < T_{\mathrm{max},e} \\
T_e &= T_{\mathrm{max},e} & T_b T &\geq T_{\mathrm{max},e}
\end{aligned}
\tag{3.2}
$$

Where:

T_e	:	Effective daily temperature	[°C]
$T_{\mathrm{max,e}}$	:	Maximum temperature beyond which phenological activity does not increase	[°C]
T_b	:	Base temperature below which phenological development stops	[°C]
T	:	(Average) daily temperature	[°C]

For pragmatic reasons, time to emergence is taken as a function of air temperature. It would be more correct to establish relations with soil temperature but this is not done due to data scarcity.

3.2.2   Phenological development stage

A crop passes through successive phenological development stages. In WOFOST these stages are expressed in degree-days and defined by two parameters. The TSUM1 parameter defines the number of degree-days for the emergence-anthesis period, while the TSUM2 parameter defines the number of degree-days for the anthesis-maturity period. The length of these stages (in days) depends on the development rate. Development rates are controlled by vernalization requirements, day length and temperature. In the model before anthesis, all factors can be active. After anthesis only temperature influence is possible.

Temperature is the main environmental factor affecting the development rate. Higher temperatures increase the development rate leading to shorter growing periods. This rate responds to temperature according to a curvilinear relationship. However, it has often been demonstrated, that over a wide range of temperatures, the development rate increases more or less linearly with temperature (van Dobben, 1962; van Keulen & Seligman, 1987).

In the model a flexible relation is used where the effective increase in temperature sum, used for the calculation of the development rate, is dependent on the daily temperature (Summerfield & Roberts, 1987). This relation is specified in an AFGEN table, allowing to account for non-linearity (lower and upper threshold values and optimum ranges). The average temperature is the independent variable in the AFGEN table (see Appendix 2).

Species originating from temperate regions (wheat, barley, potato, etc.) show a base temperature of 0–3°C, while species of subtropical and tropical origins (maize, sorghum, sugar cane, etc) have a base temperature of 9–14°C (Angus *et al.*, 1981). Within a species, cultivars may vary substantially in their temperature requirements. The temperature sum, therefore, must be characterized for each cultivar or group of cultivars (maturity classes).

The development rate based on temperature can be reduced by the effect of vernalization and day length and can thus be obtained by:

$$D_{r,t} = f_{vern} \cdot f_{dayl} \cdot \frac{DT_s}{\sum T_i} \tag{3.3}$$

Where:

$f_{\text{vern},t}$	:	Reduction factor for vernalization at time step t	[-]
$f_{\text{dayl},t}$	:	Reduction factor for day length at time step t	[-]
$D_{r,t}$	:	Development rate at time step t	$[\text{d}^{-1}]$
DT_s	:	Daily effective temperature	[°C]
$\sum T_i$	:	Temperature sum required to complete stage i	[°C d]

The temperature dependent correction factor, $\mathbf{DT}_s$ (acronym: **DTSMTB**) and the temperature sum required to complete stage i, $\sum \mathbf{T}_i$ (acronym: **TSUM1** or **TSUM2**) are crop dependent and should be provided by the user.

The development stage at time step *t* is the integral of the development rate over the time (i.e. time span from emergence to current time step) and can be calculated as:

$$D_{s,t} \;=\; D_{s,t-1} + D_{r,t}\Delta t \tag{3.4}$$

Where:

$D_{s,t}$	:	Development stage at time step t	[-]
$D_{r,t}$	:	Development rate at time step t	$[\text{d}^{-1}]$
Δt	:	Time step	[d]

3.2.3   Photoperiod sensitivity

For certain crops or cultivars, during the vegetative stage (i.e. $D_s < 1$), the effect of day length should be taken into account (e.g. "photoperiod sensitivity"). Approaches that describe the effect of day length quantitatively are given amongst others by Weir *et al.* (1984), Hadley *et al.* (1984) and Reinink *et al.* (1986). In WOFOST, a reduction factor for the development rate as a function of the day length is introduced. In case of photosensitivity a reduction factor can be calculated as:

$$f_{red} \;=\; \frac{D - D_c}{D_o - D_c} \qquad 0 \le f_{red} \le 1 \tag{3.5}$$

Where:

f_{dayl}	:	Development rate reduction factor as function of day length	[-]
D	:	Present day length (see eq. 2.25)	[h]
D_c	:	Critical day length for development below which $f_{\text{dayl}} = 0$	[h]
D_o	:	Optimum day length for development above which $f_{\text{dayl}} = 1$)	[h]

The user should provide information whether the development rate depends on temperature, on day length or on temperature and day length (acronym: **IDSL**). The critical daylength, D_c (acronym: **DLC**) and the optimum daylength, D_o (acronym: **DLO**) are crop dependent and should also be provided by the user.

Note that in modern cultivars, photosensitivity is much less pronounced than in traditional cultivars, and that for the purpose of modelling the day length influence can often be ignored.

3.2.4   Vernalization

Vernalization is the process by which flowering is promoted as plants sense exposure to the cold temperatures of winter. A requirement for vernalization is an adaptive crop trait that helps prevent flowering before winter and permits flowering in the favorable conditions of spring (Choard, 1960; Kim, Dong-Hwan *et al.* 2009). The "vernalization requirement" of the crop is the magnitude of the exposure to cold temperature in order to induce flowering.

Particularly for winter crops the influence of day length and vernalization on phenological development must be taken into account in order to avoid that the choice of the sowing date in autumn has a large impact on the flowering and maturity date of the crop.

The approach for vernalisation implemented in WOFOST is based on the work of Wang and Engel (1998) and of van Bussel et al. (2015). Vernalization is simulated by assuming that a crop requires a number of (cultivar-specific) vernalization days in order to reach its vernalization requirement. One vernalization day is added to the vernalization state when the daily average temperature is within the optimal temperature range for vernalization. A fractional day or zero is added when the temperature is outside of this range. This rate of vernalization (acronym: **VERNR**) is decribed using an AFGEN table (acronym: **VERNRTB**) which describes the temperature response curve for vernalization (figure 3.3). See appendix 2 for an explanation of the AFGEN tables.

The reduction factor on development rate is than derived by linearly scaling the current vernalization state ((acronym: **VERN**)) between a base vernalization ((acronym: **VERNBASE**)) and the number of days required to saturate the vernalization requirement (acronym: **VERNSAT**). The reduction factor can thus be expressed as:

$$f_{vern} = \frac{V - V_{base}}{V_{sat} - V_{base}} \qquad 0 \le f_{vern} \le 1 \qquad (3.6)$$

Where:

f_{vern}	:	Development rate reduction factor as function of vernalization state	[-]
V	:	Present vernalization state of the crop	[days]
V_{base}	:	Base vernalization for development (lower threshold)	[days]
V_{sat}	:	Saturated vernalization for development (upper threshold)	[days]

Note that it is possible for crops under certain conditions to de-vernalize, but this effect is not taken into account in WOFOST.

To reduce the impact of a poorly choosen VERNSAT parameter, a critical DVS is defined after which vernalization is switched off and the f_{verb} is set to 1.0. This parameter **VERNDVS** is currently set to 0.3 by default but is adjustable by the user. In the case that the vernalization requirement is not reached before VERNDVS a warning must issued to the user by any WOFOST implementation.

3.2.5   End of the crop cycle

The simulation of crop growth stops when the development stage reaches the stage at which the crop will be harvested (acronym: **DVSEND**). For crops that are harvested at maturity **DVSEND**) will be equal to 2.0. However, for crops that are deliberately harvested earlier (e.g. silage maize) the value can be lower. For crops that are harvested at a defined date, the value for **DVSEND**) will be ignored.

3.3   Daily assimilation

Daily dry matter production is the most detailed part of the model. The following steps can be distinguished and will be described separately:

- Potential instantaneous gross CO_2 assimilation of the canopy. (§3.3.2)

- Potential daily gross CO_2 assimilation rate of the canopy ([§3.3.1)

- Actual daily gross photosynthesis rate of the canopy as a result of temperature, development stage effects and water stress. (§3.3.3)
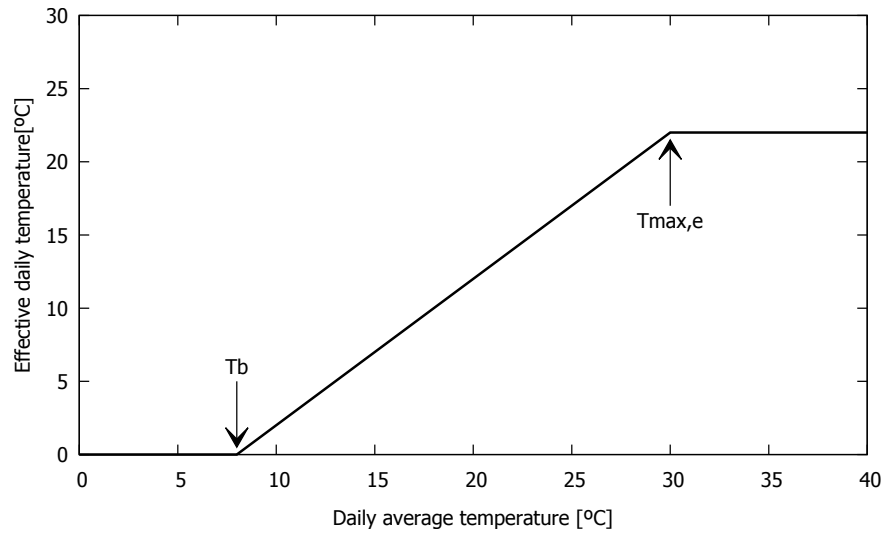
Figure 3.2: Effective temperature from sowing to emergence
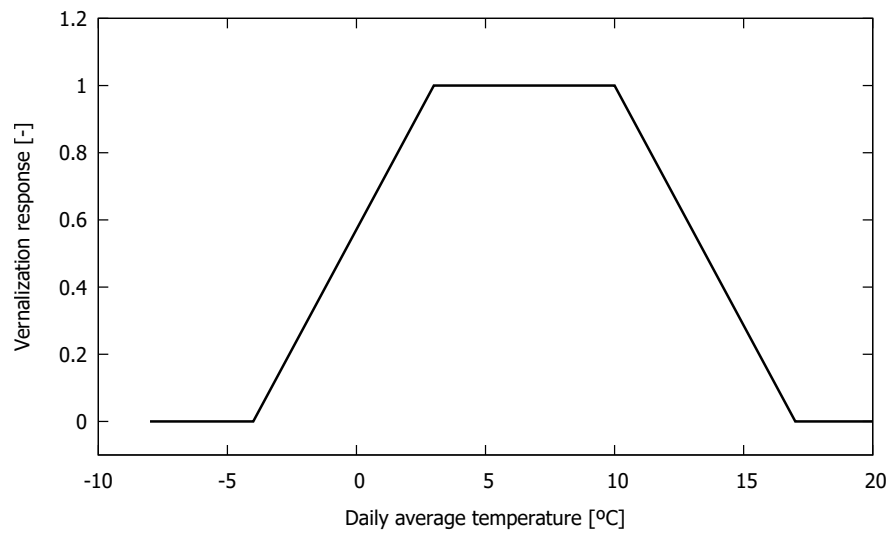
Figure 3.3: Response function for vernalization as a function of daily average temperature.

For the calculation of the potential instantaneous gross canopy CO_2 assimilation rate, an integration over depth of the crop canopy has to be performed. Therefore, at three different depths in the canopy the gross instantaneous assimilation rate is calculated, whereafter the instantaneous gross canopy CO_2 assimilation rate at canopy level is calculated as a weighted average of the instantaneous rates at the selected depths

To calculate the potential daily gross CO_2 assimilation rate of the whole canopy, an integration over time should be performed. Therefore, for given fluxes of photosynthetically active radiation, at three different periods of the day, the potential instantaneous gross canopy CO_2 assimilation rate is computed. Subsequently, the potential gross canopy CO_2 assimilation rate is calculated as a weighted average of the instantaneous rates during the selected instances Both calculations make use of the 3-point Gaussian integration method (Goudriaan, 1986; Spitters, 1986) thus nine iterations are required: three periods of the day multiplied by three depths into the crop canopy.

Finally, the actual gross photosynthesis rate is computed by applying correction factors for daytime temperature, night time temperature and water stress onto the total daily assimilation. The calculations performed will be described in more detail in the paragraphs 3.3.1 to 3.3.3.

3.3.1   Potential daily gross CO_2 assimilation rate of the canopy

As is mentioned before, in order to integrate the gross instantaneous assimilation rate over the day, three points in time are selected to calculate the photosynthetically active radiation. For this calculation, we assume that the radiation is distributed over the day according to the sine of solar elevation (as would be the case on a clear cloudless day). So the weighted average CO_2 assimilation rate can therefore be calculated for half a day only.

The three points in time are selected from noon to sunset (this explains the use of the constants 0.5 and 12.00):

$$t_h = 12 + 0.5 \cdot D \cdot (0.5 \ + \ p \ \sqrt{0.15}) \quad for \quad p = -1, 0, 1 \qquad (3.7)$$

Where:

D	:	Day length (see eq. 2.25)	[h]
t_h	:	Hour of the day	[h]
p	:	Gaussian integration points	[-]

The incoming radiation and therefore gross assimilation rate, changes with

solar elevation. The solar height as a function of the hour of the day can be calculated with:

$$\sin \beta \;=\; \sin \lambda \, \sin \sigma \;+\; \cos \lambda \, \cos \sigma \, \cos \left(2\pi \, \frac{t_h + 12}{24} \right) \qquad (3.8)$$

Where:

β	:	Solar elevation	[degrees]
σ	:	Solar declination	[degrees]
λ	:	Latitude	[degrees]
t_h	:	Hour of the day	[h]

Measured or estimated daily global solar radiation (wavelength 300 - 3000 nm) is input in the model. Only half of this incoming radiation is photosynthetically active (PAR, Photosynthetically Active Radiation, wavelength 400 - 700 nm). This fraction, which is generally called 'light' or 'visible radiation', is used in the calculation procedure of the CO_2 assimilation rate of the canopy. In the model, the instantaneous incoming photosynthetically active radiation is calculated by multiplying half of the daily global radiation with the ratio of the actual effective solar elevation and the integral of the effective solar height (see also eq. 2.28):

$$I_0 \;=\; 0.5\, S_{g,d} \, \frac{\sin \beta \,(\, 1 \,+\, 0.4 \sin \beta \,)}{\int \sin \beta_m} \qquad (3.9)$$

Where:

I_0	:	Photosynthetically active radiation flux	[J m^{-2} s^{-1}]
$S_{g,d}$	:	Daily global radiation	[J m^{-2} d^{-1}]
β	:	Solar elevation	[degrees]
$\int \sin \beta_m$	:	The corrected integral of solar height over the day for non homogeneous atmospheric transmission (eq. 2.28)	[s]

The calculated photosynthetically active radiation flux consists of a diffuse flux and a direct flux. The diffuse flux is the result of scattering of sun rays by clouds, aerosols and gases in the atmosphere. The proportion of diffuse light in the total incident light flux depends on the status of the atmosphere (see also eq. 2.30). This fraction is calculated from the atmospheric transmission using an empirical function (Spitters *et al.*, 1986).

$$I_{0,df} \;=\; D_p \, \sin \beta \qquad (3.10)$$

Where:

$I_{0,df}$	:	Diffuse part of the photosynthetically active radiation flux at top of the canopy	$[\text{J m}^{-2}\text{ s}^{-1}]$
D_p	:	Diffuse radiation perpendicular to the direction light (see eq. 4.31)	$[\text{J m}^{-2}\text{ s}^{-1}]$
$\sin\beta$	:	Solar elevation (see eq. 3.8)	[degrees]

The direct part can be easily obtained by subtracting the diffuse part from the photosynthetically radiation flux:

$$I_{0,dr} \;=\; I_0 \;-\; I_{0,df} \tag{3.11}$$

Where:

$I_{0,dr}$	:	Direct part of the photosynthetically active radiation flux at top of the canopy	$[\text{J m}^{-2}\text{ s}^{-1}]$
I_0	:	Photosynthetically active radiation flux (see eq. 3.9)	$[\text{J m}^{-2}\text{ s}^{-1}]$
$I_{0,df}$	:	Diffuse part of the photosynthetically active radiation flux at top of the canopy	$[\text{J m}^{-2}\text{ s}^{-1}]$

Once the photosynthetically active radiation fluxes have been established, the instantaneous gross assimilation rate of the canopy can be calculated (see §3.3.2). And the integration over time can take place. The integral of the total gross canopy assimilation rate over time is calculated as the weighted average of the three selected hours of the day. Multiplying by the day length results in the total daily gross rate of CO_2 assimilation.

$$A_d = D\frac{A_{C,-1} \;+\; 1.6A_{C,0} \;+\; A_{C,1}}{3.6} \tag{3.12}$$

Where:

A_d	:	Total gross assimilation rate	$[\text{kg ha}^{-1}\text{ d}^{-1}]$
D	:	Day length (see eq. 2.25)	$[\text{h}]$
A_C	:	Total inst. gross assimilation rate for the whole canopy, p= -1,0,1 (see eq. 3.31)	$[\text{kg ha}^{-1}\text{ h}^{-1}]$

3.3.2 Potential instantaneous gross CO_2 assimilation of the canopy

The total instantaneous rate of CO_2 assimilation of the canopy is calculated from the incoming fluxes of diffuse and direct photosynthetic active radiation, solar elevation and leaf area index and several parameters.

Reflection and extinction

The total incoming photosynthetically active radiation flux is partly reflected by the canopy. The reflection coefficient is defined as the fraction of the downward radiation flux that is reflected by the whole canopy. According to Goudriaan (1977), the reflection coefficient of a green leaf canopy with a random spherical leaf angle equals:

$$\rho = \frac{1 - \sqrt{1-\sigma}}{1 + \sqrt{1-\sigma}} \cdot \frac{2}{1 + 1.6\sin\beta} \qquad (3.13)$$

Where:

ρ	:	Reflection coefficient of a green leaf canopy	[-]
σ	:	Scattering coefficient fraction (transmission and reflection) of single leaves for visible radiation (=0.2; Goudriaan, cited by Spitters, 1986)	[-]
β	:	Solar elevation (see eq. 2.24)	[degrees]

The first term denotes the reflection of the canopy of horizontal leaves and the second term is the approximate correction factor for a spherical leaf angle distribution.

A fraction ($1-\rho$) of the incoming visible radiation is potentially available for absorption by the canopy. Radiation fluxes attenuate exponentially within a canopy with increasing leaf area from the top downwards:

$$I_L = I_0(1 - \rho)e^{-\kappa LAI_L} \qquad (3.14)$$

Where:

I_L	:	Net photosynthetic active radiation flux at depth L in the canopy	[J m^{-2} s^{-1}]
I_0	:	Photosynthetically active radiation flux (see eq. 3.9)	[J m^{-2} s^{-1}]
LAI_L	:	Cumulative leaf area index (from top downwards) relative depth L	[ha ha^{-1}]
ρ	:	Reflection coefficient of the canopy	[-]
κ	:	Extinction coefficient for photosynthetic active radiation flux	[-]

The diffuse and the direct flux have different extinction coefficients, giving rise to different light profiles within the canopy for diffuse and direct radiation. Therefore three different radiation fluxes are distinguished:

- the diffuse flux, with extinction coefficient κ_{df};

- the total direct flux, with extinction coefficient $\kappa_{dr,t}$;

- the direct component of direct light, with extinction coefficient $\kappa_{dr,bl}$.

Radiation becomes diffuse when sun rays are partly absorbed and partly scattered (i.e. reflected or transmitted) by a leaf. The subscript *bl* (black) is used for leaves that show neither transmission nor reflection. The extinction coefficient of 'black leaves' can be calculated as:

$$\kappa_{bl} = \frac{0.5}{\sin \beta}$$ (3.15)

Where:

κ_{bl}	:	Extinction coefficient for the direct radiation flux	[-]
β	:	Solar elevation	[degree]

For a spherical leaf area distribution (homogeneous, random), the extinction coefficient for the diffuse radiation flux equals:

$$\kappa_{df} = \kappa_{bl} \sqrt{1 - \sigma}$$ (3.16)

Where:

κ_{df}	:	Extinction coefficient for the diffuse radiation flux	[-]
σ	:	Scattering coefficient fraction of single leaves for visible radiation	[-]

In the model, the extinction coefficient for the diffuse radiation flux, κ_{df} (acronym: **KDIFTB**) is not computed but should be provided by the user. It can be measured directly under diffuse sky conditions.

In equation 3.15, 0.5 points to the average projection on the ground surface of leaves showing a spherical angle distribution, and 0.8 in equation 3.17 is the value of $0.5/\sin\beta$ averaged over elevation β of incident radiation under an overcast sky.

The average extinction coefficient for the diffuse radiation flux is about 0.72 (Goudriaan, 1977). However, in many situations, the leaf angle distribution is not spherical. For example in rice, the leaves are clustered (especially in the beginning as a result of planting on hills), and have a very vertical orientation. Other leaf angle distributions can be accounted for by a procedure described by Goudriaan (1986), which calculates the extinction coefficient for the diffuse radiation flux on the basis of the frequency distribution of leaves with angles in different classes.

In the model however, the leaf angle distribution is accounted for by using a so called cluster factor which is the measured extinction coefficient for diffuse radiation flux, relative to the theoretical one for a spherical leaf area distribution. The cluster factor is calculated as:

$$C_f \; = \; \frac{\kappa_{df}}{0.8 \sqrt{1 - \sigma}} \qquad\qquad (3.17)$$

Where:

C_f	:	Cluster factor	[-]
κ_{df}	:	Extinction coefficient for diffuse radiation flux	[-]
σ	:	Scattering coefficient fraction of single leaves for visible radiation	[-]

The direct component can be calculated as (Goudriaan, 1977):

$$\kappa_{dr,bl} \; = \; C_f \, \frac{0.5}{\sin \beta} \qquad\qquad (3.18)$$

Where:

$\kappa_{dr,bl}$	:	Extinction coefficient for the direct component of direct light	[-]
C_f	:	Cluster factor	[-]
β	:	Solar elevation	[degrees]

The extinction coefficient for the total direct radiation flux can be calculated as (Goudriaan, 1977):

$$\kappa_{dr,t} \; = \; \kappa_{dr,bl}\sqrt{1 - \sigma} \qquad\qquad (3.19)$$

Where:

$\kappa_{dr,t}$	:	Extinction coefficient for total direct radiation flux	[-]
$\kappa_{dr,bl}$	:	Extinction coefficient for the direct component of direct light	[-]
σ	:	Scattering coefficient	[-]

Light absorption

Three depths in the canopy are selected according to the Gaussian integration method (see Appendix 1) and at those levels the leaf area index, the amount of absorbed radiation and the leaf CO_2 assimilation is calculated. The total instantaneous assimilation is easily obtained by multiplying the instantaneous

assimilation with the total leaf area index (eq. 3.31). In the following text the calculation processes, concerning the instantaneous assimilation, will be explained in detail. Calculation of the leaf area index will be explained in §3.6.4.

Canopy assimilation is calculated as a weighted average of the assimilation at three depths within the canopy. The leaf area index of the selected depths (cumulated from the top of the canopy to the selected depth) can be written as (Goudriaan, 1986):

$$LAI_L = (0.5 + p\sqrt{0.15}) \cdot LAI \quad for \quad p = -1, 0, 1 \qquad (3.20)$$

Where:

LAI_L : Leaf area index at relative distance L in the canopy [ha ha^{-1}]
(L=0 at the top)

The light absorbed at a certain depth in the canopy is obtained by taking the derivative of equation 3.14 with respect to the cumulative leaf area index:

$$I_{a,L} = \frac{-dI_{0,L}}{dL} = \kappa(1-\rho)I_0 \cdot e^{-\kappa LAI_L} \qquad (3.21)$$

Where:

$I_{a,L}$: Amount absorbed of total radiation flux [1] at relative [J m^{-2} s^{-1}]
depth L
$I_{0,L}$: Net photosynthetic active radiation at relative depth L [J m^{-2} s^{-1}]
in the canopy
I_0 : Photosynthetically active radiation flux at top of the [J m^{-2} s^{-1}]
canopy
L : Relative depth in the canopy [-]
κ : The extinction coefficient for the PAR flux [-]
ρ : Reflection coefficient of the canopy (see eq. 3.13) [-]

If expressed for the different light components, the absorbed fluxes for the different components per unit leaf area at a certain depth in the canopy are:

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[1]With the 'Total radiation flux' in this paragraph the total photosynthetically active radiation flux is meant.

$$I_{a,df} = \frac{-dI_{df,L}}{dL} \qquad = \kappa_{df}(1-\rho)I_{0,df} \cdot e^{-\kappa_{df} \, LAI_L} \qquad (3.22a)$$

$$I_{a,dr,t} = \frac{-dI_{dr,t,L}}{dL} \qquad = \kappa_{dr,t}(1-\rho)I_{0,dr} \cdot e^{-\kappa_{dr,t} \, LAI_L} \qquad (3.22b)$$

$$I_{a,dr,dr} = \frac{-dI_{dr,L}}{dL} \qquad = \kappa_{dr,bl}(1-\sigma)I_{0,dr} \cdot e^{-\kappa_{dr,bl} \, LAI_L} \qquad (3.22c)$$

Where:

$I_{a,\cdot}$	:	Amount absorbed of specified radiation flux	[J m^{-2} s^{-1}]
$I_{\cdot,L}$	:	Net specified component of PAR flux at relative depth L	[J m^{-2} s^{-1}]
I_0	:	Photosynthetically active radiation flux at top of the canopy (see eq. 3.9)	[J m^{-2} s^{-1}]
L	:	Relative depth in the canopy	[-]
$\kappa_{\cdot}$	:	The extinction coefficient for specified radiation (see eq. 3.16, 3.18 and 3.19)	[-]
ρ	:	Reflection coefficient of the canopy (see eq. 3.13)	[-]
σ	:	Scattering coefficient	[-]
bl	:	Black	
df	:	Diffuse	
dr	:	Direct	
t	:	Total	

Note that of the direct component of the direct flux the non-scattered part (1-σ) is absorbed.

The total absorbed flux for shaded leaves can be calculated as the sum of the absorbed flux of diffuse radiation and absorbed flux of the diffuse radiation of the indirect component of direct radiation. The last one is equal to the difference of the absorbed flux of the total radiation minus the absorbed flux of the direct component of the direct radiation.

$$I_{a,sh} = I_{a,df} + (I_{a,dr,t} - I_{a,dr,dr}) \qquad (3.23)$$

Where:

$I_{a,sh}$	:	Absorbed amount of the total radiation flux by shaded leaves	[J m^{-2} s^{-1}]
$I_{a,df}$	:	Absorbed amount of the diffuse radiation flux	[J m^{-2} s^{-1}]
$I_{a,dr,t}$	:	Absorbed amount of the total direct radiation flux	[J m^{-2} s^{-1}]
$I_{a,dr,dr}$	:	Absorbed amount of direct component of the direct radiation flux	[J m^{-2} s^{-1}]

Instantaneous gross assimilation

The CO_2 assimilation-light response can be obtained by introducing the absorbed amount of light into an assimilation-light response function of individual leaves. This assimilation-light response curve is computed using an exponential function that requires the instantaneous assimilation rate at light saturation and the initial angle to be defined:

$$A_L = A_m(1 - \exp(-\epsilon I_a/A_m)) \tag{3.24}$$

Where:

A_L	:	Inst.[2] gross assimilation rate at relative depth L (per unit leaf area)	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
A_m	:	Inst. gross assimilation rate at light saturation	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
ϵ	:	Initial light use efficiency	$[(\text{kg ha}^{-1}\,\text{h}^{-1})/(\text{J m}^{-2}\,\text{s}^{-1}])$
I_a	:	Absorbed amount of the total radiation flux	

The instantaneous gross assimilation rate at light saturation, also called the maximum leaf CO_2 assimilation rate, A_m (acronym: **AMAXTB**) is a function of the development stage and is crop specific. Note that this correction of A_m is an empirical way of correcting for decreasing photosynthesis rate due to decreasing leaf nitrogen content due to leaf ageing and translocation of nitrogen from leaves to storage organs. The initial light use efficiency, ϵ (acronym: **EFFTB**), is also crop dependent. It is defined as a function of daily mean temperature.

An AFGEN table with the development stage as the independent variable is used to describe this dependency (see also §3.2.2). For an example see figure 3.4.

Introducing the absorbed amount of radiation by shaded leaves (eq. 3.23) into equation 3.24 yields:

$$A_{sh} = A_m\big(1 - \exp(-\epsilon I_{a,sh}/A_m)\big) \tag{3.25}$$

Where:

---

[2]Inst. = Instantaneous

A_{sh}	:	Inst. gross assimilation rate for shaded leaves	[kg ha^{-1} h^{-1}]
A_m	:	Inst. gross assimilation rate at light saturation	[kg ha^{-1} h^{-1}]
ϵ	:	Initial light use efficiency	[(kg ha^{-1} h^{-1})/(J m^{-2} s^{-1})]
$I_{a,sh}$	:	Absorbed amount of the total radiation flux by shaded leaves (see eq. 3.23)	[J m^{-2} s^{-1}]

For the sunlit leaf area, the average absorption intensity may be substituted in equation 3.24. However, it is more accurate to account for the variation in leaf angle and thus in illumination intensity (Spitters, 1986). The direct flux is absorbed by a leaf perpendicular to the direct beam with an intensity of:

$$I_{a,dr,sl} = \frac{(1-\sigma)I_{0,dr}}{\sin\beta} \qquad (3.26)$$

Where:

$I_{a,dr,sl}$	:	Absorbed amount of the direct radiation flux by leaves perpendicular to the direct beam	[J m^{-2} s^{-1}]
$I_{0,dr}$	:	Direct flux of visible radiation at the top of the canopy	[J m^{-2} s^{-1}]
σ	:	Scattering coefficient	[-]
β	:	Solar elevation	[degrees]

The amount of absorbed direct radiation by leaves (eq. 3.26) depends on the sine of incidence at the leaf surfaces. Therefore, for sunlit leaves, CO_2 assimilation rates have to be calculated separately for leaves with different angles and integrated over the sine of incidence. In the model a spherical leaf angle distribution is assumed, so no integration over leaf angles is needed.

Integration over the sine of incidence for the sunlit leaves yields (Goudriaan, personal communication):

$$A_{sl} = A_m\left(1 - (A_m - A_{sh})\frac{1 - \exp(-I_{a,dr,sl}\,\epsilon/A_m)}{\epsilon\,I_{a,dr,sl}}\right) \qquad (3.27)$$

Where:

A_{sl}	:	Inst. gross assimilation rate for sunlit leaves	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
A_{sh}	:	Inst. gross assimilation rate for shaded leaves	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
A_m	:	Inst. gross assimilation rate at light saturation	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
$I_{a,dr,sl}$	:	Absorbed amount of the direct radiation flux by leaves perpendicular to the direct beam	$[\text{J m}^{-2}\,\text{s}^{-1}]$
ϵ	:	Initial light use efficiency	$[(\text{kg ha}^{-1}\,\text{h}^{-1})/(\text{J m}^{-2}\,\text{s}^{-1})]$

The assimilation rate per unit leaf area at a specific depth in the canopy is the sum of the assimilation rates of sunlit and shaded leaves, taking into account the proportion of sunlit and shaded leaf area at that depth in the canopy.

The fraction sunlit leaf area equals the fraction of the direct radiation reaching that layer:

$$f_{sl} = e^{-\kappa_{dr,bl} \cdot LAI_L} \tag{3.28}$$

Where:

f_{sl}	:	Fraction sunlit leaf area	[-]
$\kappa_{dr,bl}$	:	Extinction coefficient for the direct component of direct radiation (see eq. 3.18)	[-]
LAI_L	:	Cumulative leaf area index at relative depth L in canopy	[-]

The total instantaneous assimilation rate at a relative depth L can be calculated as:

$$A_{T,L} = f_{sl}A_{sl} + (1 - f_{sl})A_{sh} \tag{3.29}$$

Where:

$A_{T,L}$	:	Total inst. gross assimilation rate at a relative depth L	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
A_{sl}	:	Inst. gross assimilation rate for sunlit leaves	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
A_{sh}	:	Inst. gross assimilation rate for shaded leaves	$[\text{kg ha}^{-1}\,\text{h}^{-1}]$
f_{sl}	:	Fraction sunlit leaf area	[-]

The total instantaneous assimilation rate for the whole canopy per unit leaf area can be established using the Gaussian integration method, as a weighted average of the assimilation at three levels within the canopy. However, first the leaf area index of the levels selected have to be established (eq. 3.20):

Introducing the values of the leaf area index of the three selected layers in the equations mentioned before, will yield the instantaneous assimilation at these horizons. The weighted average of these values yields the total instantaneous assimilation rate for the whole canopy per unit leaf area.

The weighted average of the total instantaneous assimilation rates can be calculated as:

$$A_{C,l} = \frac{(A_{T,L,-1} + 1.6A_{T,L,0} + A_{T,L,1})}{3.6} \tag{3.30}$$

Where:

$A_{C,l}$	:	Total instantaneous canopy assimilation rate (per unit leaf area)	$[\text{kg ha}^{-1}\ \text{h}^{-1}]$
$A_{T,L,p}$	:	Total instantaneous gross assimilation rate at relative depth L (see eq. 3.29) at p= -1,0,1 (see eq. 3.20)	$[\text{kg ha}^{-1}\ \text{h}^{-1}]$

This total instantaneous assimilation rate is calculated per unit leaf area and must therefore be multiplied with the leaf area index to yield the total assimilation rate for the whole canopy:

$$A_C = A_{C,l} \cdot LAI \tag{3.31}$$

Where:

A_C	:	Total inst. gross assimilation rate for the whole canopy	$[\text{kg ha}^{-1}\ \text{h}^{-1}]$
$A_{C,l}$	:	Total inst. gross canopy assimilation rate per unit leaf area	$[\text{kg ha}^{-1}\ \text{h}^{-1}]$
LAI	:	Total leaf area of the crop (see §3.6.4)	$[\text{ha ha}^{-1}]$

Note that the green parts of the stems and the storage organs (like panicles) may absorb a substantial amount of radiation. Therefore, the green area index of these organs is added to the total leaf area. The green area index of the stems and storage organs can be calculated by multiplying the dry weight of the organ with respectively the specific stem area and the specific pod area (see also §3.6.4 and eq. 3.25). The specific stem area and specific pod area are crop specific and should be provided by the user.

3.3.3 Actual daily gross photosynthesis rate

In the previous section, the assimilation was treated as a function of the intercepted light and of photosynthetic crop characteristics such as initial light use efficiency and maximum leaf CO_2 assimilation at light saturation. However, the assimilation process can be hampered by suboptimum temperatures and/or by reduced availability of CO_2 due to closure of the leaf stomata as means to reduce transpiration.

Thus, the gross assimilation rate depends on day-time and night-time temperature as well as on the transpiration rate of the crop. In this paragraph this dependency will be briefly explained.

Daytime temperature

The maximum leaf CO_2 assimilation rate, A_m, has to be corrected for suboptimal average daytime temperatures. The correction factor is determined by the average daytime temperature and is also crop specific. An AFGEN table (acronym: **TMPFTB**) with the average day time temperature (2.2) as the independent variable is used to describe this dependency (see also Appendix 2). For an example see figure 3.5. The correction factor has to be multiplied with A_m.

Night-time temperature

It should be noted that assimilation is an enzymatic process and such processes are temperature dependent (Downes, 1970). However, there seems to be a considerable adaption of the assimilation processes to fluctuating and varying temperatures (de Wit *et al.*, 1978). A wide temperature range for optimum photosynthetic performance under field conditions is observed (Wardlaw, 1974). Low night-time temperatures also affect the assimilation. At night the assimilates, produced during daytime, are transformed into structural biomass. This process is hampered by low temperature. If these low temperatures prevail for a several days, the primary assimilates accumulate in the leaves and the assimilation rate diminishes and ultimately halts.

In the model, this temperature effect is accounted for by introducing a correction factor, which should be multiplied with A_m. This correction factor is a function of low minimum temperature and is crop specific. An AFGEN table (acronym: **TMNFTB**) is used to describe this dependency.
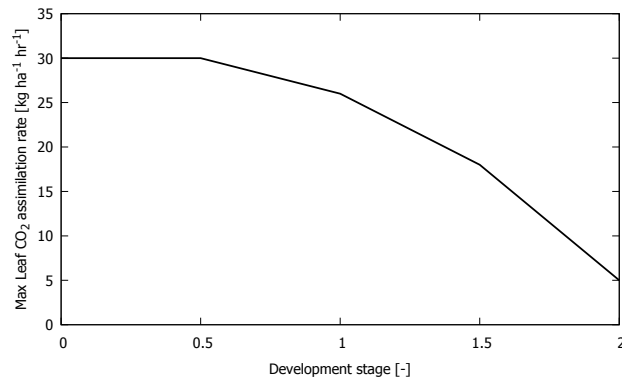
Figure 3.4: Maximum leaf CO_2 assimilation the rate as a function of development of the development stage.
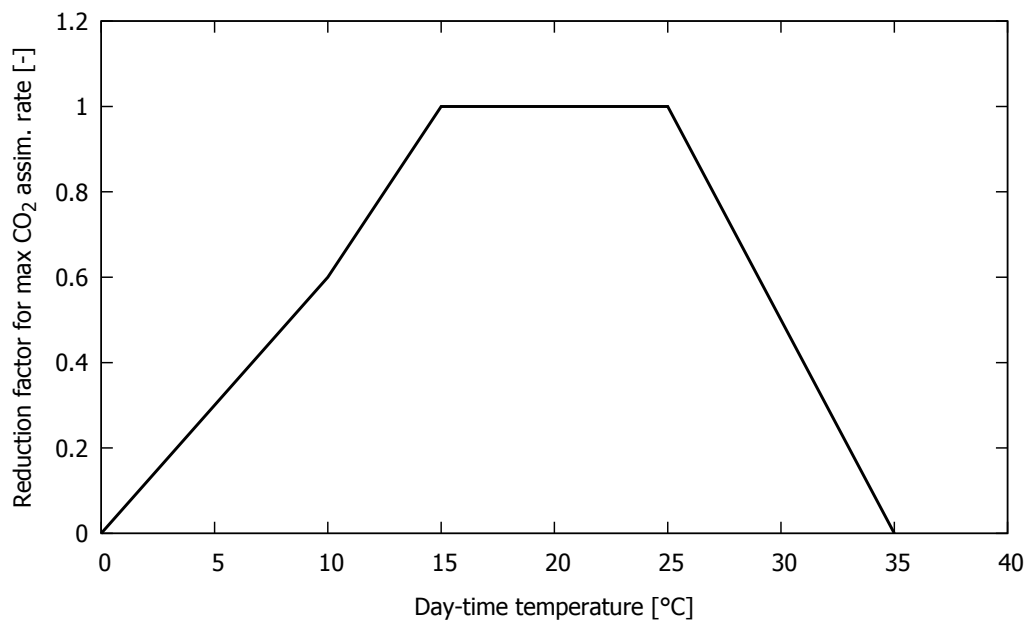
Figure 3.5: Reduction factor of the maximum leaf CO_2 assimilation rate as a function of average daytime temperature.

As a measure for quantifying the effect of low minimum temperature, the seven day running average of minimum temperature is used as the independent variable in the AFGEN table (see also Appendix 2).

$$T_{low} = \sum_{i=1}^{i=7} \frac{T_{\min,i}}{7}$$
(3.32)

Where:

T_{min}	:	Daily minimum temperature	[C]
T_{low}	:	Seven day running average of minimum temperature	[C]
i	:	Day	[-]

Water stress

The calculated daily assimilation in CH_2O per ha will be reduced when crop transpiration is reduced. The latter is caused by reduced water update by roots either due to water shortage or water surplus causing oxygen stress. In the model the effects of water stress on assimilation are related to the ratio of actual transpiration and potential transpiration (van Keulen & Seligman, 1987). The reduction factor for transpiration reduction can thus be calculated as.

$$RF_{tra} = \frac{T_{act}}{T_{\max}}$$
(3.33)

Where:

RF_{tra}	:	Reduction factor for reduced transpiration rates	[-]
T_{act}	:	Actual transpiration	[cm d^{-1}]
T_{max}	:	Maximum transpiration for given crop status as derived from the crop LAI and the reference evapotranspiration (see eq. 3.41)	[cm d^{-1}]

In §3.5 the calculation of the potential, T_p, and actual the transpiration, T_a, will be explained.

3.3.4 Photosynthesis in terms of CH$_2$O

In the photosynthesis process, CO_2 is reduced to carbohydrates (CH_2O) using the energy supplied by the absorbed light. The overall chemical reaction of this complex process is:

$$6\,CO_2 \; + \; 6\,H_2O \;\; \underrightarrow{light} \;\; C_6H_{12}O_6 \; + \; 6\,O_2 \tag{3.34}$$
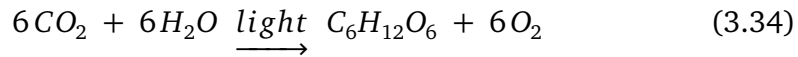
or in simplified form:

$$CO_2 \; + \; H_2O \;\; \underrightarrow{light} \;\; CH_2O \; + \; O_2 \tag{3.35}$$
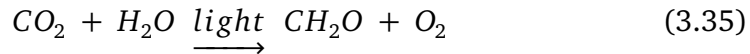
For each kg of CO_2 absorbed, $30/44$ kg of CH_2O is formed, the numerical values representing the molecular weights of CH_2O and CO_2 respectively.

$$R_d^1 \; = \; A_d^1 \, \frac{30}{44} \tag{3.36}$$

Where:

R_d	:	Gross daily CH_2O assimilation rate	[kg ha^{-1} d^{-1}]
A_d	:	Gross daily CO_2 assimilation rate (see eq. 3.12)	[kg ha^{-1} d^{-1}]

3.4   Maintenance respiration

Some of the carbohydrates formed are respired to provide energy for maintaining the existing biostructures. The maintenance processes include resynthesis of degraded proteins (especially enzymes) and maintenance of ionic gradients across cell membranes. The higher the metabolic activity of the plant, the higher the maintenance costs (Penning de Vries, 1975), probably due to a higher enzyme turnover and higher transport costs.

Maintenance respiration provides the energy for living organisms to maintain their biochemical and physiological status. Through the reaction which is the reverse of CO_2 reduction in the CO_2 assimilation, the radiation energy which was fixed in the photosynthetic process is released in a suitable form (ATP and NADPH):

$$CH_2O \; + \; O_2 \; \longrightarrow \; CO_2 \; + \; H_2O \; + \; energy \tag{3.37}$$
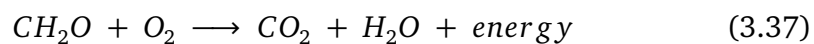
This maintenance respiration consumes roughly 15 - 30% of the carbohydrates produced by a crop in a growing season (Penning de Vries *et al.*, 1979). This indicates the importance of accurate quantification of this process in the model.

3.4.1   Maintenance respiration as a function of plant biomass

The maintenance costs may be estimated on the basis of the quantities of proteins and minerals present in the biomass and on crop metabolic activity, as presented by De Wit *et al.* (1978). This method, however, requires information on the nitrogen and mineral contents of the crop. Based on the results of this analysis, typical values for the maintenance coefficients of various plant organs have been derived by Penning de Vries & van Laar (1982). In the model, these coefficients are used to calculate the maintenance requirements of the crop. According to this approach the maintenance requirements are approximately proportional to the dry weights of the plant organs to be maintained:

$$R_{m,r} = \sum_{i=4}^{i=1} c_{m,i}\, W_i \qquad (3.38)$$

Where:

$R_{m,r}$	:	Maintenance respiration rate at reference temperature of 25 °C	$[\text{kg ha}^{-1}\ \text{d}^{-1}]$
$c_{m,i}$	:	Maintenance coefficient of organ i	$[\text{kg kg}^{-1}\ \text{d}^{-1}]$
W_i	:	Dry matter weight organ i (see eq. 3.61)	$[\text{kg ha}^{-1}]$
i	:	Leaves (lv), storage organs (so), stems (st) or roots (rt)	

The maintenance coefficient of organ i, $\mathbf{c_{m,i}}$, is crop dependent and should be provided by the user. Acronyms used in the model: **RML** (lv), **RMO** (so), **RMS** (st) and **RMR** (rt).

3.4.2   Dependency of the maintenance respiration on development stage

The calculated maintenance respiration rate (eq. 3.38) has to be corrected for senescence. This correction factor is crop specific and is defined as a function of development stage. An AFGEN table (acronym: **RFSETB**) with the development stage as independent variable, is used to describe this dependency. The maintenance respiration should be multiplied with this factor. Note that in field conditions differences in nitrogen content in the different organs due to aging of the plant may cause differences in the maintenance coefficients. This effect could be accounted for by relating the maintenance coefficients to the N content of the tissues (van Keulen & Seligman, 1987) but this is not accounted

for in WOFOST 7.2.

3.4.3   Dependency of the maintenance respiration on temperature

Higher temperatures accelerate the turnover rates in plant tissue and hence the costs of maintenance. An increase in temperature of 10°C increases maintenance respiration by a factor of about 2 (Kase & Catsky, 1984; Penning de Vries & van Laar, 1982). However, in order to be more flexible, in the model a variable Q_{10} (acronym: **Q10**) is introduced. Q_{10} is defined as the relative increase of the respiration rate per 10C temperature increase. Q_{10} should be provided by the user. The rate of the maintenance respiration at a certain temperature, can be calculated with:

$$R_{m,T} \;=\; R_{m,r}\, Q_{10}^{\frac{T-T_r}{10}} \tag{3.39}$$

Where:

$R_{m,T}$	:	Maintenance respiration rate at temperature T	[kg ha^{-1} d^{-1}]
$R_{m,r}$	:	Maintenance respiration rate at reference temperature of 25 °C (see eq. 3.38)	[kg ha^{-1} d^{-1}]
Q_{10}	:	Relative increase of the respiration rate per 10°C temperature increase	[-]
T	:	Average daily temperature	[°C]
T_r	:	Reference temperature [=25 °C in the model]	[°C]

For tropical species, the reference temperature may be 10°C higher than for species from temperate climates. The maintenance requirements of a crop are likely to be adapted to the higher growth temperatures. However, in WOFOST 7.2 the reference temperature is fixed at 25°C for all crops.

As stated before, maintenance respiration rate depends on the amount of dry matter in the various organs, the relative maintenance rate per organ and the temperature. It cannot exceed the actual gross assimilation rate. It is assumed that the vegetation will not be "self-consuming" in terms of carbohydrates. Actual gross assimilation rate minus maintenance respiration rate results in the amount of assimilates available for conversion into structural material.

3.5 Transpiration and evaporation

Transpiration, or the rate of water loss from the plants depends on the energy available for vaporization, on the difference in vapor pressure between the plant and the surrounding air and on the resistance to water vapor diffusion from the stomatal cavity to the atmosphere (van Keulen & Seligman, 1987). Potential transpiration is the water loss from a field crop which covers the soil completely and has an optimum supply of water from the soil.

3.5.1 Maximum evaporation and transpiration

The potential evapotranspiration rate of a cropped field ET_t is the sum of the maximum transpiration rate from the crop canopy $T_{\max}$ and the maximum evaporation rate from the surface below the crop canopy. The latter can either take place from a soil surface with maximum evaporation rate $E_{s,\max}$ or a water surface (in case of flooded crops like rice) with evaporation rate $E_{w,\max}$.

$$ET_t \;=\; T_{\max} + E_{s,\max} + E_{w,\max} \tag{3.40}$$

Where:

$T_{\max}$	:	Maximum crop transpiration rate	$[\text{cm d}^{-1}]$
$E0_{s,\max}$	:	Maximum evaporation of a bare soil	$[\text{cm d}^{-1}]$
$E0_{w,\max}$	:	Maximum evaporation of a water surface	$[\text{cm d}^{-1}]$

The maximum crop transpiration rate can be calculated from the reference evapontranspiration rate and the crop LAI. Moreover, for some crops the maximum crop transpiration rate can be higher than the reference evapotranspiration (section 2.3.2). Therefore, in the model a correction factor, a so called crop coefficient (acronym: **CFET**) is introduced to account for this effect. The reference evapotranspiration should be multiplied by this crop coefficient (Feddes, 1978; Doorenbos & Pruitt, 1977).

$$T_{\max} \;=\; ET0 \cdot CFET \cdot (1 - e^{-\kappa_{gb}\,LAI}) \tag{3.41}$$

Where:

$T_{\max}$	:	Maximum crop transpiration rate	$[\text{cm d}^{-1}]$
$ET0$	:	Reference crop evapotranspiration rate	$[\text{cm d}^{-1}]$
κ_{gb}	:	Extinction coefficient for global radiation	$[\text{-}]$
LAI	:	Leaf area index (see §3.6.4)	$[\text{ha ha}^{-1}]$

The extinction coefficient for global radiation κ_{gb} can be estimated as a factor times the extinction coefficient of diffuse radiation κ_{df} (3.16):

$$\kappa_{gb} = 0.75\,\kappa_{df} \qquad (3.42)$$

The evaporation rate is reduced due to the presence of vegetation, which intercepts the solar energy and reduces the windspeed. The maximum evaporation rate of a shaded soil surface as a function of the leaf area index (Goudriaan, 1977; Ritchie, 1972; 1971) can thus be estimated as:

$$E_{s,\text{max}} = E0_s \cdot e^{-\kappa_{gb}\cdot LAI} \qquad (3.43)$$

Where:

$E0_s$	:	Potential bare soil evaporation (equation 2.20)	[cm d^{-1}]
κ_{gb}	:	Extinction coefficient for global radiation	[-]
LAI	:	Leaf area index	[ha ha^{-1}]

The maximum evaporation rate from a shaded water surface can be calculated in an analogue way as equation 3.43:

$$E_{w,\text{max}} = E0_w \cdot e^{-\kappa_{gb} LAI} \qquad (3.44)$$

Where:

E$_{w,max}$	:	Maximum evaporation rate from a shaded water surface	[cm d^{-1}]
E0$_w$	:	Potential evaporation rate from a water surface (see §2.3.1)	[cm d^{-1}]
κ_{gb}	:	Extinction coefficient for global radiation	[-]
LAI	:	Leaf area index	[ha ha^{-1}]

3.5.2 Reduction of the transpiration due to water stress

For the potential yield level the actual transpiration rate is always equal to the maximum transpiration rate, because sufficient water is assumed to be available. The actual transpiration rate is calculated from the maximum transpiration rate, taking into account reductions for shortage or excess of water in the root zone. Water uptake by the roots depends on the difference in potential between the water in the plant and in the soil, and on the resistance to transport of moisture from the soil to the atmosphere (van Keulen & Seligman, 1987). In contrast to Feddes *et al.* (1978) not soil water potential, but soil water content

is chosen as the independent variable (Gollan *et al.*, 1986; Schulze 1986; Berg and Driessen, 2002).

Up to a point, the water potential in the plant can be adapted in order to maintain potential transpiration. At what soil moisture content the transition from potential transpiration to a transpiration deficit takes place, is difficult to quantify. In the model, the actual transpiration for the water limited run is obtained by multiplying the potential transpiration with a reduction factor. This reduction factor is defined as (van Diepen *et al.*, 1988):

$$R_{ws} = \frac{\theta_t - \theta_{wp}}{\theta_{ws} - \theta_{wp}} \tag{3.45}$$

Where:

R_{ws}	:	Reduction factor for transpiration in case of water shortage	[-]
θ_t	:	Actual soil moisture content (see eq. 6.1 and 6.34)	[cm^3 cm^{-3}]
θ_{wp}	:	Soil moisture content at wilting point	[cm^3 cm^{-3}]
θ_{ws}	:	Critical soil moisture	[cm^3 cm^{-3}]

The critical soil moisture content is defined as the soil moisture content below which water uptake is impaired and the crop begins to close its stomata. It is not a fixed value. Restriction of water uptake due to water stress starts at a higher water content when the potential transpiration rate is higher (Denmead & Shaw, 1962). The critical moisture content can be calculated as (van Diepen *et al.*, 1988):

$$\theta_{ws} = (1 - p)(\theta_{fc} - \theta_{wp}) + \theta_{wp} \tag{3.46}$$

Where:

θ_{ws}	:	Critical soil moisture content	[cm^3 cm^{-3}]
p	:	Soil water depletion fraction as a function of pot. evapotranspiration	[cm^3 cm^{-3}]
θ_{fc}	:	Soil moisture content at field capacity	[cm^3 cm^{-3}]
θ_{wp}	:	Soil moisture content at wilting point	[cm^3 cm^{-3}]

The soil moisture content at field capacity, θ_{fc} (acronym: **SMFCF**), and the soil moisture content at wilting point, θ_{wp} (acronym: **SMW**), are soil specific and should be given by the user. Figure 3.6 provides a graphical overview of the reduction function for transpiration (e.g. T_a/T_p) as a function of soil moisture content.

The soil water depletion fraction, p, is a function of the potential evapotran-

Table 3.1: Soil water depletion fraction (p) as a function of potential evapotranspiration of a closed crop canopy for different crop groups (Doorenbos *et al.*,1978).

Crop group	Crop ET0 in cm d-1								
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0.45	0.38	0.30	0.25	0.23	0.20	0.18	0.16	0.15
2	0.60	0.50	0.43	0.35	0.30	0.28	0.25	0.23	0.20
3	0.75	0.65	0.55	0.45	0.40	0.38	0.33	0.30	0.25
4	0.85	0.75	0.65	0.55	0.50	0.48	0.43	0.38	0.35
5	0.92	0.85	0.75	0.65	0.60	0.55	0.50	0.48	0.45

Table 3.2: Example of crops in the different crop groups (Doorenbos *et al.*, 1978).

Crop group	Representative crop types
1	leaf vegetables, strawberry
1-2	cabbage, onion
2	clover, carrot, early tobacco
2-3	banana, pepper
3	grape, pea, potato
3-4	bean, sunflower, tomato, water melon, grass
4	citrus, groundnut, pineapple
4-5	alfalfa cotton, tobacco, cassava, sweet potato, grains
5	olive, safflower, sorghum, soybean, sugarcane

spiration rate (for a closed canopy) and the crop group number. In literature, instead of the term soil water depletion fraction, also the expression easily available water is used. Easily available water is defined as the amount of water between θ_{fc} and θ_{wp} which can be extracted from the root zone without reducing the transpiration. Indicative p-values for the most important crops at different values of ET0 are presented in Table 3.1. The so-called crop group number ranges from 1 (drought-sensitive) to 5 (drought-resistant). An example of a classification of the different crop groups is presented in Table 3.2.

The soil water depletion fraction for very high values of potential evapotranspiration of a closed canopy can be as low as 0.10. For very low values of potential evapotranspiration of a closed canopy this fraction can be as high as 0.96. Note that it is possible that the reduction factor R_{ws} (eq. 3.45) might obtain values higher than one and lower than zero for certain values of p and θ_t. Since this does not make any sense, in the model the highest possible value for R_{ws} is set to one and the lowest possible value is set to zero. An empirical formula can be used to calculate the fraction of easily available soil water,

yielding identical values as the ones given in the Table 3.1 (van Diepen *et al.*, 1988).

$$ p = \frac{1}{\alpha_p + \beta_p \, ET0} - 0.10\,(5 - No_{cg}) \qquad (3.47) $$

Where:

p	:	Fraction of easily available soil water	$[cm^3 \ cm^{-3}]$
α_p	:	Regression constant (=0.76 van Diepen et al., 1988)	[-]
β_p	:	Regression constant (=1.5 van Diepen et al., 1988)	$[d \ cm^{-1}]$
ET0	:	Potential evapotranspiration rate	$[cm \ d^{-1}]$
No_{cg}	:	Crop Group number (=1 to 5, Doorenbos et al., 1978)	[-]

Note that crop group number, **No**$_{cg}$ (acronym: **DEPNR**) is input in the model and should be provided by the user.

For crop group 1 and 2 this estimate is not very accurate and an additional correction is applied to reproduce the table values correctly (van Diepen *et al.*, 1988):

$$ p = p + \frac{ET0 - 0.6}{No_{cg}\,(No_{cg} + 3)} \qquad (3.48) $$

3.5.3   Reduction of the transpiration due to oxygen stress

The transpiration rate of the plants can also be reduced when the root zone is completely saturated. Root systems which have been developed in aerobic soils do not have airducts and degenerate within several days when anaerobic conditions (waterlogging) are imposed (Penning de Vries *et al.*, 1989). Flooding quickly depletes the O_2 in the soil and root cells disintegrate when their metabolic activities are hampered by oxygen depletion. For detailed information on the physiological effects of excess water on a crop see Jackson and Drew (1984).

Reduction in transpiration occurs when the actual soil moisture content exceeds the critical soil moisture content for aeration. The critical soil moisture content for aeration can be calculated as:

$$ \theta_{air} = \theta_{max} - \theta_c \qquad (3.49) $$

Where:

θ_{air}	:	Critical soil moisture content for aeration	$[cm^3\ cm^{-3}]$
θ_{max}	:	Soil porosity	$[cm^3\ cm^{-3}]$
θ_c	:	Critical air content	$[cm^3\ cm^{-3}]$

The soil porosity, θ_{max} (acronym: **SMO**) and the critical soil air content, θ_c (acronym:**CRAIRC**), are soil specific and should be provided by the user.

In the model, maximum reduction is reached after four successive days of anaerobic conditions. In reality however, this period depends on the development stage and on the species. If at the fifth successive day oxygen shortage occurs the reduction remains the same as on the fourth day. The reduction factor for the transpiration rate due to oxygen shortage can be calculated as (van Diepen, personal communication):

$$R_{os,max} = \frac{\theta_{max} - \theta_t}{\theta_{max} - \theta_{air}} \tag{3.50a}$$

$$R_{os} = 1 - \frac{No_d}{4}\left(1 - R_{os,max}\right)\ \ with\ \ No_d \leq 4 \tag{3.50b}$$

Where:

$R_{os,max}$	:	Maximum reduction factor due to oxygen shortage	[-]
R_{os}	:	Reduction factor due to oxygen shortage	[-]
θ_{air}	:	Critical soil moisture content for aeration	$[cm^3\ cm^{-3}]$
θ_{max}	:	Soil porosity	$[cm^3\ cm^{-3}]$
θ_t	:	Actual soil moisture content (see eq. 4.20)	$[cm^3\ cm^{-3}]$
No_d	:	Number of successive days with oxygen stress	[-]

For crops which roots develop airducts, like for example rice, and for crops grown on perfectly drained land, the reduction factor for oxygen shortage equals unity. If this R_{os} is less then unity, the actual transpiration rate is reduced proportionally. Usually, in freely draining soils oxygen stress does not play any role. It may occur when the critical soil moisture content for aeration is greater than the soil moisture content at field capacity and when the subsoil is very slowly permeable. In case of groundwater influence, oxygen shortage may occur regularly.

However, the process of transpiration reduction due oxygen shortage is strongly simplified: it is just affecting transpiration; the aforementioned root decay is not modelled at all while the correct soil characterisation remains challenging. Moreover, it is important to state that the model is quite sensitive to errors in R_{os} because at (too) small values of R_{os}, T_a will be strongly affected resulting in little soil moisture extraction by the plant and again in (too) small values of

R_{os} the following day. In contrast, (too) small values of R_{ws} also result in (too) small values of T_a, and thus more correct values of R_{ws} th following day.

3.5.4 Actual transpiration

As a result of water excess and/or water shortage the reduction factor for the transpiration rate is calculated as:

$$RF_{tra} = R_{ws} \, R_{os} \tag{3.51}$$

And the actual transpiration rate as:

$$T_{act} = T_{\max} \cdot RF_{tra} \tag{3.52}$$

Figure 3.6 provides an overview of the ratio $\frac{T_{act}}{T_{\max}}$ as a function of soil moisture level θ.

3.6 Growth

The amount of CH_2O that remains after correction and reduction of the gross CO_2 assimilation rate (e.g. the net assimilation rate) is available to be converted into structural dry matter. The net assimilation rate is thus simply the difference between the gross actual assimilation rate and the losses due to maintenance respiration:

$$R_n = R_d \, - \, R_{m,T} \tag{3.53}$$

Where:

R_n	:	Net assimilation rate	$[\text{kg ha}^{-1}\,\text{d}^{-1}]$
R_d	:	Actual daily CH_2O assimilation rate (see eq. 3.33)	$[\text{kg ha}^{-1}\,\text{d}^{-1}]$
$R_{m,T}$	:	Maintenance respiration rate at temperature T (see eq. 3.39)	$[\text{kg ha}^{-1}\,\text{d}^{-1}]$

As it is assumed that the maintenance respiration cannot be larger than the actual gross assimilation rate, the net assimilation rate will be zero or larger.

The pattern of dry matter distribution over the various plant organs is closely related to the development stage of the crop. Development is defined as progression in the successive phenological stages. It is characterized by the for-
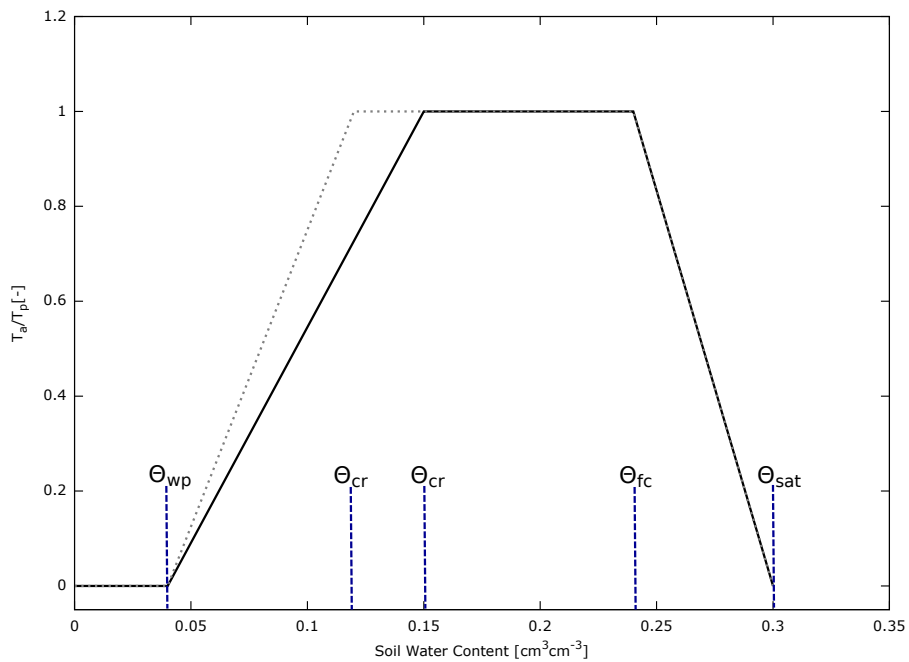
Figure 3.6: The relation between soil water content, θ, and $\frac{T_{act}}{T_{\max}}$ for a crop/soil combination. θ_{wp}, θ_{cr}, θ_{fc} and θ_{sat} represent the water content of the soil at wilting point, the critical point for potential transpiration, field capacity and saturation, respectively. The dashed line represents either a more drought resistant species under the same field conditions, or the same species under a lower evaporative demand, caused by different weather conditions (Penning de Vries et al., 1989; van Laar et al., 1992)

mation rate of the various vegetative and reproductive organs and their order of appearance. However, before the growth rates of the different organs can be computed, first the growth respiration has to be taken into account.

3.6.1 Growth respiration

The conversion of the net assimilate rate into structural plant material requires energy which is called 'growth respiration' in WOFOST. In this conversion process of the glucose molecules, CO_2 and H_2O are released. This is a partial combustion of glucose to provide energy required in the various biochemical pathways. Hence, biosynthesis of the various structural compounds can be considered a process of cut and paste, the scraps representing the weight lost in growth respiration. Each structural compound is formed along a distinct, non crop-specific pathway. Following these reactions, the weight of glucose required to produce a unit of the compound can be calculated (Penning de Vries *et al.*, 1974). The transport costs of the molecules are included. Two active passages of membranes are assumed. Each active passage requires 1 ATP, which is provided by respiring $^1/_{38}$ molecule of glucose.

The assimilates required to produce a unit weight of a certain plant organ can now be calculated from its chemical composition and the assimilate requirements of the various chemical compounds. The different plant organs and in particular the storage organs (grains, tubers, etc.) vary to much in composition among species for one general value of their assimilate requirements to be given. Therefore WOFOST uses a conversion efficiency which is crop and plant organ specific. The conversion efficiency represents the inverse of the assimilate requirement to produce one unit of structural plant material. At higher temperatures the conversion processes are accelerated, but the pathways are identical (Spitters *et al.* 1989). Hence, the assimilate requirements do not vary with temperature.

The conversion efficiency factor for the assimilates of a specified organ, $C_{e,i}$, is crop specific and are provided in the crop parameter files for different crop species. Acronyms used in the model: **CVL** (leaves), **CVO** (storage organs), **CVR** (roots) and **CVS** (stems).

To convert the net assimilates into a dry matter increase at the level of the whole plant, a conversion factor is required that takes into account the conversion efficiency of the different plant organs and the amount of assimilates partitioned to the different plant organs. Therefore the conversion factor for converting carbohydrates into structural plant material at the plant level is calculated as a weighted average of the conversion efficiencies and partitioning

factors for the various plant organs.

$$C_e = \frac{1}{\left(\sum_{i=1}^{i=3} pc_i/C_{e,i} \cdot (1 - pc_{rt}) \right) + pc_{rt}/C_{e,rt}} \qquad (3.54)$$

Where:

C_e	:	Conversion efficiency factor of assimilates, total crop	[kg kg^{-1}]
$C_{e,i}$	:	Conversion efficiency factor of the assimilates of a specified organ	[kg kg^{-1}]
pc_i	:	Partitioning factor of organ i (section 3.6.2)	[kg kg^{-1}]
i	:	Leaves (lv), storage organs (so), stems (st)	
rt	:	roots	

The dry matter growth rate of the total crop can be calculated as:

$$\Delta W = C_e \cdot R_n \qquad (3.55)$$

Where:

ΔW	:	Dry matter growth rate total crop	[kg ha^{-1} d^{-1}]
C_e	:	Conversion efficiency factor of assimilates, total crop (see eq. 3.54)	[kg kg^{-1}]
R_n	:	Net assimilation rate (see 3.53)	[kg ha^{-1} d^{-1}]

3.6.2 Dry matter partitioning

In WOFOST the dry matter is partitioned over the 4 parts of the plant according to fixed distribution factors, defined as a function of development stage. The background for this approach is mostly pragmatic: it makes it very easy to derive partitioning factors from crop experimental trials. Further, the mechanism is simple and fairly robust but it has been noticed that it strongly depends on having a correct description of the crop phenological development and cropping calendar. An improper phenological development or misplaced cropping calendar can easily lead to very high or very low leaf area index. A further drawback of the static partitioning tables is that they do not take into account the ability of the plant organs to store or process the assimilates (e.g. sink limitations), moreover there is no impact of environmental conditions on partitioning.

Dry matter is first partitioned between shoots and roots.

$$\Delta W_{rt} = pc_{rt} \cdot \Delta W \qquad (3.56a)$$

$$\Delta W_{sh} = (1 - pc_{rt})\Delta W \qquad (3.56b)$$

Where:

ΔW	:	Dry matter growth rate total crop	[kg ha^{-1} d^{-1}]
ΔW_{rt}	:	Dry matter growth rate roots	[kg ha^{-1} d^{-1}]
ΔW_{sh}	:	Dry matter growth rate shoots	[kg ha^{-1} d^{-1}]
pc_{rt}	:	Partitioning factor of roots	[kg kg^{-1}]

The growth rate of leaves, stems and storage organs is simply the product of the dry matter growth rate of the shoots and the fraction allocated to these organs.

$$\Delta W_i = pc_i \cdot \Delta W_{sh} \qquad (3.57)$$

Where:

ΔW_i	:	Dry matter growth rate of organ i	[kg ha^{-1} d^{-1}]
ΔW_{sh}	:	Dry matter growth rate of shoots	[kg ha^{-1} d^{-1}]
pc_i	:	Partitioning factor of organ i	[kg kg^{-1}]
i	:	Leaves (lv), storage organs (so), stems (st)	

The partitioning factors, **pc$_i$**, are a function of development stage and are crop specific. In the model, the dependency is described using AFGEN tables with the development stage as the independent variable (see Appendix 2). Acronyms used in the model: **FLTB** (lv), **FOTB** (so), **FRTB** (rt) and **FSTB** (st).

At any development stage the following relation must be valid, if not, the simulation will be stopped (see also fig. 3.7):

$$pc_{lv} + pc_{st} + pc_{so} = 1 \qquad (3.58)$$

Where:

pc_i	:	Partitioning factor of organ i	[kg kg^{-1}]
i	:	Leaves (lv), storage organs(so), stems (st)	

The actual gross CO_2 assimilation rate has to be identical to the amount of structural plant material produced plus the amounts used for maintenance respiration and conversion (see figure 5.1). The carbon balance has to be zero.

$$0 = \frac{R_d - R_{m,T} - R_g \left(pc_{rt} + (pc_{lv} + pc_{st} + pc_{so}) \cdot (1 - pc_{rt}) \right)}{R_d} \qquad (3.59)$$

Where:

R_g	:	Growth respiration rate (see eq. 3.53)	[kg ha^{-1} d^{-1}]
R_d	:	Actual daily CH$_2$O assimilation rate (see eq. 3.33)	[kg ha^{-1} d^{-1}]
$R_{m,T}$	:	Maintenance respiration rate (see eq. 3.39)	[kg ha^{-1} d^{-1}]
pc_i	:	Partitioning factor of organ i	[kg kg^{-1}]
i	:	Leaves (lv), storage organs (so), stems (st), roots (rt)	

As mentioned earlier, it is assumed that maintenance respiration can not exceed the actual gross assimilation rate. However, in case the daily CH$_2$O assimilation rate comes close to zero, this might happen and therefore simulation should be stopped. Introducing a division by R_d in the carbon check (eq. 3.59) will identify the occurrence of such an event.

3.6.3 Growth of stems, roots and storage organs

In the model, the death rate of the storage organs is considered to be zero. For the roots and the stems increase in living biomass can be easily determined as the growth rate minus death rate. This yields the net growth rate (eq. 3.60). The death rate is crop specific and is defined as the daily amount of the living biomass which no longer participates in the plant processes. The death rate of stems and roots is considered to be a function of development stage. This dependency is described using an AFGEN table with the development stage as the independent variable (see also Appendix 5). The death rate of leaves is more complicated. Leaf senescence due to shading (high LAI), water stress and physiologic ageing should be accounted for.

The net growth rate of the stems and roots can described by:

$$\Delta W n_i = \Delta W_i - \dagger_i W_i \qquad (3.60)$$

Where:

ΔWn_i	:	Net dry matter growth rate of organ i	[kg ha^{-1} d^{-1}]
ΔW_i	:	Dry matter growth rate of organ i (see eq. 3.57)	[kg ha^{-1} d^{-1}]
W_i	:	Dry matter weight organ i	[kg ha^{-1}]
$\dagger_i$	:	Death rate organ i	[kg kg^{-1} d^{-1}]
i	:	Stems (st), roots (rt)	

The death rates of stems and roots are crop specific and should be provided by the user. A dependency of the development stage is assumed. AFGEN tables (acronym: **RDRRTB** (rt), **RDRSTB** (st)) with the development stage as the independent variable are used to describe this dependency.

Although the process which describes the death rate of leaves is more complicated than the calculation of the death rate of stems and roots, the calculation to establish the total dry weight of living leaves is the same as the computation of the dry matter weight of stems and roots. The total dry matter weight of living leaves, stems and roots can be found by integration over time of the net dry matter growth, ΔWn_i, yields the dry matter.

$$W_{t,i} = W_{t-1,i} + \Delta Wn_i \Delta t \tag{3.61}$$

Where:

$W_{i,t}$	:	Dry matter weight organ i at time step t	$[\text{kg ha}^{-1}]$
ΔWn_i	:	Net dry matter growth rate of organ i	$[\text{kg ha}^{-1}\text{ d}^{-1}]$
Δt	:	Times step	$[\text{d}]$
i	:	Stems (st), roots (rt), leaves (lv)	

In the model, the initial values of the dry weight of the various organs are calculated. An initial value for the total dry weight of the crop (acronym: **TDWI**) should be provided by the user and can be derived from planting density and seed weight. This value is multiplied by the partitioning factors, pc_i, at emergence, yielding the initial values of dry weight of the various organs.

3.6.4 Growth of leaves

The area of green leaves is the major determinant for light absorption and photosynthesis of the crop. Under optimal conditions, light intensity and temperature are the environmental factors influencing the rate of leaf area expansion. Light intensity determines the rate of photosynthesis and hence the supply of assimilates to the leaves.

Temperature affects the rates of cell division and extension (Ng & Loomis, 1984; Sheehy *et al.*, 1980; Acock *et al.*, 1978). During the early stages of crop growth, temperature is the overriding factor. The rate of leaf appearance and final leaf size are constrained by temperature through its effect on cell division and extension, rather than by the supply of assimilates (Hunt, 1982; Causton & Venus, 1981; van Dobben, 1962). The growth curve in the early stage has an exponential form and it is assumed that the exponential growth

rate of the leaf area index continuous until the source-limited increase of the leaf area index equals the exponential growth rate.

The growth rate of the leaf area index per time step in the early, exponential growth stage, can be calculated as:

$$L_{Exp,t} = LAI_t \, RL \, T_e \qquad (3.62)$$

Where:

$L_{Exp,t}$	:	Growth rate of the leaf area index at time step t during exponential growth stage	[ha ha^{-1} d^{-1}]
LAI_t	:	Leaf area index at time step t	[ha ha^{-1}]
RL	:	Maximum relative increase of leaf area index	[C^{-1} d^{-1}]
T_e	:	Daily effective temperature (number of degrees above the base temperature for leave ageing **TBASE**)	[C]

The accumulated leaf area index at time step t during the exponential growth stage can be described as:

$$LAI_t = LAI_{t-1} + L_{Exp,t} \, \Delta t \qquad (3.63)$$

Where:

$L_{Exp,t}$	:	Growth rate of the leaf area index at time step t during exponential growth stage	[ha ha^{-1} d^{-1}]
LAI_t	:	Leaf area index at time step t	[ha ha^{-1}]
Δt	:	Time step	[d]

During the development of the crop, leaf area expansion is increasingly restricted by assimilate supply (i.e. source limited increase). Branching and tillering generate an increasing number of sites per plant, where leaf initiation can take place. As mentioned earlier, in the model it is assumed that the exponential growth rate of leaf area index will continue until it equals the source limited growth rate of the leaf area index.

The growth rate of the leaf area index at time step t during the source limited growth stage can be described by:

$$L_{Sc,t} = \Delta W \, n_{lv} \, S_{la} \qquad (3.64)$$

Where:

$L_{Sc,t}$: Growth rate of the leaf area index at time step t [ha ha^{-1} d^{-1}]
during the source limited growth stage

ΔWn_{lv} : Net dry matter growth of leaves at time step t [kg ha^{-1} d^{-1}]

S_{la} : Specific leaf area at time step t [ha kg^{-1}]

The net dry matter growth of leaves, ΔWn_{lv}, can be found by subtracting the weight of leaves which died during the current time step from the dry matter growth of leaves, ΔW_{lv}. This process will be described later in more detail in this paragraph.

The specific leaf area, S_{la} (acronym: **SLATB**), is defined as the increase of the leaf area of the crop per kg weight increase of the living leaves. S_{la} is crop specific and a function of the development stage (see figure 8). In the model this dependency is described using an AFGEN table with the development stage as the independent variable.

The accumulated leaf area index at time step t during the source limited growth stage can be described as:

$$LAI_t = LAI_{t-1} + L_{Sc,t} \, \Delta t \qquad (3.65)$$

Where:

$L_{Sc,t}$: Growth rate of the leaf area index at time step t [ha ha^{-1} d^{-1}]
during the source limited growth stage

LAI_t : Leaf area index at time step t [ha ha^{-1}]

Δt : Time step [d]

In the model, **LAI$_t$** is initialized by taking the fraction of initial biomass (acronym: **TWDI**) partitioned to the leaves and multiply at with the specific leaf area at the current DVS. Note that in older versions of WOFOST a specific leaf area index at emergence (acronym: **LAIEM**) was used which is now deprecated.

In the model, however, the accumulated leaf area cannot be calculated directly. The leaf area index has to be corrected for leaf senescence which occurred during the current time step. The leaf senescence can be caused by physiological ageing, water stress and/or high leaf area index (i.e. mutual shading) and is described in section 3.6.5.

In order to correct for leaf senescence, the specific leaf area of each time step, S_{la}, the growth of the dry matter weight of leaves per time step, ΔW_{lv} and the physiological age, P_{age} (see eq. 3.69), are stored in three different arrays. These arrays are organized as follows: the first element of the arrays represents the most recent age class (or time step) and the last element of the arrays represents the oldest age class (or time step). It should be clear that the position

of an element in the arrays represents its age class, in time steps. The dry matter weight of the leaves, which have died during the current time step, has to be. subtracted from the growth of dry matter weight per time step. One array contains thus the net dry matter growth of the leaves per time step, ΔWn_{lv}.

After the correction for leaf senescence, the accumulated leaf area can be established. The net dry matter weight of the leaves, $\Delta Wn_{lv,}$ in the remaining and new leaf classes is multiplied with the specific leaf areas (see eq. 3.64) to get the growth rate of the leaf area index of the living leaves per age class. Multiplication with Δt and summation over the classes (eq. 3.65) yields the total leaf area index. The green area index of the stems and the storage organs is added to this amount. The total dry matter weight of living leaves can be found in a similar way by using equation 3.61.

As is mentioned earlier, the green area index of the stems and storage organs, may absorb a substantial amount of radiation. Therefore it should be added to the total leaf area index. The green area index of these organs can be calculated by:

$$GAI_i \;=\; SS_i W_i \tag{3.66}$$

Where:

GAI_i	:	Green area index of organ i	$[\text{ha ha}^{-1}]$
SS_i	:	Specific green area of organ i	$[\text{ha kg}^{-1}]$
W_i	:	Dry matter organ i (see eq. 3.61)	$[\text{kg ha}^{-1}]$
i	:	Stems (st), storage organs (so)	

The specific green area of stems (acronym: **SSA**) and storage organs (acronym: **SPA**) are crop specific and should be provided by the user. The specific storage organ area is also known as the specific pod area.

Special attention should be paid to the fact that during the exponential growth stage, the specific leaf is not established. Therefore, during this period, for each time step, the specific leaf area has to be calculated according to:

$$S_{\exp,t} \;=\; \frac{L_{\exp,t}}{\Delta W_{lv}} \tag{3.67}$$
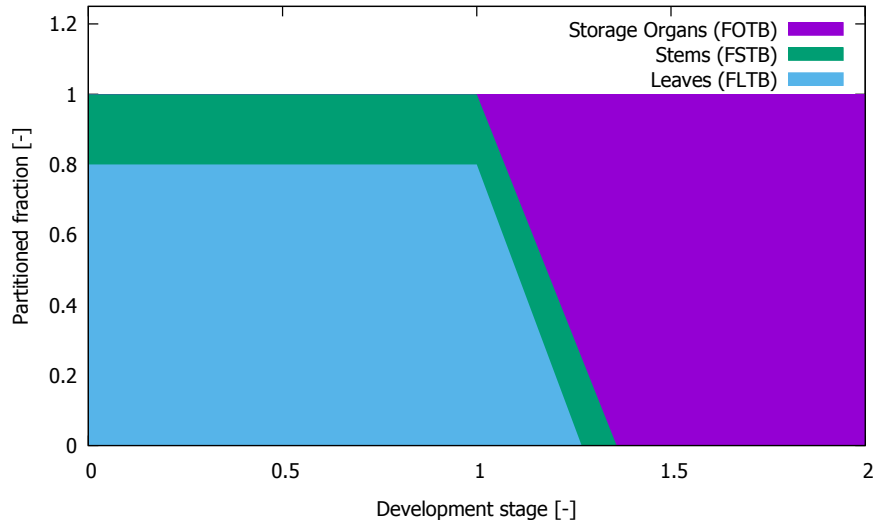
Where:

Figure 3.7: Example of the partitioning factors for potato of the different organs as a function of development stage.
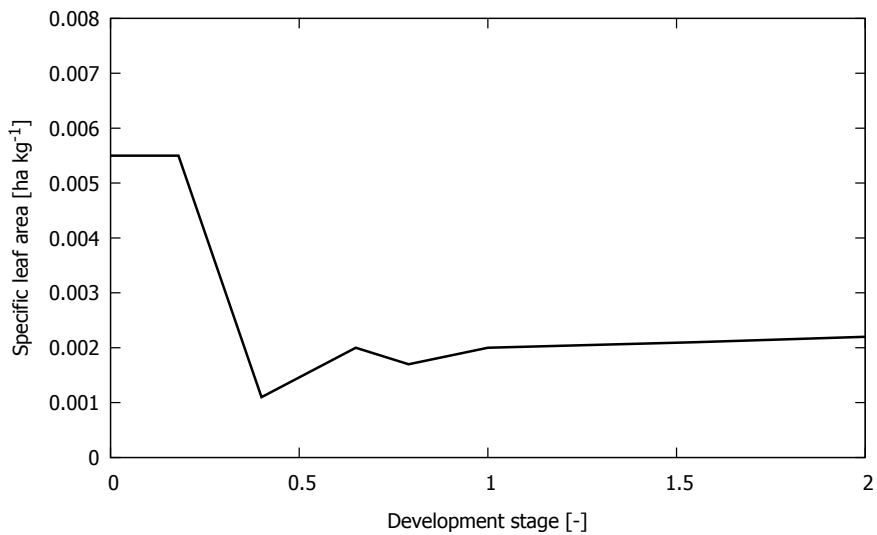

Figure 3.8: Specific leaf area as a function of development stage (example for rice).

$S_{exp,t}$	:	Specific leaf area at time step t during the exponential growth stage	$[ha\ kg^{-1}]$
ΔW_{lv}	:	Dry matter increase of leaves (see eq. 3.57)	$[kg\ ha_{-1}\ d^{-1}]$
$L_{exp,t}$	:	Growth rate of the leaf area index at time step t during exponential growth stage (see eq. 3.63)	$[ha\ ha^{-1}\ d^{-1}]$

In de model, it is assumed that senescence does not occur during the exponential growing stage. This means that ΔW_{lv} can be used in stead of the net dry matter growth, ΔWn_{lv}.

3.6.5 Death of leaves (senescence)

As stated before, leaf senescence is more complicated. Senescence refers to the loss of capacity to carry out essential physiological processes and to the loss of living biomass. The fundamental processes involve physiological ageing and protein breakdown. These processes are difficult to quantify. Leaves are assumed to die when they have completed their life cycle. The dying rate may be accelerated as a result of drought stress or of mutual shading.

physiologic ageing
Leaves die due to exceedance of the life span for leaves (i.e. physiologic ageing). Life span is defined as the maximum time in days a leaf can live at a constant temperature of 35°C. Life span is crop specific. The concept of lifespan is compatible with a definition in terms of temperature sum as given by Gallagher (1979). The physiologic ageing factor per time step can be calculated as:

$$f_{rai} = \frac{T - T_{b,age}}{35 - T_{b,age}} \qquad (3.68)$$

Where:

f_{rai}	:	Physiologic ageing factor for leaf age increase	[-]
T	:	Daily (average) temperature	[°C]
$T_{b,age}$	:	Lower threshold temperature for physiologic ageing	[°C]

The lower threshold temperature for physiologic ageing, $T_{b,age}$ (acronym: **TBASE**), is crop specific and should be provided by the user. The integral of the physiologic ageing factor over time yields the physiologic age.

$$P_{age,t} = P_{age,t-1} + f_{rai}\Delta t \qquad (3.69)$$

Where:

$P_{age,t}$: Physiologic age at time step t [d]
f_{rai} : Physiologic ageing factor for leaf age increase [-]
Δt : time step [d]

Leaves may attain the age defined by the crop specific life span (acronym: **SPAN**). However, as is mentioned earlier, they can not exceed it. In the model the ages of the leaf classes are checked. The first class younger than the defined life span becomes the oldest class. Note that death of old leaves takes place after ageing, being the result of the daily shifting from one leaf class to the next (Johnson & Thornley, 1983). In this way, the life time of leaves is the maximum number of days that a leaf class contributes to the LAI and to photosynthesis.

Death rate due to water stress
The potential death rate of leaves due to water stress can be calculated as:

$$\Delta W_d^1 = W_{lv} (1 - RF_{tra}) \dagger_{max,lv} \tag{3.70}$$

Where:

ΔW^1_d : Potential death rate of leaves due to water stress [kg ha^{-1} d^{-1}]
$\dagger_{max,lv}$: Maximum relative death rate of leaves due to water stress [kg kg^{-1} d^{-1}]
W_{lv} : Dry matter weight of the leaves (see eq. 3.61) [kg ha^{-1}]
RF_{tra} : Reduction factor for transpiration (see §3.5) [-]

The maximum relative death rate of leaves due to water stress, $\dagger_{max,lv}$ (acronym: **PERDL**) is crop specific and should be provided by the user.

Death rate due to high leaf area index
Leaf senescence also occurs due to high leaf area index (i.e. mutual shading). A relative death rate due to self–shading is defined which increases linearly from zero at a certain, critical leaf area index, to its maximum value at twice this critical leaf area index. Typical values for the maximum relative death rate and the critical LAI are 0.03 d^{-1} and 4 ha ha^{-1}, respectively (Spitters *et al.* 1989).

The potential death rate of leaves due to high LAI can be calculated as:

$$\Delta W_d^2 = W_{lv} \cdot 0.03 \cdot \frac{LAI - LAI_c}{LAI_c} \tag{3.71}$$

Where:

ΔW^2_d	:	Potential death rate of leaves due to high LAI	$[\text{kg ha}^{-1}\,\text{d}^{-1}]$
W_{lv}	:	Dry matter weight of the leaves	$[\text{kg ha}^{-1}]$
LAI	:	Leaf area index	$[\text{ha ha}^{-1}]$
LAI_c	:	Critical leaf area index	$[\text{ha ha}^{-1}]$

The critical leaf area index, LAI_c, can be computed by:

$$LAI_c = \frac{3.2}{\kappa_{df}} \tag{3.72}$$

Where:

LAI_c	:	Critical leaf area index	$[\text{ha ha}^{-1}]$
κ_{df}	:	Extinction coefficient for the diffuse radiation flux	[-]

The last term of the right hand side of the equation 3.71 must be between 0 and 0.03. A value lower than 0 will be set to 0 and a value higher than 0.03 will be set to 0.03. In the model, the highest value of the two calculated potential death rates of leaves, ΔW^1_d and ΔW^2_d, is selected for further calculations of the reduction of dry matter weight increase, per time step of the leaf classes, as is will be explained now.

The weight of leaves which have died during the current time step, can be calculated by multiplying the death rate (due to water stress and/or high LAI), with the time step.

$$W_d = \max(\Delta W^1_d, \Delta W^2_d) \cdot \Delta t \tag{3.73}$$

Where:

W_d	:	Weight of leaves that have died during current time step	$[\text{kg ha}^{-1}]$
ΔW^1_d	:	Potential death rate of leaves due to water stress	$[\text{kg ha}^{-1}\,\text{d}^{-1}]$
ΔW^2_d	:	Potential death rate of leaves due to high LAI	$[\text{kg ha}^{-1}\,\text{d}^{-1}]$
Δt	:	Time step	$[\text{d}]$

The weight of the leaves which have died, W_d, is subtracted from the weight of the oldest leaf class. If there is only one class the result should be positive. When more leaf classes exist, the oldest leaf class may be emptied completely, the remainder is subtracted from the next leaf class. Emptying the oldest leaf class goes on, until the original amount is dissipated completely and the remaining amount of leaves remains positive. All leaves are shifted every time step (daily) to the next class.

3.6.6   Root growth

Growth of roots in terms of depth is implemented in a simple way in WOFOST. The model assumes that at the start of the crop simulation, the crop has an initial rooting depth which is usually set to 10 cm. After initialization, the crop grows with a fixed daily increase in rooting depth until either a crop-specific maximum depth or a soil-defined maximum depth is reached. In versions of WOFOST that implement a shallow groundwater table, the increase in root depth will also cease if the roots are within 10cm of the groundwater table and the crop cannot form airducts. WOFOST does not define a root density profile and assumes that plant roots can subtract water equally from the entire rooted layer.

Growth of roots in terms of biomass follows the same logic as other plant organs in that the roots receive a fraction of the net daily assimilates based on the partitioning fraction to roots for that day. Similar to stems, death of root material depends on the development stage through a relative death rate that causes a fraction of the roots to die after a certain development stage.

In the model there is no relationship between the amount of biomass partitioned to the roots and the increase of the depth of the roots, with the exception that the increase in root depth will cease if there is no partitioning of biomass to roots anymore. Also there is no impact of environmental conditions (such as drought) on root growth.

In the model, the following crop and soil specific parameters are required:

- Initial rooting depth, RD_i (acronym: **RDI**);

- Maximum rooting depth determined by the crop, RD_{crop} (acronym: **RDMCR**);

- Maximum daily increase in rooting depth, RR_{max} (acronym: **RRI**);

- Maximum rooting depth determined by the soil, RD_{soil} (acronym: **RDM-SOL**).

The daily increase of the rooting depth is crop specific.

The root growth can be calculated as:

$$\Delta RD \;=\; RR_{max} \cdot \Delta t \tag{3.74}$$

Where:

ΔRD   :   Increase of the rooting depth   [cm]
RR_{max} :   Maximum daily increase in rooting depth   [cm d^{-1}]
Δt   :   Time step   [d]

In the model it is assumed that the extension growth of the roots continues until the maximum rooting depth is reached. The rooting depth can be established by:

$$RD_t = RD_{t-1} + \Delta RD \tag{3.75}$$

Where:

RD_t :   Rooting depth at time step t   [cm]
ΔRD   :   Increase of the rooting depth   [cm]

In the model, the maximum rooting depth is established by taking the lowest value of the maximum rooting depth determined by the crop, RD_{crop} and the maximum rooting depth determined by the soil, RD_{soil}. It is assumed that the maximum rooting depth is always equal or higher than the initial rooting depth.

3.7 Crop variables

The crop species are characterized by a set of parameters and functions. In the following subsections the estimated values, derived from experimental data, found in literature will be discussed in some detail.

3.7.1 Distribution and absorption of light in the canopy

The radiation flux, incident on a leaf, is partly absorbed and partly scattered. Scattering consists of reflection and transmission. Species differ in the optical properties of their leaves. In the model, a value of 0.20 is used for the scattering coefficient of individual leaves for PAR.

The light distribution within the canopy is characterized by the extinction coefficient (κ). As a reference, the situation is considered where the leaves show a spherical angle distribution (i.e. as if they were placed on the surface area of a sphere), and are distributed randomly within the canopy volume. Assuming the above scattering coefficient of 0.20, the theoretical value of the extinction coefficient for the diffuse radiation flux is 0.72 (Goudriaan, 1977). Actual values, however, can deviate substantially from this theoretical value. Crops with

more erect leaves (like many cereals) have lower κ values, whereas crops with more prostrate leaves show higher values of κ.

In the model, a spherical leaf angle distribution is assumed. Alternative distributions can easily be implemented using the procedure described by Goudriaan (1988). A clustered distribution of leaves increases mutual shading, resulting in reduced light absorption and hence a lower value for κ. However, especially in dicotyledons, new leaves are formed, preferably in gaps within the canopy, thus increasing the value of κ. In the model, an actual value for the extinction coefficient for diffuse radiation is used. The ratio between this actual value and the above theoretical value is used as a cluster factor. The various extinction coefficients and the fraction sunlit leaf area are multiplied by this factor.

Light absorption by organs other than leaves results in a calculated extinction coefficient which is too high, if the measured extinction is related to leaf area only. If light absorption and assimilation by these organs are important, as for ears and panicles in cereals, these processes should be accounted for explicitly in the model; e.g. by treating them as light competing assimilators. This is also necessary for other factors, such as foliar diseases, that affect the photosynthetic capacity of the leaves and are distributed non−uniformly over canopy depth.

Typical values of κ are 0.4 to 0.7 for monocotyledons and 0.65 to 1.1 for broad leaved dicotyledons (Monteith, 1969). The extinction coefficient can be estimated from measurements of PAR above and below a canopy with a known LAI, making sure that PAR is measured rather than total global radiation. The extinction coefficient for total radiation is about $\frac{2}{3}$ that of PAR.

The extinction coefficient has to be measured under a uniform overcast sky. Direct radiation has to be avoided as the solar elevation determines the extinction coefficient for direct radiation. In the morning all direct radiation will be absorbed and scattered in the top layer of the canopy. At noon, direct radiation will penetrate further in the canopy. If measurements have to be taken at a clear sky, a board can be used to shade the light measurement instrument. Otherwise, the average extinction coefficient over the day has to be calculated or the value has to be corrected for solar elevation. Light extinction can be measured by comparing radiation intensity above and below the canopy using a lightbar. From the LAI and the measured light extinction, the extinction coefficient for the diffuse flux can be calculated. When global radiation is measured the extinction coefficient for the diffuse flux will be about $\frac{2}{3}$ of the extinction coefficient calculated for global radiation, because absorption of near the infrared radiation by the canopy is less efficient.

An important factor which may confound the interpretation of measurements,

is the light absorption by other organs than leaves. In the calculation of the extinction coefficient for diffuse light, from measurements, this effect should be accounted for.

3.7.2   Photosynthesis-light response of individual leaves

The response of leaf photosynthesis to light intensity is characterized by its slope at low light intensity (ϵ) and its maximum rate at light saturation (A_m). With respect to the photosynthetic pathway, three groups of species can be identified: C_3 and C_4 species and CAM plants. Lists of C_4 species have been published by Downton (1975) and Raghavendra & Das (1978).

At a leaf temperature of 20C, both C_3 and C_4 species have an initial light use efficiency of approximately 12.5 μg CO_2 J^{-1} absorbed PAR or 0.45 kg CO_2 ha^{-1} leaf h^{-1} (J m^2 $S^{-1})^{-1}$ (Ehleringer & Pearcy, 1983). In C_3 species, ϵ decreases with increasing temperature due to accelerated photo-respiration. This temperature effect is relatively small: ϵ changes by about 1% with each change of 1C in temperature (Farquhar *et al.*, 1980; Ehleringer, 1978; Leverenz & Öquist, 1987). In C_4 species, ϵ is not affected by temperature because photo-respiration is suppressed in the C_4 pathway.

Among both C_3 and C_4 species, there is hardly any variation in (Ehleringer & Pearcy, 1983) ϵ. However, when ϵ is expressed per unit of incident PAR, instead of per unit of absorbed PAR, differences may occur, due to differences in the absorption coefficient of the leaves (Hunt *et al.*, 1985). Yellowing of leaves results in increased reflection and transmission and, therefore, in an decrease of ϵ.

Measured values of the gross assimilation rate of leaves at light saturation (A_m) show a large variation. The main sources of variation are differences in measurement conditions of temperature and ambient CO_2 concentration, differences in physiological and anatomical properties of the leaves as a result of differences in leaf age and pre—treatment, and variation among species and cultivars.

The influence of temperature on the rate of leaf photosynthesis is described in the model by multiplying the value of A_m by a temperature—dependent factor. The relationship between temperature and Am is based on Versteeg & van Keulen (1986). Various reaction types are distinguished according to crop species and habitat.

The photosynthetic capacity of the leaves is affected by the preceding conditions of radiation and temperature to which they were exposed: leaves adapt

their photosynthetic capacity to the environment. Therefore, A_m shows a seasonal course, which correlates with the time course of radiation and temperature (Parsons & Robson, 1981). This adaptation may be mimicked by using a seven—day running average of the value of A_m which has been adjusted for the environmental conditions (Schapendonk & Gaastra, 1984; Acock *et al.*, 1978). A consequence of this adaptation is that the photosynthetic characteristics of leaves of plants grown in climate rooms, are not representative for plants grown in the field.

The photosynthetic capacity of a leaf is also affected by its age: A_m reaches a maximum shortly after full expansion of the leaf, followed by a gradual decline with ageing (Rawson *et al.*, 1983; Dwyer & Stewart, 1986). Differences in photosynthetic capacity of the leaves are closely related to their nitrogen content, whether these variations are due to age, growing conditions or fertilizer application (van Keulen & Seligman, 1987). Leaves lower in the canopy have a lower photosynthetic capacity because they are older and are adapted to lower radiation levels (Acock *et al.*, 1978; Williams, 1985). They also have lower nitrogen concentrations. The value of A_m used in the model, refers to the photosynthetic capacity of full—grown leaves at the top of the canopy, as these leaves absorb most of the radiation. Effects of canopy senescence are introduced by a multiplication factor which is a function of development stage.

The photosynthetic capacity of leaves varies with crop species and cultivar. The coefficient of variation in A_m among genotypes within a species is of the order of 5—10% (Spitters & Kramer, 1986). Species can be grouped according to C_3 and C_4 types. Characteristic values range from 15—50 kg CO_2 ha^{-1} leaf h^{-1} for C_3 species and from 40-90 kg CO_2 ha^{-1} h^{-1} for C_4 species, depending on leaf N concentration and temperature (Spitters *et al.*, 1986). Other values mentioned, range from 10—50 kg CO_2 ha^{-1} leaf h^{-1} for C_3 species and from 10-90 kg CO_2 ha^{-1} h^{-1} for C_4 species (Goudriaan, 1982; van Keulen & Seligman, 1987).

Species from ruderal habitats show higher values than species from shaded habitats. In the model, estimates of A_m must be used, which are found by fitting the exponential function [equation 3.24] to data of gross photosynthesis of individual leaves. Such estimates may deviate from the measured values of photosynthetic efficiency at low light and photosynthesis at light saturation. If no firmly based value of A_m is available, a value of 40 kg CO_2 ha^{-1} h^{-1} for C_3 species and 70 kg CO_2 ha^{-1} h^{-1} for C_4 species is, in general, a reasonable estimate.

3.7.3   Respiration

Respiration is usually measured as CO_2 evolution in the absence of light energy. This dark respiration can be partitioned into growth and maintenance respiration; estimation procedures being reviewed by Amthor (1984). Typical values for maintenance coefficients are 0.03 for leaves, 0.015 for stems and 0.01 for roots (Spitters *et al.*, 1989). For tropical crops lower values are used: 0.02 for the leaves and 0.01 for the other plant organs (Penning de Vries *et al.*, 1989). As mentioned previously, these coefficients are affected by temperature, nitrogen content and mineral content of the plant tissue, and by the metabolic activity of the crop.

Measured rates of dark respiration of full—grown leaves, showed a large variation among species and among cultivars (M.J. de Kock, AB-DLO, Wageningen, unpubl.). The maintenance coefficients applied in the model are not based on conclusive evidence. This introduces a significant uncertainty in simulating the rate of crop growth, especially when the standing biomass is large compared to the current rate of photosynthesis, as at the end of the growth period.

Chapter 4

Soil modules

4.1 Water balance modules

Plant growth involves intake of atmospheric CO_2 through stomatal openings in the epidermis. Most of the water that plants take up from the soil is again lost to the atmosphere by transpiration through the same openings. The daily turnover can be considerable: transpiration from 0.4 cm of water from a crop surface on a clear sunny day corresponds with a water loss from the root zone of 40.000 kg ha^{-1} d^{-1}. If soil moisture take up by the roots is not replenished, the soil will dry out to such an extent that the plants wilt and - ultimately - die.

A crop growth simulation model must therefore keep track of the soil water balance which compares for a given period of time, incoming water in the rooted soil with outgoing water and quantifies the difference between the two as a change in the amount of soil moisture stored.

The actual root zone soil moisture content can be established according to (Driessen, 1986):

$$theta_t \ = theta_{t-1} \ + \frac{IN_{up} \ + \ IN_{low} \ - \ T_a}{RD}\Delta t \qquad (4.1a)$$

$$IN_{up} = P \ + \ I_e \ - \ E_s \ + \ \delta SS_t \ /\Delta t - \ SR \qquad (4.1b)$$

$$IN_{low} = CR \ - \ Perc \qquad (4.1c)$$

Where:

θ_t	:	Actual moisture content of the root zone at time step t	$[cm^3\ cm^{-3}]$
IN_{up}	:	Rate of net influx through the upper root zone boundary	$[cm\ d^{-1}]$
IN_{low}	:	Rate of net influx through the lower root zone boundary	$[cm\ d^{-1}]$
T_a	:	Actual transpiration rate of crop	$[cm\ d^{-1}]$
RD	:	Actual rooting depth	$[cm]$
P	:	Precipitation rate	$[cm\ d^{-1}]$
I_e	:	Effective daily irrigation	$[cm\ d^{-1}]$
E_s	:	Soil evaporation rate	$[cm\ d^{-1}]$
δSS_t	:	Surface storage	$[cm]$
SR	:	Rate of surface runoff	$[cm\ d^{-1}]$
CR	:	Rate of capillary rise	$[cm\ d^{-1}]$
Perc	:	Percolation rate	$[cm\ d^{-1}]$
Δt	:	Time step	$[d]$

Processes directly affecting soil moisture content of the root zone can be defined as:

- infiltration is transport from the soil surface into the root zone;

- evaporation is the loss of soil moisture to the atmosphere through the soil surface;

- transpiration by plants is loss of soil moisture to the atmosphere from the entire root zone;

- percolation is downward transport of water from the root zone to the layer below the root zone;

- capillary rise is upward transport into the rooted zone.

The water balance equation has to be solved for each time interval during the crop growth cycle.

For the calculation of potential production the soil moisture content is assumed to be at field capacity and no calculations need to be performed to simulate the water balance in the soil. Only the crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy.

For the calculation of the water limited production two different soil water balances are distinguished. The first water balance (called *Classic water balance*)

applies to a freely draining soil, where groundwater is so deep that it cannot have influence on the soil moisture content in the rooting zone. The soil profile is divided in two compartments, the rooted zone and the lower zone between actual rooting depth and maximum rooting depth. The subsoil below the maximum rooting depth is not defined. The second zone merges gradually with the first zone as the roots grow deeper towards the maximum rooting depth. This water balance applies to (regional) applications with limited information on soil properties.

Second, the WOFOST implementation connected to the SWAP model has a detailed water balance including multiple soil layers and variable integration time steps to account for highly non-linear processes in the soil. Besides estimating water availability, SWAP also deals with soil temperature and solute transport which allows to make detailed simulations of the behaviour of water and solutes in the soil and its impact on plant growth.The SWAP water balance is not treated in this manual as SWAP has its own set of documentation [1] where the theory and usage of the model is described.

4.1.1   Classic waterbalance: potential production

The purpose of the water balance for potential production is to quantify the crop water requirements for continuous growth without drought stress. It is assumed that the soil is permanently at field capacity.

$$\theta_t = \theta_{fc} \tag{4.2}$$

Where:

θ_t	:	Actual soil moisture content	[cm^3 cm^{-3}]
θ_{fc}	:	Soil moisture content at field capacity	[cm^3 cm^{-3}]

Rainfall, irrigation, capillary rise and drainage are not taken into account. The only two processes to consider are evaporation of the surface and transpiration of the crop. The calculation of the crop transpiration is described under section §3.5 while evaporation is treated in the same way as in the water balance for free drainage conditions (§4.1.2).

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[1]http://www.swap.alterra.nl

4.1.2 Classic Water balance: water-limited production under free drainage conditions

This soil module computes the variables of the soil water balance in the water-limited production scenario for a freely draining soil. No influence from groundwater is assumed. The purpose is to quantify the crop water use while subject tot either drought stress or water excess, and to quantify a possible reduction of the crop transpiration rate, leading to a reduced growth.

For the rooted zone the water balance equation is solved every daily time step. At the upper boundary, processes comprise the infiltration of water from precipitation or irrigation, evaporation from the soil surface and uptake of water and transpiration by the crop. If rainfall intensity exceeds the infiltration and surface storage capacity of the soil, water runs off. Water can be stored in the soil till the field capacity is reached. Additional water percolates beyond the lower boundary of the rooting zone. The flow rates are limited by the maximum percolation rate of the root zone and the maximum percolation rate of the water to the subsoil.

The textural profile of the soil is conceived homogeneous. Initially the soil profile consists of three layers (zones):

- the rooted zone between soil surface and actual rooting depth

- the lower zone between actual rooting depth and maximum rooting depth

- the subsoil below maximum rooting depth

The extension of the root zone from initial rooting depth to maximum rooting depth is described in §3.6.6. Its effect on the soil moisture content is accounted for in this soil water balance calculation. From the moment that the maximum rooting depth is reached the soil profile is described as a two layer system (Driessen, 1986). The lower zone no longer exists.

Initial soil water content and initial soil water amount

The initial value of the actual soil moisture content in the rooted part of the soil can be calculated as:

$$\theta_t = \theta_{wp} + \frac{W_{av}}{RD} \tag{4.3}$$

Where:

θ_t	:	Actual soil moisture content in rooted z one	$[cm^3\ cm^{-3}]$
θ_{wp}	:	Soil moisture content at wilting	$[cm^3\ cm^{-3}]$
W_{av}	:	Initial amount of available water in the soil in excess of θ_{wp}	$[cm]$
RD	:	Actual rooting depth (see §5.5)	$[cm]$

It should be mentioned that the initial actual soil moisture content, θ_t in WOFOST, cannot be lower than the soil moisture content at wilting point. In case the crop cannot develop airducts, the initial soil moisture content cannot be higher than the soil moisture content at field capacity. If the crop can develop airducts the initial soil moisture content cannot exceed the soil porosity. $\mathbf{W_{av}}$ (acronym: **WAV**), the initial amount of available soil moisture in excess of θ_{wp} should be provided by the user.

Multiplying the actual soil moisture content with the rooting depth yields the initial amount of water in the rooted zone. The initial amount of soil moisture in the lower zone, the zone between the rooted zone and the maximum rooting depth, can is as:

$$W_{lz} = W_{av} + RD_{\max}\ \theta_{wp} - RD\ \theta_t \qquad (4.4)$$

Where:

W_{lz}	:	Amount of soil moisture in the lower zone	$[cm]$
W_{av}	:	Initial amount of available soil moisture in excess of θ_{wp}	$[cm]$
$RD_{\max}$	:	Maximum rooting depth	$[cm]$
RD	:	Actual rooting depth	$[cm]$
θ_t	:	Actual soil moisture content in rooted zone	$[cm^3\ cm^{-3}]$
θ_{wp}	:	Soil moisture content at wilting point	$[cm^3\ cm^{-3}]$

The soil moisture content of the lower zone is also limited by the field capacity in case the crop cannot develop airducts, else the soil moisture content is limited by the soil porosity.

In the model, initially, the variable D_{slr}, days since last rain, is set to one. If the actual soil moisture content is halfway between the field capacity and wilting point a value of five days is assumed.

Evaporation

The evaporation from the surface below the canopy to the atmosphere can either come from a soil surface or a water surface. It also depends on the amount of available water in the soil and the infiltration capacity of the soil. If the water layer on the surface, the so called surface storage, exceeds 1 cm, the actual evaporation rate from the soil is set to zero and the actual evaporation rate from the surface water is equal to the maximum evaporation from a shaded water surface. If the surface storage is less than 1 cm and the infiltration rate of the previous day exceeds 1 cm d^{-1}, the actual evaporation rate from the surface water is set to zero and the actual evaporation rate from the soil is equal to the maximum evaporation from a shaded soil surface.

Without water on the soil surface, the variable D_{slr}, days since last rain, is use to control the decay in surface evaporation rate due to the drying out of the soil surface. The reduction of the evaporation is thought to be proportional to the square root of time (Stroosnijder, 1987, 1982). The initial value of D_{slr} depends on the moisture content in the top layer. It is set to value of five days if the soil moisture content is halfway between the field capacity and wilting point, otherwise a value of one day is used. The value of the variable days since last rain, D_{slr} increases every day thereby decreasing the actual soil evaporation rate. Its value is reset to one if the infiltration rate of the previous is larger than 1 cm d^{-1}, The soil evaporation is calculated as:

$$E_s = E_{s,\max}(\sqrt{D_{slr}} - \sqrt{D_{slr} - 1}) \tag{4.5}$$

Where:

E_s	:	Evaporation rate from a shaded soil surface	[cm d^{-1}]
$E_{s,\max}$	:	Maximum evaporation rate from a shaded soil surface (see eq. 3.43)	[cm d^{-1}]
D_{slr}	:	Days since last rain	[d]

When a small amount of water has infiltrated, or rather wetted the soil surface, this amount can be evaporated the same day, irrespective of D_{slr}. Therefore, the actual evaporation from the soil surface, as calculated according to equation 4.5, should be corrected for this amount of water infiltrating the soil. This amount should be added to the actual evaporation rate. However, it should be noted that the actual evaporation never can exceed the maximum evaporation rate.

Percolation

If the soil moisture content of the root zone is above field capacity, water percolates to the lower part of the potentially rootable zone and to the subsoil. In the model, a clear distinction is made between percolation from the actual rootzone to the so-called lower zone, and percolation from the lower zone to the subsoil. The former is called Perc and the latter is called Loss. The percolation rate from the rooted zone is calculated as:

$$Perc = \frac{W_{rz} - W_{rz,fc}}{\Delta t} - T_a - E_s \qquad (4.6)$$

Where:

Perc	:	Percolation rate from the root zone to the lower zone	$[\mathrm{cm\ d^{-1}}]$
W_{rz}	:	Amount of soil moisture in the root zone	$[\mathrm{cm}]$
$W_{rz,fc}$	:	Equilibrium amount of soil moisture in the root zone (see eq. 4.7)	$[\mathrm{cm}]$
Δt	:	Time step	$[\mathrm{d}]$
T_a	:	Actual transpiration rate (see eq. 3.51)	$[\mathrm{cm\ d^{-1}}]$
E_s	:	Evaporation rate from a shaded soil surface (see eq. 4.5)	$[\mathrm{cm\ d^{-1}}]$

The equilibrium amount of soil moisture in the root zone is calculated as the soil moisture content at field capacity times the depth of the rooting zone:

$$W_{rz,fc} = \theta_{fc}\, RD \qquad (4.7)$$

Where:

$W_{rz,fc}$	:	Equilibrium amount of soil moisture in the root zone	$[\mathrm{cm}]$
θ_{fc}	:	Soil moisture content at field capacity	$[\mathrm{cm^3\ cm^{-3}}]$
RD	:	Actual rooting depth	$[\mathrm{cm}]$

The percolation rate is limited by the conductivity of the wet soil (acronym: **SOPE**) in the same way as the infiltration is limited. The conductivity is soil specific and should be given by the user. Note that the percolation from the root zone to the lower zone can be limited by the uptake capacity of the lower zone. Therefore, the value calculated with equation 4.6 is preliminary. The capacity should first be checked.

The loss of water from the lower zone to the subsoil, the so-called Loss, should take the amount of water in the lower zone into account. If the amount of

water in the lower zone is less than the equilibrium amount of soil moisture, a part of the percolating water will be retained and the percolation rate will be reduced, thus:

$$Loss = \frac{W_{lz} - W_{lz,fc}}{\Delta t} + Perc \tag{4.8}$$

Where:

Loss	:	Percolation rate from the lower zone to the subsoil	$[\text{cm d}^{-1}]$
Perc	:	Percolation rate from root zone to lower zone (see eq. 4.6)	$[\text{cm d}^{-1}]$
W_{lz}	:	Amount of soil moisture in the lower zone	$[\text{cm}]$
$W_{lz,fc}$	:	Equilibrium amount of soil moisture in the lower zone (see eq. 4.9)	$[\text{cm}]$
Δt	:	Time step	$[\text{d}]$

The loss of water from the potentially rootable zone, is also limited by the maximum percolation rate of the subsoil. This maximum percolation rate (acronym: **KSUB**) is soil specific and should be provided by the user. The equilibrium amount of soil moisture in the lower zone can be calculated as the soil moisture content at field capacity times the depth of the root zone:

$$W_{lz,fc} = \theta_{fc} \left(RD_{\max} - RD \right) \tag{4.9}$$

Where:

$W_{rz,fc}$	:	Equilibrium amount of soil moisture in the lower zone	$[\text{cm}]$
θ_{fc}	:	Soil moisture content at field capacity	$[\text{cm}^3 \text{ cm}^{-3}]$
$RD_{\max}$	:	Maximum rooting depth	$[\text{cm}]$
RD	:	Actual rooting depth	$[\text{cm}]$

The saturated soil conductivity (acronym: **K0**) is soil specific. In the model, K0 is calculated from the pF curve assuming $pF = -1.0$ (i.e. a hydraulic head of 0.1 cm) The percolation rate from the lower zone to the sub soil is not to exceed this value (van Diepen *et al.*, 1988).

As mentioned before, the value calculated with equation 4.6, should be regarded as preliminary. The storage capacity of the receiving layer may become limiting. The storage capacity of the lower zone, also called the uptake capacity, is the amount of air plus the loss (van Diepen *et al.*, 1988). The storage capacity can de defined as:

$$UP = \frac{(RD_{\max} - RD)\,\theta_{\max} - W_{lz}}{\Delta t} + Loss \qquad (4.10)$$

Where:

UP	:	Uptake capacity of lower zone	[cm d^{-1}]
RD$_{\max}$	:	Maximum rooting depth	[cm]
RD	:	Actual rooting depth	[cm]
W$_{lz}$	:	Amount of soil moisture in lower zone	[cm]
$\theta_{\max}$	:	Soil porosity (maximum soil moisture)	[cm^3 cm^{-3}]
Δt	:	Time step	[d]
Loss	:	Percolation rate from the lower zone to the subsoil	[cm d^{-1}]

The percolation to the lower part of the potentially rootable zone can not exceed the uptake capacity of the lower zone. Therefore the percolation rate is equal to the minimum of the calculated percolation rate (eq. 4.6) and the uptake.

Preliminary calculation of the infiltration rate

The infiltration rate depends on the amount of available water and the infiltration capacity of the soil. If the actual surface storage is less than or equal to 0.1 cm, the preliminary infiltration capacity is simply described as:

$$IN_p = (1 - F_I\,C_I)P + I_e + \frac{SS_t}{\Delta t} \qquad (4.11)$$

Where:

IN$_p$	:	Preliminary infiltration rate	[cm d^{-1}]
F$_I$	:	Maximum fraction of rain not infiltrating during time step t	[-]
C$_I$	:	Reduction factor applied to F$_I$ as a function of the precipitation intensity	[-]
P	:	Precipitation rate	[cm d^{-1}]
I$_e$	:	Effective irrigation	[cm d^{-1}]
SS$_t$	:	Surface storage at time step t (see eq. 4.15)	[cm]
Δt	:	Time step	[d]

The maximum fraction of rain not infiltrating during time step t, **F**$_I$ (acronym: **NOTINF**) can be either set to a fixed value or be made variable by multiplying F$_I$ with a precipitation dependent reduction factor **C**$_I$ (acronym: **NINFTB**). If the fraction is variable, it means that it is maximum for high rainfall amounts,

and that it will be reduced for low rainfall. The user should provide F_I. Tabulated values of C_I are included in the model and are assumed to be fixed. The infiltration rate calculated is preliminary, as the storage capacity of the soil is not yet taken into account.

If the actual surface storage is more than 0.1 cm, the available water which can potentially infiltrate, is equal to the amount of water, present on the surface, that is supplied via rainfall and irrigation and depleted via evaporation from the water surface:

$$ IN_p = P + I_e - E_w + SS_{\frac{t}{\Delta t}} \tag{4.12} $$

Where:

IN_p	:	Preliminary infiltration rate	$[\text{cm d}^{-1}]$
P	:	Precipitation intensity	$[\text{cm d}^{-1}]$
I_e	:	Effective irrigation	$[\text{cm d}^{-1}]$
E_w	:	Evaporation rate from a shaded water surface	$[\text{cm d}^{-1}]$
SS_t	:	Surface storage at time step t (see eq. 6.29)	$[\text{cm}]$
Δt	:	Time step	$[\text{d}]$

However, the calculated infiltration rate is hampered by the conductivity of the soil. The calculated infiltration rate cannot exceed the conductivity of the soil, which is used as an infiltration limit. The conductivity of the soil (acronym: **SOPE**) is soil specific and should be given by the user.

Adjusted infiltration

The total loss of water from the root zone can now be calculated as the sum of the transpiration, the evaporation and the percolation. The sum of this loss and the available pore space in the root zone define the maximum infiltration rate. The infiltration rate cannot exceed this value. The maximum possible infiltration rate is given by:

$$ IN_{\max} = \frac{(\theta_{\max} - \theta_t)RD}{\Delta t} + T_a + E_s + Perc \tag{4.13} $$

Where:

IN_{max}	:	Maximum infiltration rate	$[\text{cm d}^{-1}]$
θ_{max}	:	Soil porosity (maximum soil moisture)	$[\text{cm}^3 \text{ cm}^{-3}]$
θ_t	:	Actual soil moisture content	$[\text{cm}^3 \text{ cm}^{-3}]$
RD	:	Actual rooting depth	$[\text{cm}]$
Δt	:	Time step	$[\text{d}]$
T_a	:	Actual transpiration rate	$[\text{cm d}^{-1}]$
E_s	:	Evaporation rate from a shaded soil surface	$[\text{cm d}^{-1}]$
Perc	:	Percolation rate from root zone to lower zone	$[\text{cm d}^{-1}]$

Finally, the adjusted infiltration rate is calculated as:

$$IN = Min(IN_p, IN_{max}, SOPE) \tag{4.14}$$

Surface runoff

Surface runoff is taken into account by defining a maximum value for the surface storage. If the surface storage exceeds the maximum value for surface storage the exceeding amount of water will run off. The surface storage at time step t can be calculated as:

$$SS_t = SS_{t-1} + (P + I_e - E_w - IN)\Delta t \tag{4.15}$$

Where:

SS_t	:	Surface storage at time step t	$[\text{cm d}^{-1}]$
P	:	Precipitation intensity	$[\text{cm d}^{-1}]$
I_e	:	Effective irrigation rate	$[\text{cm d}^{-1}]$
E_w	:	Evaporation rate from a shaded water surface	$[\text{cm d}^{-1}]$
IN	:	Infiltration rate (adjusted)	$[\text{cm d}^{-1}]$

The surface runoff can be calculated as:

$$SR_t = SS_t - \min(SS_t, SS_{max}) \tag{4.16}$$

Where:

SR_t	:	Surface runoff at time step t	$[\text{cm}]$
SS_t	:	Surface storage at time step t	$[\text{cm}]$
SS_{max}	:	Maximum surface storage	$[\text{cm}]$

SS$_{max}$ (acronym: **SSMAX**) is an environmental specific variable and should be provided by the user.

Rates of change and root extension

The rates of change in the amounts of water in the root zone and the lower zone are calculated straightforward from the flows found above:

$$\Delta W_{rz} = (IN - T_a - E_s - Perc)\Delta t \qquad (4.17a)$$
$$\Delta W_{lz} = (Perc - Loss)\Delta t \qquad (4.17b)$$

Where:

ΔW_{rz}	:	Change of the amount of soil moisture in the root zone	[cm]
ΔW_{lz}	:	Change of the amount of soil moisture in the lower zone	[cm]
T_a	:	Actual transpiration rate	[cm d^{-1}]
E_s	:	Evaporation rate from a shaded soil surface	[cm d^{-1}]
IN	:	Infiltration rate	[cm d^{-1}]
Perc	:	Percolation rate from root zone to lower zone	[cm d^{-1}]
Loss	:	Percolation rate from lower zone to sub soil	[cm d^{-1}]
Δt	:	Time step	[d]

Due to extension of the roots into the lower zone, additional soil moisture becomes available. The amount of the extra soil moisture in the new root zone and the amount of water in the reduced lower zone can be calculated as:

$$\Delta W_{rz} = \Delta W_{lz} = -W_{lz}\frac{RD_t - RD_{t-1}}{RD_{max} - RD_{t-1}} \qquad (4.18)$$

Where:

RD_t	:	Rooting depth at time step t	[cm]
RD_{t-1}	:	Rooting depth at time step t-1	[cm]
RD_{max}	:	Maximum rooting depth	[cm]
W_{lz}	:	Amount of soil moisture in the lower zone	[cm]
ΔW_{rz}	:	Change of the amount of soil moisture in the root zone	[cm]
ΔW_{lz}	:	Change of the amount of soil moisture in the lower zone	[cm]

Note that equation refeq:6.32 will only be executed when there is a root growth ($RD_t - RD_{t-1} > 0$) avoiding a division by zero when the roots have reached their maximm depth.

With equation 4.17a the actual amount of water in the root zone and in the lower zone can be calculated according to:

$$W_{rz,t} \; = \; W_{rz,t-1} \; + \; \Delta W_{rz} \qquad (4.19a)$$

$$W_{lz,t} \; = \; W_{lz,t-1} \; + \; \Delta W_{lz} \qquad (4.19b)$$

Where:

$W_{rz,t}$	:	Amount of soil moisture in the root zone at time step t	[cm]
$W_{lz,t}$	:	Amount of soil moisture in the lower zone at time step t	[cm]
$W_{rz,t-1}$	:	Amount of soil moisture in the root zone at time step t-1	[cm]
$W_{lz,t-1}$	:	Amount of soil moisture in the lower zone at time step t-1	[cm]
ΔW_{rz}	:	Rate of change of the amount of soil moisture in the root zone	[cm]
ΔW_{lz}	:	Rate of change of the amount of soil moisture in the lower zone	[cm]

Actual soil moisture content

The actual soil moisture content can now be calculated according to (see also eq. 4.1a):

$$\theta_t \; = \; \frac{W_{rz,t}}{RD} \qquad (4.20)$$

Where:

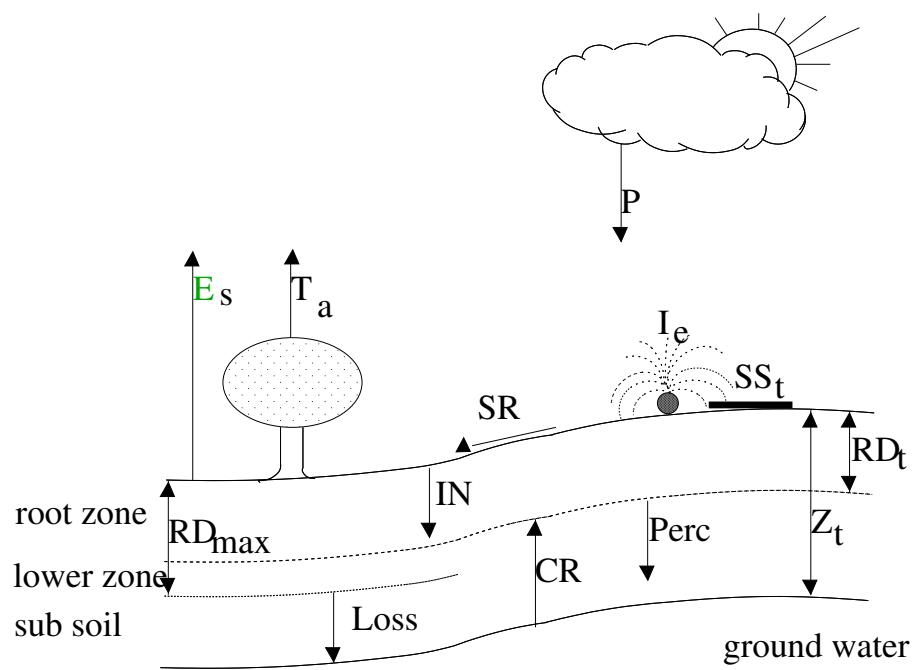|			
θ_t	:	Actual soil moisture content at time step t	$[\text{cm}^3 \text{ cm}^{-3}]$
$W_{rz,t}$	:	Amount of soil moisture in the root zone at time step t	[cm]
RD	:	Actual rooting depth	[cm]

Figure 4.1: Schematic representation of the different components of a soil water
balance

Chapter 5

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APPENDIX 1: Gaussian Integration

The Gaussian integration method as applied in the model, is based on a study by Goudriaan (1986). In the following text this method will be briefly explained.

The rate of crop photosynthesis can be computed from the photosynthesis - light response curve of individual leaves, the incoming radiation and the leaf area index. Leaf area distribution, extinction and reflection coefficients must also be known since they influence the distribution of the available radiation. This computational problem was essentially solved by De Wit (1965). He applied a stratification of the leaf canopy, calculated the absorbed radiation and the corresponding rates of photosynthesis of sunlit and shaded leaves in each layer. The contributions of the individual layers were added to find the rate of crop photosynthesis. This procedure was repeated every 15 minutes to obtain the daily total of crop photosynthesis. This procedure is lucid and flexible, but rather time consuming. Therefore, its use during an entire season as one would want in simulation of crop growth, might become problematic.

For application in such models Goudriaan and Van Laar (1978) developed a summary model for the daily total of crop photosynthesis, based on a semi-empirical equation, fitted to computer output of the detailed model.

Usually integration in time or in spatial dimension is done by means of the well-known numerical methods such as Eulerian (rectangular), Simpson or Runga - Kuta methods. These methods are excellent and generally applicable because they permit feedback of the integrated value (state variable) on the rate itself. But when there is no such feedback, and the profile of the rate is known on forehand, a method, devised by the German mathematician Gauss, is much more efficient and accurate.

Several examples of processes where this feedback is absent can be defined in the crop growth modeling. In those cases the Gaussian integration can be applied. Examples in the WOFOST model where this method is used:

- the calculation of crop photosynthesis from a known light profile. Integration of the light response curve over the leaf area depth of the canopy.

- integrate an independently given diurnal course (for example assimilation) into a daily total.

Gaussian integration is explained in several textbooks on numerical methods (Lanczos, 1957; Scheid, 1968). The basic idea is to compute the rate at positions in the total integration interval area as representative as possible. In its simplest form, the Gaussian one-point method, one single value of the rate is taken halfway through the integration interval. It gives a more accurate result than the rectangular integration method, because errors left and right of the evaluation point in the center practically cancel.

In a more formal analysis the integration interval is normalized to unity, and centralized between x=$-\frac{1}{2}$ and x=$\frac{1}{2}$. The polynomial given by y=a+bx+cx^2+dx^3 ... will have value a at the center point x=0. Therefore, the integrated value obtained by the one point Gaussian integration, will also be equal to a. Analytical integration of the polynomial term by term shows that the integrals of all odd terms disappear around x=0, That means that the one-point method not only exactly integrates $y = a$, but also $y = a + bx$. Similarly the two-point method will exactly $integrate\, y = a + bx + cx^2$ and $y = a + bx + cx^2$+dx^3. The next step is the three point method which will enable exact integration of the fourth order term (and automatically the fifth as well).

The three points of the Gaussian numerical integration are situated symmetrical around x = 0, in order to integrate the interval [-0.5,0.5]. Therefore, one of the three function evaluation points will be at the center, x=0. The other two points will be located at either side of the Y-axis at distance γ (so x=-γ and x=γ). Now the interval [-0.5 ,0.5] is divided in three parts, around these three points. The lengths of these sub-intervals determine the weights which must be imposed on the Y-values corresponding to these three x-values and considered representative for their sub-interval. Because of the symmetry again, the weights belonging to -γ and γ are equal. When these weights are considered 1, the weight of the central sub-interval is equal to ω.

The values of the relative distance γ and of the weight ω can be derived from the requirement that both the second and the fourth order terms of the polynomial will be exactly integrated (Goudriaan, 1986):
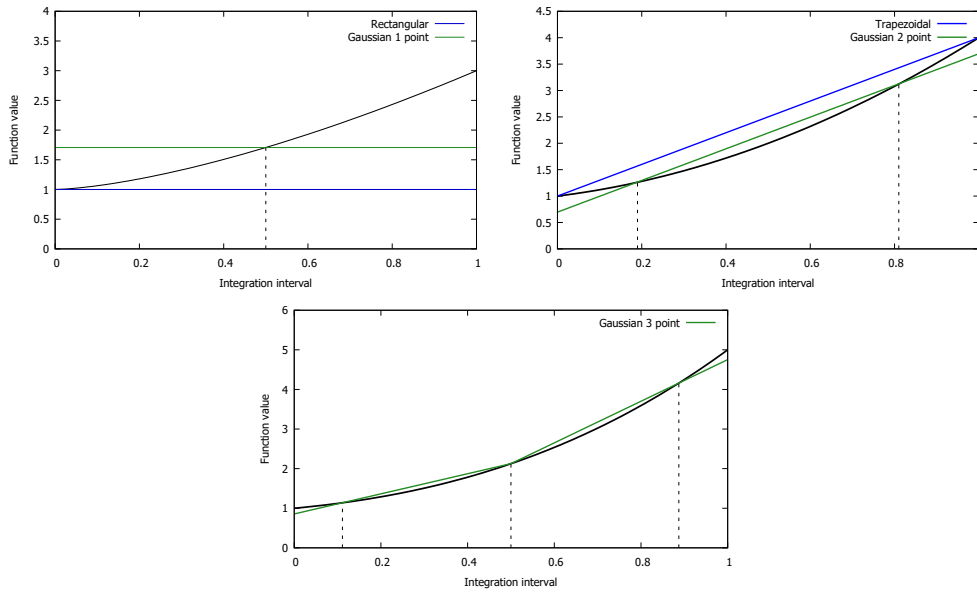
Figure 1: Numerical integration methods for general use and the corresponding Gaussian methods for use when there is no feedback. 1 - Rectangular - Gaussian one point; 2 - Trapezoidal - Gaussian two point; 3 - Gaussian three point

$$
\begin{array}{ccc}
 & Numerical\ result & Analytical\ result \\[2mm]
2^{nd}order & \dfrac{(-\gamma)^2 + 0 \cdot \omega + \gamma^2}{1 + \omega + 1} & = \displaystyle\int_{-\frac{1}{2}}^{-\frac{1}{2}} x^2 dx = \dfrac{1}{12} \\[6mm]
4^{th}order & \dfrac{(-\gamma)^4 + 0 \cdot \omega + \gamma^4}{1 + \omega + 1} & = \displaystyle\int_{-\frac{1}{2}}^{-\frac{1}{2}} x^4 dx = \dfrac{1}{80}
\end{array}
$$

$$
\begin{array}{cc}
2^{nd}order & 4^{th}order \\[2mm]
\dfrac{(-\gamma)^2 + \gamma^2}{1 + \omega + 1} = \dfrac{1}{12} & \dfrac{(-\gamma)^4 + \gamma^4}{1 + \omega + 1} = \dfrac{1}{80} \\[4mm]
\dfrac{2\gamma^2}{2 + \omega} = \dfrac{1}{12} & \dfrac{2\gamma^4}{2 + \omega} = \dfrac{1}{80} \\[4mm]
24\gamma^2 = 2 + \omega & 160\gamma^4 = 2n + \omega
\end{array}
$$

Substitution yields the following values for the relative distance and the weight:

$$\gamma = \sqrt{\frac{24}{160}} = \sqrt{0.15}$$
$$\omega = 1.6$$

Examples of the use of Gaussian Integration in the model

Canopy assimilation is calculated as a weighted average of the assimilation at three horizons within the canopy. The leaf area index of the selected horizons can be calculated as:

$$L = (0.5 + p\sqrt{0.15})LAI \qquad where\ p = -1, 0, 1 \Rightarrow$$
$$L_1 = 0.1127017 \cdot LAI$$
$$L_2 = 0.5 \cdot LAI$$
$$L_3 = 0.8872983 \cdot LAI$$

The weighted average of the assimilation over the three selected horizons is:

$$A_h = \frac{LAI(A_{-1} + 1.6A_0 + A_1)}{3.6} \Rightarrow$$
$$A_h = LAI(0.2778A_{-1} + 0.4444A_0 + 0.2778A_1)$$

Where:

] A_h : Hourly canopy assimilation $[\text{g CO}_2\ \text{m}^{-2}\ \text{h}^{-1}]$

To integrate the instantaneous canopy assimilation over the day, again the Gaussian approach of numerical integration is applied. The three selected points refer to the period from noon to sun set. Daily canopy assimilation is obtained as the weighted average of the instantaneous assimilation rates at the selected time points:

$$t_h = 12 + 0.5D(0.5 + p\sqrt{0.15}) \qquad where\ p = -1, 0, 1$$

$$A_d = \frac{D(A_{h,-1} + 1.6A_{h,o} + A_{h,1})}{3.6}$$

Where:

D : Day length   [h]

th : Hour of day   [h]

A_d : Daily canopy assimilation $[g\ CO_2\ m^{-2}\ d^{-1}]$

APPENDIX 2: AFGEN function

AFGEN stands for **A**rbitrary **F**unction **GEN**erator. It a function which is used for linear interpolation in a one-dimensional array with paired data. The uneven places in the array represent the X-values, whereas the Y-values are represented by the even places of the array. Such an array can be used to describe the dependency of variable Y of variable X in case no mathematical description is available or is too cumbersome. A plotted example is depicted in figure A2:
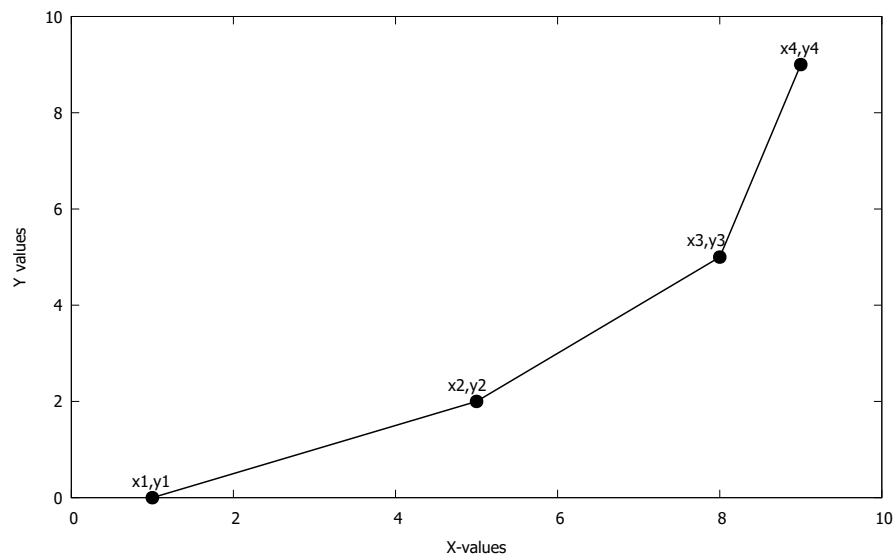
Figure 2: Linear interpolation

The array belonging to this example has to be filled as:

Place	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Value	X_1	Y_1	X_2	Y_2	X_3	Y_3	X_4	Y_4

The arguments of the AFGEN function in order of their place in the argument

list are: name of the table, number of pairs, X value to be interpolated. The X-values have to be arranged from low to high values and are not allowed to be interchanged. Every X-value has to precede its connected Y-value.

Three situations for interpolation can occur:

1. The argument x at which interpolation should take place is less or equal to the first X-value in the array. The Y-value is set to the first Y-value in the array.

2. The argument x value at which interpolation should take place is between the first and the last X-value in the array. The Y-value can now be found via linear interpolation. First the X values left and right from the argument x have to be detected, then the Y-value can be calculated:

$$y \; = \; Y_{n-1} \; + \; (x - X_{n-1}) \frac{Y_n - Y_{n-1}}{X_n - X_{n-1}}$$

3. The argument x at which interpolation should take place is equal to or larger then the last X-value in the array. The Y-value is set to the last Y-value in the array.

APPENDIX 3: Parameters in WOFOST

Crop specific parameters

Acronym	Symbol	Description	Units
Initial values			
LAIEM		leaf area index at emergence **(deprecated!)**	ha ha^{-1}
TDWI	W	initial total dry weight of the crop	kg ha^{-1}
RGRLAI	RL	maximum relative increase in leaf area index	ha ha^{-1} d^{-1}
Emergence			
TBASEM	T_b	lower threshold temperature for emergence	°C
TSUMEM	R	temperature sum from sowing to emergence	°C
TEFFMX	R	maximum effective temperature for emergence	°C
Phenology			
DLC	D_c	critical day length for development (lower threshold)	h
DLO	D_o	optimum day length for development	h
IDSL	-	indicates whether pre-anthesis development depends on temperature (0) temperature and daylength (1) temperature, daylength and vernalization (2)	
DTSMTB	DT_s	daily increase in temperature sum as a function of daily mean temperature (AFGEN table)	°C
TSUM1	ΣT_i	threshold temperature sum from emergence to anthesis	°C
TSUM2	ΣT_i	threshold temperature sum from anthesis to maturity	°C
DVSEND	-	development stage at harvest	[-]
VERNRTB	-	Relative rate of vernalization as a function of daily mean temperature	[d]
VERNSAT	V_{sat}	Saturated vernalization requirements	[d]
VERNBASE	V_{base}	Base vernalization requirements	[d]

VERNDVS	-	DVS after which vernalization will be disabled	[-]

Green Area

SLATB	S_{la}	specific leaf area as a function of development stage (AFGEN table)	ha kg^{-1}
SPA	SS_{so}	specific pod area	ha kg^{-1}
SPAN	-	life span of leaves growing at an average temperature of 35 °C	d
SSA	SS_{st}	specific stem area	ha kg^{-1}

Assimilation

AMAXTB	A_m	maximum CO2 assimilation rate as a function of development stage of the crop (AFGEN table)	kg ha^{-1} h^{-1}
EFFTB	ϵ	initial light use efficiency of CO2 assimilation of single leaves as a function of daily mean temperature	kg ha^{-1} h^{-1} J^{-1} m^{2}s
KDIFTB	κ_{df}	extinction coefficient for diffuse visible light as a function of development stage	-
TMNFTB	-	correction factor of daily gross CO2 assimilation rate as a function of T_{low} (AFGEN table)	°C
TMPFTB	-	correction factor of maximum leaf CO2 assimilation rate as a function of sub-optimum average day temperatures, T_{day} (AFGEN table)	°C

Conversion of assimilates into biomass

CVL	$C_{e,lv}$	efficiency conversion of assimilates into leaf dry matter	kg kg^{-1}
CVO	$C_{e,so}$	efficiency conversion of assimilates into storage organ dry matter	kg kg^{-1}
CVR	$C_{e,rt}$	efficiency conversion of assimilates into root dry matter	kg kg^{-1}
CVS	$C_{e,st}$	efficiency conversion of assimilates into stem dry matter	kg kg^{-1}

Maintenance respiration

Q10	Q_{10}	increase of the respiration rate per 10 °C temperature increase	kg ha^{-1} d^{-1}
FSETB	-	reduction factor for the maintenance respiration as a function of DVS	-
RML	$c_{m,lv}$	maintenance respiration rate coefficient of leaves d^{-1}	
RMO	$c_{m,so}$	maintenance respiration rate coefficient of storage organs d^{-1}	
RMS	$c_{m,rt}$	maintenance respiration rate coefficient of stems d^{-1}	
RMR	$c_{m,rt}$	maintenance respiration rate coefficient of roots d^{-1}	

Partitioning

FLTB	pc_{lv}	fraction of above-ground dry-matter increase partitioned to leaves as a function of development stage (AFGEN table)	-
FOTB	pc_{so}	fraction of above-ground dry-matter increase partitioned to storage organs as a function of development stage (AFGEN table)	-
FRTB	pc_{rt}	fraction of total dry-matter increase partitioned to roots as a function of development stage (AFGEN table)	-
FSTB	pc_{st}	fraction of above-ground dry-matter increase partitioned to stems as a function of development stage (AFGEN table)	-

Death rate

PERDL	$\dagger_{max,lv}$	maximum relative death rate of leaves due to water stress	d^{-1}
RDRRTB	$\dagger_{rt}$	relative death rate of roots as a function of DVS (AFGEN table)	$kg\ kg^{-1}\ d^{-1}$
RDRSTB	$\dagger_{st}$	relative death rate of stems as a function of DVS (AFGEN table)	$kg\ kg^{-1}\ d^{-1}$
TBASE	$T_{b,age}$	lower threshold temperature for physiological ageing of leaves	°C

Water use

CFET	-	correction factor for evapotranspiration	-
DEPNR	No_{cg}	crop group number	-
IAIRDU	-	indicates presence (1) or absence (0) of airducts in the plant	-
IOX	-	enables (1) or disables (0) oxygen stress	-

Rooting

RDI	RD_I	initial rooting depth	cm
RDMCR	RD_{crop}	crop-dependent maximum rooting depth	cm
RDMSOL	RD_{soil}	soil-dependent maximum rooting depth	cm
RRI	RR_{max}	maximum daily increase of rooting depth	$cm\ d^{-1}$

Soil specific parameteres

Acronym	Symbol	Description	Units
Soil water retention			
SMW	θ_{wp}	soil moisture content at wilting point	$cm^3\ cm^{-3}$
SMFCF	θ_{fc}	soil moisture content at field capacity	$cm^3\ cm^{-3}$
SM0	θ_{max}	soil porosity	$cm^3\ cm^{-3}$
WAV	W_{av}	initial available soil water amount in excess of θ_{wp}	cm
NOTINF	F_I	maximum fraction of rain not infiltrating into the soil	-

CRAIRC	θ_c	critical soil air content	$cm^3 \ cm^{-3}$
CONTAB	K(pF)	^{10}log hydraulic conductivity as a function of the pF (AFGEN table)	log(cm)
Percolation			
K0	K	hydraulic conductivity	$cm \ d^{-1}$
SOPE	-	maximum percolation rate rote zone	$cm \ d^{-1}$
KSUB	-	maximum percolation rate subsoil	$cm \ d^{-1}$
SSMAX	SS_{max}	maximum surface storage capacity	cm
DD	DD	drainage depth	cm
ZTI	-	initial depth of the groundwater table	cm